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Concepts and Synthesis

From metrics to meaning: diversity as an essentially contested concept

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Biodiversity is among ecology's most widely invoked but least consistently defined concepts. Despite decades of theoretical and methodological developments, ecologists continue to disagree about what "diversity" measures and how it should be quantified. These disagreements have direct consequences to conservation science, policy making, and public engagement. We argue that this enduring debate is not a sign of conceptual failure but evidence that *diversity* is an *essentially contested concept* (ECC) *sensu* Gallie [1]. Diversity is internally complex, appraisive, and historically dynamic: it comprises multiple, value-laden dimensions whose relative importance depends on context and purpose. Using examples from taxonomic diversity, we show that common metrics (e.g., richness, Shannon, Simpson, and Hill numbers) encode distinct value judgments (normative commitments) about how abundances shape diversity and, in turn, determine which species are considered most important to biodiversity. Likewise, spatial frameworks such as additive and multiplicative partitioning embody different normative assumptions about whether diversity represents the sum of local contributions or the relationships among communities. Beyond metrics, both definitional ambiguity and persistent knowledge shortfalls reinforce diversity's plural and evolving character. Our goal is to show that recognizing diversity as an ECC is not a weakness of ecological thought, but rather a call for more reflective, inclusive, responsible research, teaching, and policy, anchoring biodiversity science within a richer understanding of its ethical and epistemic foundations. Diversity's very "elusiveness" is what makes it powerful: it invites ecologists, policymakers, and citizens alike to reflect on what they value in the living world and to be explicit about how those values shape science and decision-making. Recognizing biodiversity as an ECC reframes disagreement as an opportunity rather than an obstacle. It calls for transparency about normative commitments, pluralism in measurement, and reflexivity

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Abbreviations: ECC, essentially contested concept; KMGBF, Kunming–Montreal Global Biodiversity Framework.

in linking ecological analysis to ethical and political goals. Treating diversity as an ECC clarifies why no single metric can be definitive and offers a principled foundation for navigating conceptual plurality across ecological research, conservation planning, and global biodiversity governance.

KEYWORDS
biodiversity; diversity metrics; essentially contested concepts; normative commitments; Shannon entropy; Simpson index; Hill numbers; alpha–beta–gamma diversity; philosophy of ecology; conservation policy

1 | INTRODUCTION

Globally, we spend about $140 billion USD per year on biodiversity conservation [2]. The Kunming–Montreal Global Biodiversity Framework (KMGBF; 2022) calls for raising this by an additional $700 billion annually by 2050. The scale of biodiversity investment dwarfs the cost of ending global hunger [4], yet we still struggle to define what we are paying for. Such figures underscore the substantial value society places on biodiversity, but also raise a fundamental question: what, *exactly*, are we conserving and managing?

Definitions such as those offered by the World Health Organization (2025) describe biodiversity as "the variability among living organisms from all sources," encompassing genetic, species (taxonomic), and ecosystem levels, among others. While sufficient as general descriptions, such definitions have limited use for guiding specific decision-making at any spatial scale. Instead, conservation planning requires biodiversity to be described in ways that are quantifiable, comparable, and sensitive to change over time and space. Nevertheless, ecologists have long pursued empirical approaches to studying biodiversity, developing a wide array of metrics and concepts to quantify its variation across communities and ecosystems. Although these were originally motivated by scientific inquiry, they have become central to conservation planning and policy. Critically, they reflect two key considerations: the *dimensions* of variation being considered (e.g., taxonomic, functional, phylogenetic, genomic) and the *mathematical approaches* used to quantify those dimensions, including richness counts and abundance-sensitive or probability based indices (e.g., Shannon, Simpson, Hill numbers). Yet these are not merely technical alternatives; they embody normative commitments[1] about which aspects of life matter most, how those aspects should be quantified, and how the resulting quantities should be interpreted and valued [6, 7, 8]. These commitments ultimately shape conservation and management priorities, industry targets, and policy outcomes. We view *diversity* and *biodiversity* as converging at the intersection of ecology, conservation, and ethical reflection on the value of life. Each invites ecologists, policymakers, and citizens to examine what they hold to be significant in the living world and to make those commitments explicit in how knowledge and action are shaped. Ecologists, in particular, contribute the technical and conceptual means to quantify diversity, yet these scientific tools inevitably embody normative assumptions once interpreted through the ethical and societal lens that the concept of biodiversity provides.

If we are going to invest substantial resources to conserve biodiversity, should we not be able to clearly articulate what we are conserving? The practical implications of this question are anything but abstract. Consider a conservation "trolley problem[2]" (Figure 1): this schematic illustrates how the evaluation of "diversity" depends on the metric applied.

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[1] *Normative commitments* are value-based presuppositions about what *ought* to hold, as opposed to descriptive assumptions about what *is*; and they guide the framing of concepts, and the standards by which explanations or justifications are deemed legitimate

[2] A trolley problem is a thought experiment in moral philosophy that poses a dilemma between two or more harmful outcomes, typically

Given constraints in funding, time, and space, a conservation biologist must decide which of two communities (A or B) to protect. Both communities differ in their rank–abundance structures (left and centre panels), and their diversity profiles (right panel) show that Community A has higher species richness but lower evenness, while Community B has fewer species but a more even distribution of abundances. As will be reviewed in section 2, diversity can be expressed using Hill numbers, which vary across a parameter q to reflect different weightings of species abundances. Using this framework, Community A appears more diverse at low q values (where richness dominates), whereas Community B appears more diverse at higher q values (where common species are weighted more heavily). The figure highlights that judgments about which community is "more diverse" are contingent on normative choices about what aspect of diversity matters most.

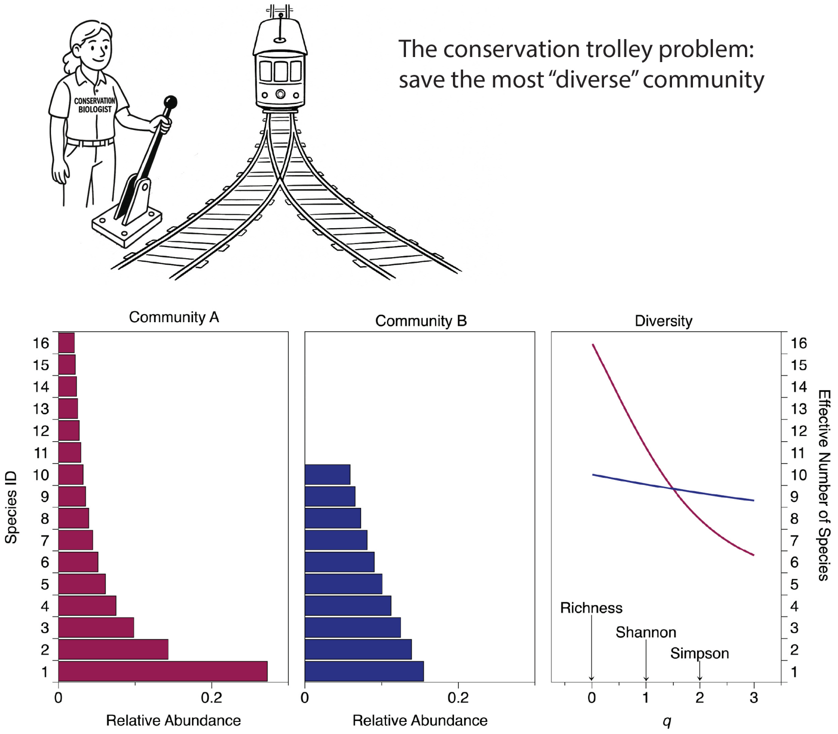

FIGURE 1 A conservation trolley problem [*sensu* 9]. The biologist must recommend on which of the two sites to allow development. Diversity at each site is shown as the effective number of species, also know as the Hill number (see section 2.3). The parameter q comes from the Hill number formula, see Equation 3). The choice of q is not a scientific decision. There is no right or wrong choice for the value of q. Different values prioritize different aspects of diversity over others. The choice of any particular value constitutes a normative commitment to that particular priority. When $q = 0$, the index reflects species richness, i.e., the number of different species present in the community. When $q = 1$, the index reflects the Shannon entropy index (Equation 1) and when $q = 2$ the index reflects the Simpson diversity index (see Equation 2; see subsection 2.1).

This ambiguity is not merely hypothetical. KMGBF Target #1 for 2030 calls for "all areas of high biodiversity

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whether to divert a runaway trolley to save a greater number of people at the cost of intentionally harming fewer, used to probe ethical reasoning about consequences, duties, and moral responsibility.

importance” to be managed to reduce biodiversity loss. Yet the framework itself acknowledges that “there is no single definition” of such areas, leaving it to countries (or other regional authorities) to decide based on their specific contexts and priorities [3]. This admission reveals a central challenge: despite its prominence in global science and policy, biodiversity lacks a universally agreed definition or mode of quantification. Yet conservation decisions are often made without a full understanding of why one metric is chosen over another, or of the conceptual and normative commitments each metric or dimension entails. These underlying assumptions ultimately shape how biodiversity is quantified, valued, and/or prioritized.

In this paper, we argue that biodiversity, and ecological *diversity* more broadly, is best understood as an *essentially contested concept* (ECC), in the sense articulated by Gallie [1]. Unlike ordinary contested concepts, which may be resolved through clearer definitions or sharper measurements, ECCs remain inherently plural: they admit multiple, mutually incompatible yet reasonable interpretations. The disagreements are not merely semantic but reflect divergent normative commitments about what is valuable. Familiar examples include *fairness* in legal sentencing, *democratic* representation, and the *aesthetic* value of works of art. *Diversity*, we contend, belongs to this same class of enduring conceptual disputes in which scientific definitions are inseparable from underlying ethical and epistemological commitments.

ECCs share a set of features that underlie their persistent disagreement and debate about their meaning and application [1, 10]. They are internally complex, comprising multiple, and sometimes conflicting properties. In the case of *diversity*, these include species richness, evenness, and the relative weight (or value) assigned to each species abundances, among others. ECCs also display a dual character: they are both descriptive, referring to measurable ecological states, and appraisive, embedding normative commitments about what is valuable or desirable. For biodiversity, this duality connects scientific assessments to ethical and policy concerns, such as what constitutes ecological health, resilience, or desirable function. More concretely, these commitments influence decisions about habitat prioritization, resource allocation, and recovery benchmarks, linking scientific (ecological) measurement to value-based goals in practice. This is precisely what makes such decisions normatively loaded[3], since determining which properties to prioritize inherently reflects ethical considerations and broader conservation and management objectives. We use the term *normative commitments* rather than *assumptions* when qualifying and quantifying biodiversity to emphasize that these are not merely implicit premises, but value-laden stances that actively shape interpretation, judgment, and decision-making.

As Gallie (1955) first argued, and as Connolly (1993) later elaborated, contestation is not a flaw but a constitutive feature of ECCs, reflecting the evolving interplay between empirical knowledge, social values, and normative commitments. ECCs give rise to ongoing, sincere disagreements about their proper use; disagreements that are rational and well-founded, yet ultimately irresolvable. In ecology, shifting priorities over time have reshaped what *diversity* means, driving a proliferation of quantification methods and expanding the dimensions emphasized, from species identity to traits, evolutionary history, rarity, abundance structure, and scale. Recognizing *diversity* as an ECC instead reframes persistent disagreement as an opportunity to promote clarity, embrace pluralism, and increase transparency. By making explicit the normative commitments embedded in biodiversity metrics and dimensions explicit, ecologists can more effectively bridge theory and practice, foster interdisciplinary dialogue, and help ensure that biodiversity fulfills its promise as a unifying framework for ecological research and policy [12, 13, 14]. The plurality of metrics and dimensions should not be dismissed as confusing. Rather, it represents an opportunity to clarify the foundations of biodiversity quantification, examine why certain metrics are chosen, and link those choices to conservation goals. In doing so, it becomes clear that biodiversity conservation and management are not merely technical undertakings,

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[3] *Normatively loaded* =df describes a term, concept, or claim that carries implicit evaluative or prescriptive content, such that it reflects judgments about what *ought* to be the case rather than being purely descriptive.

but inherently normative practices, shaped by value-laden commitments regarding what *diversity* ought to quantify and represent [15, 12, 16]. As Burch-Brown and Archer [17] argue, the very concept of biodiversity carries normative weight: decisions about which dimensions of variation to prioritize reflect judgments about what kinds of life and difference are worth valuing and protecting.

We propose that understanding biodiversity as an essentially contested concept helps clarify the persistent disagreements over its definition and measurement that shape research, conservation practice, policy, and public engagement. Our goal is to equip readers with conceptual tools for critically evaluating diversity frameworks and making explicit, context-appropriate choices in how they define and apply the concept. While some points will be familiar to experienced ecologists and conservation practitioners, we have found through research, teaching, and policy work that these conceptual and normative tensions are often under-acknowledged, leading to confusion or misplaced certainty. Finally, certain arguments recur across sections by design: this deliberate repetition reinforces the structure of our argument, illustrates how similar normative commitments surface in different domains, and allows each section to stand independently for readers from diverse disciplinary backgrounds.

The argument unfolds in four stages, each building toward the claim that the framework of the essentially contested concept (ECC) brings clarity to enduring debates about biodiversity. We start by examining how ecologists quantify *diversity*, revealing the implicit normative commitments embedded in different metrics. This analysis sets the stage for asking whether these recurring disagreements arise because *diversity* functions as an essentially contested rather than an ordinary concept. Concluding that it does, we consider what the ECC framework contributes in terms of conceptual clarity and practical guidance, and how ecologists might engage with it across research, conservation, management, and policy. We conclude with a synthesis that reflects on the broader implications of this perspective for ecological theory and practice.

2 | QUANTIFYING DIVERSITY: UNITY, DIVISION, AND DEBATE

For clarity and focus, we limit our discussion to *taxonomic diversity*, defined by the relative abundances and identities of species within ecological communities. We acknowledge, of course, that diversity is also commonly conceptualized across other important dimensions, including functional, phylogenetic, and genetic, all of which have been recognized as important for conservation [18]. Each of these adds (potentially) distinct dimensions and often introduces competing criteria for what it means for a system to be *diverse*. Rather than resolving this plurality, such extensions deepen the essentially contested nature of the concept, reinforcing that *diversity* resists any single, unambiguous definition.

How we quantify biodiversity shapes both our understanding of ecosystems and the decisions we make about their conservation and management. Yet quantifying diversity is far from straightforward and remains a major source of disagreement. Ecologists have suggested various metrics and frameworks to quantify and compare diversity across different scales. While these approaches provide mathematical clarity, they can also introduce complexities for practitioners and the public. Additionally, they involve normative commitments and judgments, prompting important questions about what exactly is being measured and the reasons behind it. While “quantifying” biodiversity often evokes retrospective assessment (e.g., monitoring), it is equally important to acknowledge that diversity values can, and in many cases *ought to*, serve as forward-looking targets that inform proactive conservation and management strategies [19, 20].

To understand why biodiversity qualifies as an ECC, we examine four interrelated aspects of how ecologists think about and measure *diversity*. First (§2.1), we consider some commonly used metrics and perspectives that reflect not merely methodological variation, but fundamentally different views on what *diversity* is (or ought to be) and the normative commitments they embody. This step involves deconstructing these metrics to expose the value-laden assumptions embedded within them. Second (§2.2), we revisit alpha (α), beta (β), and gamma (γ) diversity as scale-dependent constructs that embed normative judgments about meaningful ecological variation. Third (§2.3), we explore the unifying framework of "effective species counts" (also known as Hill numbers), which offer coherence but still contain the normative commitments of other metrics. Finally (§2.4), we distinguish between disagreements rooted in technical requirements (e.g., scale-consistency, sampling standardization), and those stemming from in normative commitments, such as how rarity ought to be valued or how diversity ought to scale across communities. This separation clarifies that many debates about biodiversity metrics are not about mathematical flaws, but about value-laden judgments regarding what *diversity* ought to capture. Together, these four interrelated aspects support our central claim: biodiversity is not merely a technical construct, but an essentially contested concept, i.e., plural, value-laden, and continuously debated. While many additional aspects could be explored, we focus on these four because they vividly illustrate how conceptual, normative, and methodological disagreements intersect, revealing why *diversity* remains both scientifically central and persistently contested.

In this section, we deliberately frame quantitative arguments through the lens of conservation decisions and scenarios to underscore the normative implications embedded in different diversity metrics. These examples demonstrate how seemingly technical choices about measuring diversity can decisively shape real-world conservation priorities, trade-offs, and outcomes.

2.1 | Our choice of metrics entails normative commitments

> *Diversity metrics are not value-neutral; they embed normative commitments (value judgments) about how biodiversity should be represented. Each metric differs in its weighting of rare versus common species, thereby influencing the extent to which rarer taxa contribute to the overall measure of diversity. While often unacknowledged, choosing between richness, Shannon entropy, or Simpson's index entails implicit decisions about which species are most relevant; decisions that should be made explicit when interpreting and applying diversity measures.*

Perhaps one broadly uncontentious definition of *diversity* is as a form of uncertainty. However, what is essentially contestable is how that uncertainty should be defined and measured, particularly in terms of the weight—*value*—assigned to each species within a local community or area, a point we clarify further in this section. Even species richness reflects a limited form of uncertainty: it captures how many distinct events (outcomes) are possible (i.e., the number of species), but not how likely each outcome is to occur.

In this section, we examine Shannon, Simpson, and species richness as conceptual exemplars, illustrating how diversity metrics encode distinct value judgments and embedded normative commitments. We begin with the classic Shannon (entropy-based) diversity index:

$$H = \sum_{i=1}^{S} p_i\,(-\log p_i),$$

where p_i is the probability of an event *i* and *S* is the number of events. In ecology, each species is treated like an event (or an outcome) and its relative abundance p_i is the probability of the i^{th} species to be found in a given sample of a community. Perhaps more intuitively for ecologists, Shannon's equation can be expressed in terms of raw counts as:

$$H_\alpha = \sum_{i=1}^{S} \frac{n_i}{N} \left(-\log \left(\frac{n_i}{N} \right) \right), \tag{1}$$

where H_α is the Shannon entropy (diversity index) of a single community (α-diversity) or area, S is the total number of species in a given sample of the community, n_i is the number of individuals belonging to species i, and $N = \sum_{i=1}^{S} n_i$ is the total number of individuals across all species within the sample.

The Shannon diversity index originates in information theory, where entropy quantified the unpredictability of a system's state [21]. In information theory, the *surprise* (unpredictability) associated with an outcome or event (species) is defined as the negative logarithm of its probability, $-\log p_i$. This means that less likely events (species) are more surprising. For example, consider tossing a coin: if the coin is fair, both heads and tails have a probability of $\frac{1}{2}$, and the surprise of each outcome is $-\log_2(\frac{1}{2}) = 1$ bit. If the coin is biased such that heads occur with probability $\frac{7}{8}$ and tails with $\frac{1}{8}$, then observing tails yields a surprise of $-\log_2(\frac{1}{8}) = 3$ bits, while heads give only $-\log_2(\frac{7}{8}) \approx 0.19$ bits. Shannon entropy captures the *expected surprise*, or average uncertainty, across all possible outcomes, weighted by their probabilities. The more evenly species are distributed, like a fair coin where each outcome is equally likely, the greater the uncertainty or surprise in predicting the identity of a randomly drawn individual, resulting in higher entropy. Conversely, in communities dominated by a few species, like a biased coin where one outcome is far more probable, there is less uncertainty and therefore lower entropy.[4]

In ecology, Margalef (1958) and Pielou (1966) adapted this concept to measure species diversity as the uncertainty in identifying a randomly selected individual from a community, capturing both richness and evenness. Higher values of H_α indicate greater uncertainty, meaning individuals are more evenly distributed among species and thus harder to predict. Lower values occur when one or a few species dominate, making the species identity of a random individual more predictable. In this context, Shannon entropy reflects both the number of species and how evenly individuals are distributed among them, linking unpredictability, information content, and ecological structure in a single metric.

Table 1 breaks down the Shannon entropy formula to highlight how each component encodes specific normative commitments. This disaggregation allows us to identify which elements and mathematical operations of this metric encode specific normative choices. Of particular note is the logarithmic term, $-\log p_i$, which transforms relative abundances (probabilities) so that rarer species contribute more heavily to the overall diversity value. It introduces a *specific* scaling of rarity that is often left implicit, and justification may simply be that "We used Shannon because it's commonly used." This transformation is a *choice* that embeds assumptions that can be normatively contested. For example, the logarithmic scale implies diminishing returns for very rare or very common species, which may not align with all ecological, conservation, or management goals or values. In this way, $-\log p_i$ is not value-neutral: it encodes a *particular* vision of how differences among species should be weighted in diversity quantification or interpreted in terms of ecological value, shaping which aspects of community structure are emphasized or downplayed.[5] This

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[4] Interestingly, the concept of surprise also resonates with the interpretation of p-values in frequentist inference; a small p-value (e.g., 0.01) corresponds to high surprise and can be expressed as $-\log_2(0.01)$. This is known as the Shannon Information Index (S-value) in statistics [e.g., 22].

[5] Changing the logarithmic base in Shannon's entropy alters only the *units* of measurement (bits, nats, bans), not the underlying ranking or proportional relationships among communities. The absolute magnitude of entropy values scales by a constant factor ($1/\ln b$), but this constant applies equally to all communities. Thus, if one community is more diverse than another under a given normative commitment (e.g., using Shannon rather than Simpson), it will remain so regardless of the logarithmic base chosen for Shannon. The choice of base affects representation rather than evaluation, i.e., the normative commitment lies in adopting a logarithmic measure of uncertainty in the first place, not in the particular base used.

illustrates how the quantification of *diversity*, even through a single equation, can reflect underlying epistemic and normative commitments, reinforcing its status as an ECC.

TABLE 1 How a single equation conceals plural meanings. In information theory, *surprise* (or *self-information*) is a measure of the information content of an event (a species in ecology). The less probable a species is, the more surprising and informative it is when it occurs in a community (or place). It is defined as $I(x) = -\log_b p(x)$, where $I(x)$ is the self-information of an event, $p(x)$ is the probability of the event x, and b is the logarithm base (2 is commonly used in information theory so that Shannon entropy is expressed in bits—units representing binary choices; in ecological applications, Shannon is typically calculated using the natural logarithm, base *e*). As such, information can be defined as the negative logarithm of a species' probability, defined as the relative frequency (abundance) of any given species. Shannon entropy is then given by $H = \sum_{i=1}^{S} p(x_i) \cdot (-\log_b p(x_i))$, where S is the number of species in a community or locality.

Component	Mathematical Form	Conceptual Role	Ecological Interpretation
Species probability	$p_i = \frac{n_i}{N}$	Relative frequency of species i	Proportion of individuals belonging to species i; probability of drawing species i.
Negative logarithm of probability	$-\log_b(p_i)$	Surprise or information content	Rare species have high surprise; common species low surprise.
Product	$p_i \cdot (-\log_b p_i)$	Weighted surprise	Combines likelihood with surprise.
Summation	$\sum_{i=1}^{S}$	Weighted average of surprises across species	Expected information from a randomly drawn species.

Another classic abundance-based diversity index is the Simpson (1949) index. Simpson's paper, *Measurement of Diversity*, aimed to quantify ecological diversity and, unlike Shannon's work, was not grounded in information theory. Simpson criticized earlier indices of diversity like Fisher's *alpha* [26] for relying on specific assumptions about species abundance distributions, particularly the logarithmic series, which made them sensitive to violations and less generalizable to population-level properties. Note that Shannon entropy, while logarithmic, is non-parametric and assumes no underlying distribution; lower values under a log-series simply reflect the observed data, not a flaw in the index. Simpson's index emphasizes dominance [27] by measuring the likelihood of repeated identity, i.e., the probability that two randomly drawn individuals belong to the same species. It captures a distinct dimension of diversity: one not based on surprise, as in Shannon's index, but still reflecting uncertainty through the prevalence of common species. Lower values indicate greater unpredictability and serve as an inverse indicator of dominance. The Simpson index quantifies diversity using squared relative abundances:

$$\lambda = \sum_{i=1}^{S} p_i^2, \tag{2}$$

where $p_i = \frac{n_i}{N}$ is the relative abundance of species i (i.e., probability to be found in the community), n_i is the count of individuals of species i, $N = \sum_{i=1}^{S} n_i$ is the total number of individuals, and S is the total number of species. Since the original Simpson index (Equation 2) decreases with increasing diversity (higher values indicate dominance), ecologists often use its complement, known as Gini–Simpson index of Diversity: $D = 1 - \lambda$. Note that, because Simpson's index is based on a quadratic form (squared probabilities), it places more weight on common species and is less influenced by rare ones. This is a normative commitment.

While qualitative descriptions help distinguish the normative commitments embedded in diversity indices, quantitative contrasts reveal precisely how those commitments are encoded, showing which species, and which abundance classes, are privileged in the calculation of diversity. As shown in Figure 2, both Shannon and Simpson indices can be expressed as per-species contribution functions based on relative abundance $p \in (0, 1]$. Shannon assigns each species a contribution $c(p) = -p \cdot \ln(p)$, which peaks at $p = 1/e \approx 0.37$,[6] reflecting maximal contribution from species of intermediate abundance. Simpson assigns $c(p) = p^2$, a monotonically increasing function that emphasizes dominant species while assigning little weight to rare ones. The area under each curve reflects the total expected contribution across all possible abundances: $1/4$ for Shannon[7] and $1/3$ for Simpson[8]. Although their peaks are not dramatically different in magnitude, the shapes of the contribution curves are fundamentally distinct. Shannon's curve is concave and roughly symmetric, spreading weight across a broad range of intermediate abundances, while Simpson's is convex and steeply increasing, concentrating weight toward dominant species. The higher total area under Simpson's curve reflects its strong emphasis on common species, whereas Shannon's more even distribution highlights a wider array of abundance classes. These differences, though purely mathematical, may surprise many ecologists—revealing just how deeply each index embeds normative commitments about which species "count" most when measuring diversity.

If conservation priorities were aligned with these contribution functions, Shannon would prioritize species with relative abundances near $p \approx 0.37$, where individual contributions to diversity are maximized, typically species of intermediate abundance. In contrast, Simpson's contribution function increases monotonically with p, assigning the highest weight to species with $p = 1$, thereby privileging dominant species that comprise a large proportion of the community. If two sites each host 10 species, one with equal abundances ($p = 0.1$ each), the other with a dominant species at $p = 0.7$ and the rest at $p \approx 0.033$, Shannon's index assigns the dominant species a contribution of $-0.7 \ln 0.7 \approx 0.25$, and each rare species about 0.11, while Simpson assigns $p^2 = 0.49$ to the dominant species and just ≈ 0.0011 to each rare one. This illustrates quantitatively how using Shannon implies a conservation commitment to representing a broader range of species more evenly, whereas using Simpson prioritizes community evenness and dominant species, effectively down-weighting the importance of rare species in conservation decisions. Alternatively, if diversity is quantified as species richness, then the normative commitment is that all species contribute equally to diversity, implying a commitment to valuing the rarest and most dominant species equally. Although one often describes these differences using qualitative terms like "rare," "common," or "dominant," the distinctions are grounded in precise mathematical formulations, making the normative commitments embedded in each metric quantitatively explicit and consequential.

2.2 | Diversity at different spatial scales: partitioning frameworks and their normative foundations

> *Partitioning biodiversity into α, β, and γ components reflects core commitments about what diversity is and where it matters. Additive frameworks treat diversity as a sum of local contributions, emphasizing site-level richness, while multiplicative frameworks view diversity as a scaling relationship, highlighting differentiation across space [28]. Choosing between them means deciding whether to emphasize the accumulation of species or the maintenance of ecological distinctiveness across spatial scales.*

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[6] Let $c_i(p) = -p \cdot \log_b(p)$ with $p \in (0, 1]$ and base $b > 1$. Change the base such that $c_i(p) = -\frac{p \ln p}{\ln b}$. Since $\ln b$ is a constant, we can simply find the value of p that maximizes $f(p) = -p \ln p$. Take the derivative, set equal to zero and solve for p. $f'(p) = -(\ln p + 1) = 0 \therefore p = 1/e \approx 0.3679$. This is true for any base $b > 1$.

[7] The integral $\int_0^1 -p \ln p \, dp = \frac{1}{4}$, obtained by integration by parts with $u = \ln p$ and $dv = p \, dp$.

[8] $\int_0^1 p^2 \, dp = \left[\frac{p^3}{3}\right]_0^1 = \frac{1}{3} - 0 = \frac{1}{3}$.

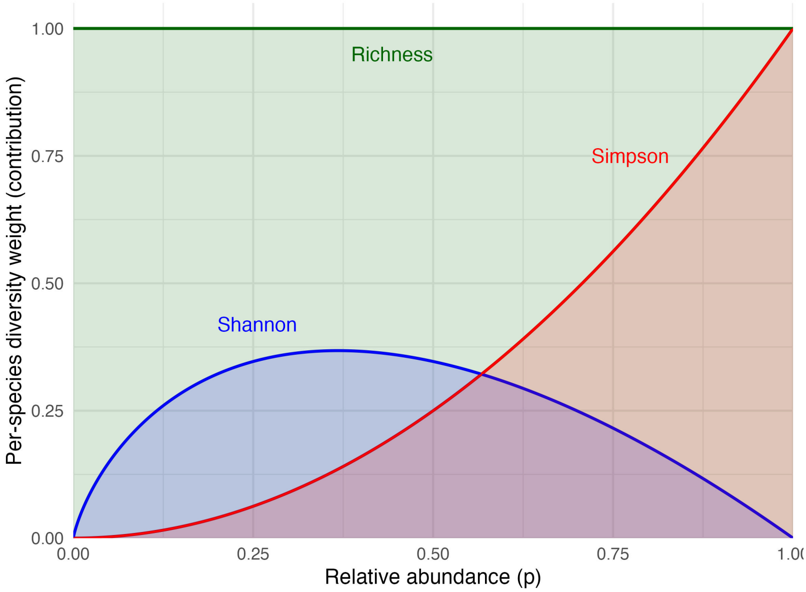

FIGURE 2 Per-species contribution curves for Richness, Simpson, and Shannon diversity indices as a function of species relative abundance.

Ecologists recognize multiple types of biodiversity that operate across spatial scales, with Whittaker's influential framework distinguishing local alpha (α), among-site beta (β), and regional gamma (γ) diversity components [29]. In formal quantification, α, β, and γ diversity are conceptualized as a nested hierarchy, with γ representing total regional diversity and α and β as its constituent components. The general idea is that they can be partitioned to reveal how local diversity and among-community differences contribute to regional biodiversity. Although we have deliberately emphasized α diversity in the first part of this section, this should not be read as a dismissal of β and γ. Our intent was to use α as a clear analytic entry point for illustrating why diversity is an ECC. The same tensions extend directly to β and γ diversity, where alternative formulations emphasize different aspects of rarity, commonness, and scale-dependence. In this sense, all three components reflect a common underlying tension: biodiversity cannot be captured by a single, uncontested definition, but must be interpreted through the normative commitments embedded in the frameworks we adopt. Whittaker's tripartite framework is more than a partitioning scheme, it is a conceptual battleground over what diversity at multiple scales represents in terms of ecological processes[9] and conservation or management priorities [35, 36], each shaped by different normative commitments. Again, note that, although we emphasize here taxonomic diversity, β and γ diversity can also be applied to other dimensions such as functional, phylogenetic, or genomic diversity, each carrying its own assumptions and normative implications about what kinds of variation matter most.

A lasting debate in the diversity literature concerns whether α, β, and γ diversity should be combined additively or multiplicatively [37, 38, 39, 40]. However, some have argued that the distinction between additive and multiplicative partitioning is a false dichotomy, given the substantial conceptual and mathematical similarities between the two approaches (Veech and Crist 38). Additive partitioning, typically based on entropy measures such as Shannon, make β

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[9] See e.g., Tuomisto and Ruokolainen [30] and responses [31, 32, 33, 34].

diversity more responsive to turnover driven by low-abundance taxa. In contrast, multiplicative partitioning, especially when formulated through Hill numbers (see §2.3), adjusts sensitivity via the parameter q: lower values of q emphasize species richness and rare species, while higher q values (e.g., Simpson diversity at q=2) concentrate weight on dominant species, resulting in β values that reflect consistent abundance structure across sites (communities) and downplay rare species. At the regional scale (γ), this means that entropy-based, additive frameworks capture patchiness and the contribution of rare or unevenly distributed species, whereas multiplicative Hill-based frameworks, especially at higher q, reflect regional diversity that is shaped more by species that are locally dominant and widespread, yielding lower β turnover and γ is less influenced by rare-species-driven turnover. These distinctions are not merely academic, additive versus multiplicative partitioning also has empirical consequences for conservation prioritization [41, see also below]. In the additive view [42], γ diversity is partitioned as the sum of within-community (α) diversity and among-community (β) diversity:

$$\gamma = \alpha + \beta \qquad \beta = \gamma - \alpha$$

The additive formulation gained traction for its intuitive logic: α diversity adds up, and β captures the additional diversity that emerges when multiple communities are considered together. It is especially useful for species richness or entropy-based metrics (e.g., Shannon), where α, β, and γ are expressed in comparable units and can be meaningfully summed. Conceptually, it treats diversity as a cumulative property: γ as the regional pooled (summed) value built from the average contributions of individual communities (α) and their average distinctiveness (β).

The multiplicative view, originally proposed by Whittaker (1972) and preceding the additive formulation, instead expresses regional (γ) diversity as the product of within-community (α) diversity and among-community (β) diversity:

$$\gamma = \alpha \times \beta \qquad \beta = \frac{\gamma}{\alpha}$$

Here, β is interpreted as the "effective number of distinct communities" in a region, scaling up α diversity to the regional level γ. This is the natural formulation when using a Hill numbers [see §2.3; 43, 37, 44, 45] perspective, where diversity is expressed as effective numbers of species. Conceptually, multiplicative partitioning emphasizes scaling rather than summation: local diversity is replicated across distinct communities, and γ represents the outcome of this replication. In practice, ecologists often calculate mean α and pooled γ diversity, and then derive β as the residual difference or ratio between the two. As such, β is best understood as an *emergent property* of spatial variation in diversity rather than a directly measured quantity. Note that the quantities above, in practice, are often decomposed into finer-grained units (i.e., sites, pair of sites, and species) for α, β, and γ, respectively.

The normative commitments underlying diversity partitioning go beyond how rarity and dominance are weighted. These extend to assumptions about which ecological processes matter most, which scales are most relevant, and what goals are prioritized in conservation or management. In the additive view, β is residual diversity and quantifies whatever is "left over" once you subtract the average α from γ. This makes β directly dependent on the scale and magnitude of α, so if local communities are very diverse, β will appear smaller, even if turnover (i.e., the degree of compositional dissimilarity or species replacement among communities) is strong. By contrast, in the multiplicative view, β is a scaling factor and quantifies how many times more diverse the region is compared to the average community. Here, β is independent of the magnitude of α and is therefore more interpretable as a relative measure of turnover. Note that additive β values are commonly understood to be difficult to compare across systems with different levels of local richness or entropy, since their magnitude is shaped by the scale and absolute value of α, not solely by the degree of compositional turnover. This view reflects a widely held concern, though it has been argued that α and β

diversity are statistically dependent under both additive and multiplicative partitioning (Veech and Crist 38).

A natural consequence is that researchers may choose the additive framework when aiming to quantify absolute contributions to regional diversity, aligning with conservation goals focused on identifying key sites or communities within a specific region. In contrast, the multiplicative framework may be preferred when comparing relative turnover across ecosystems, reflecting conservation or management priorities that emphasize proportional differences across landscapes or regions. For instance, under the additive framework, two sites each contributing 10 unique species to a regional pool of 100 are treated as equally valuable, since total diversity is calculated by summing absolute contributions. In contrast, the multiplicative framework emphasizes proportional gains: a site that increases regional diversity from 10 to 20 and another that increases it from 20 to 30 both add 10 units, but the first represents a doubling (2×), while the second represents only a 1.5-fold increase. This contrast illustrates how additive and multiplicative approaches encode different priorities (i.e., cumulative contributions versus relative distinctiveness). As such, these choices reflect distinct normative commitments: whether conservation should prioritize total gains in biodiversity within a region or emphasize the relative distinctiveness of sites across broader spatial comparisons.

In practice, the choice between additive and multiplicative shapes not only determines how we partition biodiversity, but also how we interpret ecological processes and make conservation decisions. The approaches to partitioning diversity reflect different normative views: additivity treats diversity as a cumulative, resource-like quantity, while multiplicative frames it as a relational, scaling property shaped by differentiation among communities. This latter perspective emphasizes the role of ecological distinctiveness in driving regional richness and aligns with conservation strategies that prioritize heterogeneity over simple species accumulation. As such, additive frameworks may foreground contributions of specific sites or habitats, while multiplicative frameworks highlight turnover, heterogeneity, and scaling behaviour. Neither framework can be regarded as universally superior; rather, each provides insight into particular aspects of biodiversity while inevitably obscuring others. Acknowledging the normative commitments embedded in these frameworks is therefore essential, as they shape the way analyses are designed, how results are interpreted, and ultimately how concepts such as "loss" or "gain" in biodiversity are operationalized. See section 3 for a more fulsome consideration of these commitments.

Finally, beyond the additive versus multiplicative debate, Whittaker's widely adopted tripartite diversity framework, partitioning diversity into α, β, and γ, has itself faced critique. Among the components of Whittaker's partitioning scheme, β diversity remains especially contentious, despite being the most developed in terms of available metrics. While some view it as a foundational concept for understanding ecological turnover and spatial structure, others criticize it as ambiguous and inconsistently defined across studies. One proposal [46] is to distinguish between two conceptually distinct forms: "differentiation diversity," based on compositional dissimilarity between samples, and "proportional diversity," based on how diversity scales across space. This distinction suggests that β diversity may not represent a singular concept, but rather a cluster of interpretations, each shaped by distinct ecological contexts and normative assumptions. This ambiguity is not merely academic: it can directly affect how landscapes are prioritized for conservation. For example, some planning approaches use β diversity to identify complementary sites that together maximize regional coverage of species, while others interpret it as a signal of ecological distinctiveness or turnover that should be protected in its own right [47, 48, 39].

2.3 | Effective numbers of species: a common currency for divergent normative commitments

> *Hill numbers recast indices like Shannon and Simpson as the effective number of equally abundant species, placing them on a common, linear scale that reflects both richness and evenness. This transformation*

> *not only clarifies how different indices weight species, but also reflects a normative stance: that diversity should behave like a countable, scalable quantity. Despite often being framed as a unifying framework for diversity metrics, Hill numbers still rest on specific value judgments, emphasizing further that no diversity metric is normatively neutral.*

In *Diversity and Evenness: A Unifying Notation and Its Consequences*, Hill (1973) introduced a mathematical framework that attempts to unify several (not all) common diversity indices, including Richness, Shannon, and Simpson, under a single formulation. While the proliferation of α, β, and γ diversity measures reflects varied conceptual commitments, Hill numbers[10] offer a widely accepted unifying approach. The core innovation is the exponential transformation, which converts traditional indices into the number of equally abundant species required to produce the same diversity. For example, a community with species abundances $\{0.7, 0.1, 0.1, 0.1\}$ has a Shannon entropy of:

$$H = -\sum p_i \ln p_i = -\left(0.7 \ln 0.7 + 3 \times 0.1 \ln 0.1\right) \approx 1.03$$

Although the entropy value in Shannon (as with other diversity metrics) is mathematically informative, quantifying uncertainty in species identity, it is expressed in logarithmic units (nats when using natural logarithms [ln], and bits when using base-2 logarithms [$\log_2$]), which are not intuitively interpretable as species counts. Taking the exponential of H translates it into the effective number of equally abundant species (see below for an intuitive interpretation), making the result easier to interpret and compare across communities:

$${}^1D = e^H \approx e^{1.03} \approx 2.8,$$

(${}^1D$ is the Hill number when $q = 1$). This means that this uneven community of 4 species is equivalent, in terms of number of species, to a community of just 2.8 *equally abundant* species. In other words, unequal representation among species lowers the effective diversity compared to the species richness of 4, which treats all species equally and ignores differences in abundance, and on this view appearing to be more *diverse*. This contrast implicitly reflects a normative commitment: that meaningful diversity metrics should account for evenness in species abundances, not just presence.

Although the "effective number of equally abundant species" can yield non-integer values (e.g., 2.8 species), it offers a clear, comparable measure of diversity that accounts for both richness and evenness. It tells us how many equally abundant species would be needed to match the *diversity* of an uneven community. However, note that what *diverse* means in this statement is defined by the choice of a parameter (q) in the formula for calculating the effective number (see Equation 3). And the choice of this parameter reflects particular normative commitments. For instance, a community with four species of unequal abundance may have the same Shannon-based Hill number as a perfectly even community of 2.8 species. This doesn't mean the community has 2.8 species, but that its overall diversity behaves as if it did, given the particular parameter choice.[11] The more uneven the distribution, the fewer equally abundant species would be needed to produce the same level of uncertainty or diversity. It follows that species

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[10] Hill numbers are also known as the effective number of species, effective number of equally abundant species, or numbers equivalents.

[11] The idea of expressing diversity as an "effective number of species" is conceptually analogous to the notion of an "effective population size" in population genetics. In both cases, a complex, uneven system is translated into the size of an idealized, perfectly even system that would exhibit the same key property—diversity in the case of Hill numbers, or the rate of genetic drift in the case of effective population size. Both serve as effective-size measures that make abstract quantities more interpretable while preserving their underlying mathematical meaning.

richness corresponds to Hill number ${}^0D$, as it requires no transformation: its value is simply the count of species, regardless of their relative abundances. In a perfectly even community, richness and the exponential of Shannon entropy would be equal, but as unevenness increases, the exponentiated entropy falls below richness, revealing how relative abundance structure reduces effective diversity.

For a conservationist normatively committed to ${}^1D$ and all that it entails, this means that although the site has 4 species, its unevenness reduces its effective diversity to 2.8. Put differently, if one accepts ${}^1D$ here, protecting this community contributes as much *diversity* as protecting a perfectly even site with only 2.8 species. Now compare that to another site with 3 equally common species ($p = 1/3$); its effective diversity is exactly 3. Even though the first site has more species, the second offers more balanced contributions, making it potentially more valuable from a diversity standpoint, depending on conservation goals (i.e., if the goal is to manage for ${}^1D$-type diversity). While Shannon entropy quantifies the uncertainty in species identity, it does not by itself reveal how that uncertainty compares to a baseline of evenness; this is what the exponential transformation provides.

Jost (2007) illustrates the potential interpretive power of Hill numbers with a simple example: if a continent loses half of its 30 million equally common species, species richness drops by 50%, while Shannon and Simpson indices barely change (17.2 to 16.5 for Shannon and 0.99999997 to 0.99999993 for Simpson). Hill numbers, by contrast, reflect this loss directly, preserving intuitive expectations: Shannon diversity (${}^1D$) drops from approximately 30 million to 15 million equally abundant species equivalents, reflecting the 50% decline exactly. Simpson diversity (${}^2D$), on the other hand, remains virtually unchanged at 1, consistent with the fact that all species were equally common and thus indistinguishable in dominance structure. As such, even this "intuitive" view embeds a normative commitment that each species should not count equally, which, like all diversity metrics, reflects assumptions about what diversity ought to represent. This reinforces the broader point that all diversity metrics, including Hill numbers, embed specific assumptions about what diversity *ought* to reflect.

Hill numbers rescale traditional diversity indices[12] onto a linear scale that aligns with our intuitive understanding of species counts. This allows direct comparisons across communities and satisfies the replication principle (see §2.4); that is, two completely distinct communities each with diversity D combine to form a community with diversity $2 \times D$. Unlike Shannon or Simpson indices, which do not scale additively, Hill numbers preserve this linearity by construction, making them easier to interpret and sum across regions (e.g., sums of α diversity across regions). The transformations involved in Hill numbers are governed by:

$$
{}^qD = \begin{cases} \left(\sum_{i=1}^{S} p_i^q\right)^{1/(1-q)} & \text{for } q \neq 1, \\ \exp\left(-\sum_{i=1}^{S} p_i \ln p_i\right) & \text{for } q = 1. \end{cases} \tag{3}
$$

Here, the mathematical transformation depends on the value of $q \geq 0$. For $q = 0$, the sum reduces to species richness (${}^0D$): no transformation is needed, and all species are counted equally. For $q = 1$, the logarithmic form of Shannon entropy is transformed using the exponential function; this is where the exponentiation is literal and necessary to return the value to a linear scale (${}^1D$). And for $q = 2$, the transformation involves squaring the species proportions (p_i^2) and taking the inverse (${}^2D$); again, a nonlinear operation that rescales the result into a linear "equally abundant species equivalents." At $q = 2$, the Hill number is the inverse of the Simpson concentration index, representing the number of equally common species that would result in the same value of species dominance.

Other values of q can also be used to explore different sensitivities to species abundances. As q increases beyond

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[12] Note that Hill numbers generalize to functional, genomic, and phylogenetic diversity [49].

2, the diversity measure becomes increasingly dominated by the most abundant species, while values of q between 0 and 1 give relatively more weight to rare species. This flexibility allows ecologists to construct diversity profiles made out of plots of ${}^qD$ across a range of q to visualize how community diversity changes depending on the emphasis placed on rare versus common species (for an example, see Figure 1).

It should be obvious by now that each choice of q represents a different normative commitment by embedding assumptions about which species matter most: whether diversity should prioritize rarity, dominance, or strike some form of a balance between the two. The weights applied to species in the Hill number framework remain consistent with those of the original diversity indices. For instance, in the case of Shannon entropy ($q = 1$), species are weighted by their contribution function $c(p_i) = -p_i \ln p_i$, which peaks at $p = 1/e \approx 0.37$; for Simpson diversity ($q = 2$), the contribution is $c(p_i) = p_i^2$, which increases monotonically with abundance and thus emphasizes dominant species. These per-species contribution functions (as depicted in Figure 2) show how different indices encode different normative commitments about which abundance classes matter most. Because Hill numbers at each order q are strictly increasing functions of these indices (e.g., ${}^1D = e^H$ for Shannon, and ${}^2D = 1/\sum p_i^2$ for Simpson), the relative contributions of species remain unchanged in terms of their influence on the untransformed index.

This means that Figure 2 remains valid for interpreting species weights for the Hill number framework given, as the shape of the contribution curves (i.e., relative influence of species across abundance) remain unchanged when diversity indices are transformed into Hill numbers. The Hill number transformation rescales the total diversity value (e.g., from 1.03 nats to $e^{1.03} \approx 2.8$), but it does not alter the underlying contribution of each species to that value. In other words, a species that contributes most to Shannon entropy before exponentiation remains the one contributing most after exponentiation; the transformation simply maps the entropy scale to an effective species count scale without changing the internal weighting structure.

While the species weights used in calculating Shannon entropy and Simpson's index are preserved under the Hill number transformation (i.e., the contribution curves in Figure 2 remain valid), the partial derivatives of Hill numbers with respect to species abundances differ from those of the original indices. In other words, although diversity values change monotonically with abundance in both representations, the rate of change (i.e., how much diversity shifts when a given species' abundance changes) does not match between the raw index and its Hill-transformed counterpart. We will not explore this point further for space reasons, but suffice it to say that, for example, the Hill version of Shannon ($q = 1$) becomes more sensitive to changes in rare species in already diverse communities, as the effect is scaled by total diversity. This introduces an additional layer of normative commitment, emphasizing not only rarity, but the contextual importance of rarity within more diverse systems.

Although we concentrated here on Hill numbers for α diversity, they generalize to β and γ diversity across a continuum of diversity orders (q). Note, however, that not all diversity indices can be expressed as numbers equivalents, which means they do not translate directly into a count-like interpretation (i.e., equally abundant species equivalents); a point we will not expand on in this paper, but it is helpful for the reader to recognize that Hill numbers are part of a subset of diversity measures that preserve a direct and scalable interpretation across α, β, and γ levels, thus potentially facilitating comparisons and communication across ecological and conservation contexts. However, Hill numbers are designed to support multiplicative partitioning of diversity, while Shannon entropy supports additive partitioning in logarithmic space, offering a different view of how diversity accumulates across levels of organization. Here too, as explored in the previous sections, the choice between α, β and γ, the selection of different diversity orders (q), and the decision to use multiplicative versus additive partitioning each carry normative commitments. Together, these choices reflect distinct assumptions about how diversity should be quantified, structured, interpreted, preserved, and compared across ecological levels.

2.4 | Technical requirements are not normative commitments

> *The technical criteria for good diversity metrics ensure mathematical coherence and interpretability but are not themselves value-laden. Recognizing this separation clarifies that debates over biodiversity's meaning arise not from these technical requirements, but from deeper normative choices, such as how to value rarity or scale diversity across ecological levels.*

Jost (2007) outlined some defining characteristics of an informative diversity metric:

1. It should behave intuitively so that changes in diversity can be meaningfully interpreted, rather than relying only on statistical significance;
2. It should be expressed as "numbers equivalents" (the effective number of species), which have the important replication property: if two equally diverse but completely distinct communities are combined, overall diversity should double (i.e., the *replication principle*);
3. It should provide simple, interpretable magnitudes, such as "the number of equally common species" or "the number of equally large, distinct communities," which makes it easy to visualize and compare changes across ecosystems;
4. And it should be consistent across scales (α, β, γ) so that each component has a clear interpretation and avoids anomalies like inflated similarity indices.

While these properties enhance the internal coherence, interpretability, and comparability of diversity metrics, they do not in themselves constitute sources of essential contestation. They reflect methodological criteria for how a good diversity measure should behave once the concept is defined, rather than philosophical stances about what diversity *ought* to capture; or at least, they operate outside the scope of what we, the authors, consider to fall within the domain of an essentially contested concept for biodiversity. For instance, the replication principle (characteristic 2 above) is a mathematical feature that supports a multiplicative framework as it ensures that diversity scales proportionally under perfect differentiation; but it is not itself a normative commitment. However, embracing replication, along with other properties like scale consistency and numbers equivalence, contributes to a broader normative orientation: one that favours a multiplicative understanding of diversity as a scaling property across ecological levels. In this sense, Jost's criteria can be understood less as competing visions of what diversity "means" and more as views on which conditions any viable metric should satisfy if it is to serve as a robust tool for research and applied contexts. That said, these conditions may vary depending on the context (e.g., comparing variation within one ecosystem/region or across ecosystems/regions).

To better distinguish normative commitments from mathematical or statistical properties, consider how diversity metrics and sampling handle species rarity and sampling effort. For example, Shannon gives more weight to rare species, making it more sensitive, though also more vulnerable, to sampling biases, as rare species may be missed entirely or appear disproportionately important in small or uneven samples. Simpson, by contrast, downweights rare species and is more robust to such distortions. These behaviours reflect normative choices about how to value rarity, but the resulting sensitivities to sampling are not themselves what makes *diversity* an ECC. A clear example of this distinction lies in how ecologists address unequal sampling across communities. Diversity can only be meaningfully compared when sampling effort is standardized, but the methods used (e.g., equal sampling effort, equal sample size [i.e., rarefaction], equal coverage) each carry different statistical implications (see Roswell et al. 2021 for a synthesis of underlying sampling issues and possible solutions). These are not claims about what diversity *is*, but rather methodological strategies to improve comparability. For instance, equal-effort sampling may seem fair, yet it fails to account for differences in species abundance distributions and often underestimates richness in more diverse communities [51]. Likewise, rarefaction imposes equal sample sizes, but can distort comparisons by disproportionately underestimating abundance-based diversity in richer communities, especially those with many rare species. Finally, different diversity indices vary in their sensitivity to which species (and their abundances) are detected or missed in a given sample [52]. These challenges highlight the statistical sensitivity of diversity estimation. Still, such technical adjustments, while essential for analytical rigour, operate independently of the deeper normative debates about what diversity ought to represent.

To make an ECC framework operational for diversity, it is essential to distinguish between value-laden choices, such as how to weight rarity or structure contributions (multiplicative versus additive) and formal characteristics like replication and statistical properties, which ensure technical behaviour but should not be seen as conceptually contested. This boundary-setting helps clarify where true conceptual disputes lie and prevents confusion between normative commitments and technical requirements. Without this distinction, debates risk conflating philosophical disagreements with procedural constraints, obscuring the actual source of contention. For instance, principles like replication or expressing diversity as numbers equivalents enhance coherence and interpretability by addressing *how* diversity should behave once defined, but not *what* diversity ought to represent (i.e., be defined). These principles resolve technical concerns rather than the deeper normative tensions that make diversity an essentially contested concept, at least in our view, for what properties of biodiversity to consider within the domain of an essentially contested concept.

3 | DIVERSITY AS AN ESSENTIALLY CONTESTED CONCEPT

Diversity is one of ecology's most frequently invoked yet most variably interpreted concepts. Its contested character arises from the fact that it is multidimensional, scale-dependent, and measured with metrics that embody both mathematical choices and normative commitments. Disagreement spans conceptual and empirical domains alike—from how communities and diversity metrics are defined to the knowledge shortfalls and detection limits that constrain biodiversity data. Understanding the persistence of these disagreements requires recognizing that diversity is not only empirically complex but also *normatively charged*. Philosophers of science have long emphasized that even mathematically formalized concepts are shaped by ethical, political, and contextual values [e.g., 53, 54, 55]. Ecological measures are no exception: biodiversity metrics and conservation practices, though presented as objective tools, often encode non-epistemic values [56, 57], reflecting deeper judgments about which forms of life and organization are worth knowing and protecting. Recognizing this entanglement of empirical and normative dimensions provides a foundation for understanding diversity as an essentially contested concept.

Normative assumptions supply the standards for applying a concept (i.e., what counts as better or worse, relevant or irrelevant) so when reasonable ecologists endorse different value-laden standards, disagreement becomes constitutive rather than incidental. In other words, the divergence in views stems not from misunderstanding or error, but from legitimate differences in what aspects of biodiversity are valued and why. A concept qualifies as *essentially contested* when these normative commitments are internal to its meaning, making disputes persistent, rationally sustained, and not fully resolvable by empirical evidence alone.

As discussed in section 2, every common metric of diversity carries normative commitments. Giving equal weight to all species conveys the intuition that every species counts; privileging dominance perhaps highlights function; emphasizing rarity foregrounds vulnerability and ethical concern. Table 2 makes these commitments explicit for three standard measures of taxonomic diversity, while Table 3 shows how similar commitments appear in different partitioning frameworks. These embedded commitments explain why ecologists can disagree even when working from the same datasets: interpretations of “health” or “priority” depend on the values built into the metric. Such commitments are not mere technical details but points where scientific reasoning and ethical judgment intersect [58]. Recognizing them fosters transparency, clarifies disagreement, and links ecological analysis to conservation and policy contexts.

TABLE 2 Normative assumptions underlying three commonly used measures of ecological diversity when applied to conservation decisions or policy.

Measure	Embedded Normative Assumptions	
Species Richness (S)	**S-1**	Assumes all species are equally valuable; presence alone contributes to diversity.
	S-2	Ignores abundance: one individual counts the same as thousands.
	S-3	Embeds the view that taxonomic distinctness itself has intrinsic conservation value.
	S-4	*Policy implication*: favours protecting areas with many species, irrespective of population size or ecological role.
Shannon Entropy (H′)	**H′-1**	Diversity is construed as the distribution of individuals, implying more even distributions are normatively preferable.
	H′-2	Rare species contribute to Shannon entropy, but less than more abundant ones, reflecting a balance between richness and evenness rather than a specific emphasis on rarity.
	H′-3	Frames diversity in information-theoretic terms, as uncertainty in predicting a random draw.
	H′-4	*Policy implication*: favours ecosystems with high richness and evenness, potentially prioritizing balance across species.
Simpson’s Index (D or $1-$ D)	**D-1**	Weights common species most heavily, assuming dominant taxa are central to diversity.
	D-2	Rare species contribute little to Simpson’s index, reflecting a perspective that rarity matters only when species become locally abundant.
	D-3	Values community cohesion and resistance to monopolization by a single species.
	D-4	*Policy implication*: supports conservation strategies that maintain dominance balance and overall evenness, but may undervalue the importance of rare species.

Beyond metrics, other sources of contestation arise from definitions and data scope. What constitutes an “ecological community” remains unsettled [see e.g., 59, 60]: for example, communities may be defined taxonomically (species detected within a sampling unit) or functionally (species that interact or share context). Sampling units differ in size and individuation[13], and communities are temporally dynamic. These choices directly influence diversity estimates and their interpretation. This often requires criteria that are not purely empirical but also theoretical or normative, since boundaries in nature are frequently ambiguous and context-dependent, and communities are temporally dynamic, thus changing over time due to ecological or observational processes. These definitional and methodological choices can directly influence diversity estimates and how they are interpreted. In applied contexts, such as conservation planning, protecting an area based solely on a sampled community may overlook cryptic turnover, transient species, or broader ecosystem functions, leading to mismatches between measured diversity and perceived ecological value. Although it can be argued that most ecologists have ways to operationalize these definitions in practice, such operationalizations often rest on context-dependent choices that introduce implicit normative assumptions about which

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[13] *Individuation* =df in ecology, the process of delineating and recognizing entities such as species, populations, or communities as distinct units. This often requires criteria that are not purely empirical but also theoretical or normative, since boundaries in nature are frequently ambiguous and context-dependent.

interactions, which taxonomic groups, spatial extents, or temporal windows matter most.

TABLE 3 Normative commitments underlying different diversity partitioning frameworks. Additive and multiplicative formulations embody distinct views of what diversity represents, how it scales, and what should be prioritized in ecological interpretation and conservation. This view reflects a widely held concern, though others have argued that these frameworks may be more of a conceptual continuum than a true dichotomy.

Partitioning	**Normative commitments and assumptions**
General α–β–γ partitioning	Diversity is inherently hierarchical across spatial scales, and how it is partitioned reflects assumptions about where diversity resides and which levels are most informative for explanation or conservation. Whittaker's framework, in particular, embeds implicit commitments about ecological processes and the spatial priorities of conservation action. *Conservation implication:* Decisions hinge on the rationale for protection; e.g., are sites prioritized because they are locally rich, because they are compositionally distinct from others, or because they best capture regional diversity through representativeness?
Additive framework	Diversity is viewed as a cumulative resource, with regional diversity (γ) partitioned into the sum of local contributions (α) and residual among-site diversity (β). This approach aligns with conservation strategies focused on maximizing total biodiversity and often emphasizes rarity through entropy-based measures. Here, β captures the additional diversity not explained by average local richness, making it inherently scale-dependent and less comparable across systems with varying α diversity. It foregrounds the role of individual sites or habitats in contributing to the overall regional diversity pool. *Conservation implication:* This approach supports strategies that prioritize accumulation, protecting as many species and sites as possible, where each additional site or rare species adds measurable value to overall biodiversity.
Multiplicative framework	Regional diversity (γ) is expressed as the product of local diversity (α) and site differentiation (β), reflecting a multiplicative view that aligns with conservation goals emphasizing distinctiveness and landscape heterogeneity. This framework emphasizes common species to enable cross-system comparisons, while downweighting rarity. Here, β captures, under the Hill number framework, the effective number of distinct communities as an emergent property of spatial turnover, emphasizing proportional differences across sites rather than cumulative species counts. *Conservation implication:* This approach supports strategies that prioritize spatial complementarity, protecting a network of compositionally distinct sites to maximize regional representativeness and minimize redundancy.
Choice of partitioning scheme	Reflects a value-laden decision about whether biodiversity should be conceptualized as cumulative or relational. Additivity privileges aggregation and total contributions, while multiplicativity privileges differentiation and proportional scaling. Each framework foregrounds certain ecological processes while obscuring others, ultimately shaping how biodiversity "loss" or "gain" is defined in management or policy contexts. *Conservation implication:* The choice supports different approaches to prioritization, either maximizing total biodiversity through cumulative gains (additivity) or preserving distinctiveness and complementarity across sites (multiplicativity). These have implications for how conservation success is measured and justified.

Knowledge shortfalls further compound these challenges. Linnean, Wallacean, Darwinian shortfalls, among others [see 61, for a review][14] and functional, phylogenetic, and genetic gaps mean that any metric reflects only the

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[14] *Biodiversity shortfalls*: Several distinct but related knowledge gaps constrain ecological understanding. The *Linnean shortfall* refers to the

biodiversity we currently observe and conserve (Diniz-Filho et al. 62). The notion of *dark diversity*, i.e., species ecologically capable of existing in a community but absent or undetected, underscores the gap between realized and potential diversity. Decisions based solely on observed diversity risk overlooking communities with high unexpressed potential. In this sense, dark diversity is analogous to the rights of future generations in moral philosophy: it represents unrealized but normatively salient potential. Just as moral reasoning that considers only currently existing individuals overlooks the interests of those who could exist in the future, conservation reasoning that attends solely to observed diversity risks disregarding communities with latent ecological potential.[15] Recognizing such unobserved potential extends ethical and analytical consideration from the realized to the *realizable*, aligning ecological assessment with a broader sense of responsibility for *possibility* itself.

Taken together, we argue that these empirical, definitional, and normative challenges provide compelling support for treating biodiversity as an *essentially contested concept*, in the sense articulated by Gallie [1]. To elaborate, Gallie identified seven characteristic features of such concepts that while they do not constitute a strict definition, offer a diagnostic framework for recognizing when persistent disagreement reflects deeper normative tensions. In this sense, a concept that satisfies all or most of them can reasonably be classified as an ECC. Biodiversity aligns with all seven: it is (*i*) *appraisive*, since assessments of "high" or "low" diversity presuppose judgments of ecological value or integrity; (*ii*) *internally complex*, comprising multiple interacting properties—richness, evenness, composition, and scale; (*iii*) admits *describability*, given that no single metric captures its essence and multiple, legitimate formulations coexist. There is also (*iv*) *reciprocal recognition* among proponents, as proponents of different perspectives and metrics acknowledge alternatives while defending their own. Biodiversity exhibits (*v*) *historicity*, evolving alongside shifts in theory, method, and conservation priorities; and (*vi*) *progressive competition*, where ongoing debates have spurred conceptual and methodological refinements such as the Hill-number framework. Lastly, biodiversity is (*vii*) *open to modification*, adapting to new contexts through revised indices, dimensions and scopes (taxonomic, functional, phylogenetic), and evolving conservation goals.

In short, disputes over diversity are not simply semantic or technical but hinge on reasonable, value-laden standards internal to the concept itself. *Diversity* is therefore not merely contested in the ordinary sense but *essentially* contested. Recognizing this status helps explain why disagreement over its meaning never disappears, and why such disagreement can be creative rather than obstructive. Framing diversity as an ECC legitimizes pluralism, clarifies the grounds of dispute, and encourages transparent, context-appropriate applications in both ecological research and conservation practice.

4 | ENGAGING WITH DIVERSITY AS AN ECC

> *To live with diversity is to live with contestation; our task is not to resolve it but to reason well within it.*

The debate about how to quantify diversity is not a new issue. Over fifty years ago, Stuart Hurlbert (1971) dismissed the idea of "species diversity" as a *non-concept*, arguing that it conflated distinct dimensions—richness and evenness—into a single, ambiguous measure. However, from the perspective of an ECC, this ambiguity is not a flaw. Rather than disqualifying diversity as *meaningless*, recognizing it as essentially contested reframes the disagreement as inherent and even valuable. This approach underscores the diverse ways that ecologists define, measure, and

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fact that many species remain undescribed or unnamed; the *Wallacean shortfall* highlights our limited knowledge of the spatial distributions of even described species; and the *Darwinian shortfall* points to incomplete understanding of species' traits, interactions, and evolutionary relationships.

[15] Just as accounting for dark diversity is controversial in ecology, so are claims of rights for future people, see Meyer [§2.1, 63].

prioritize different aspects of biodiversity. What Hurlbert viewed as conceptual incoherence can be understood as an inevitable and productive characteristic of a concept that evolves alongside changing ecological goals and values. In conservation ethics, this reframing is made operational by a three-tier structure in which *naturalness* is treated as the ultimate value, midlevel principles (autonomy, integrity, resilience) are balanced defeasibly, and biodiversity provides the lower-tier, case-sensitive metrics for adjudicating among those principles [57]. Recognizing diversity as an ECC does not make it useless; instead, it reshapes disagreement into a generative feature of ecological reasoning, clarifying how normative and empirical commitments interact in practice.

If we accept that diversity is not reducible to a single, uncontested quantity, then the role of ecologists and conservation scientists is not to eliminate disagreement, but to navigate it constructively. Doing so requires a change in how we engage with biodiversity as both a scientific and policy-relevant concept. The following five practices offer concrete ways to work productively within an ECC framework, helping to align scientific rigour with transparency and ethical responsibility:

Make normative commitments transparent

Ecologists should be transparent about the normative commitments inherent in their chosen metrics. When a study prioritizes species richness, emphasizes functional roles, or highlights rarity, those choices should be acknowledged as *value-laden* rather than implying that they are neutral. This transparency allows others to interpret results in light of these commitments, to compare findings across different frameworks, and to understand why various studies may lead to different recommendations. Being clear about values and assumptions builds trust with policymakers and the public, who might otherwise perceive diversity indices as opaque or arbitrary.

Embrace pluralism

Recognizing diversity as essentially contested fosters pluralism instead of reductionism. Rather than searching for a single "best" measure, conservation science can benefit from complementary dashboards that track multiple dimensions, each aligned with specific management goals. This pluralism legitimizes different perspectives, such as safeguarding evolutionary history, promoting ecosystem resilience, or ensuring equitable access to nature's benefits, while clarifying that no single metric can capture them all. By acknowledging the coexistence of competing but legitimate interpretations, ecologists can better tailor their analyses to the relevant questions and values.

Treat as a source of innovation

Ecologists and conservation biologists should view contestation as a source of innovation. Disputes over how to measure or prioritize diversity have historically driven methodological innovation, from the development of Hill numbers to the rise of eDNA-based indices. Following this path, researchers should approach conceptual disagreements not as flaws but as opportunities to advance theory, refine tools, and improve conservation practice. Embracing contestation expands the toolbox of methods rather than narrowing it.

Educate experts and engage the public

Recognizing diversity as an ECC also calls for changes in how we teach and communicate. For experts, training in biodiversity science should include philosophical and normative literacy and not only how to calculate indices, but why particular metrics reflect specific value commitments [e.g., 8]. For the broader public, including decision- and policy-makers, diversity metrics should be communicated not as purely technical outputs, but as tools shaped by priorities that are open to discussion. Framing diversity as a contested but constructive concept empowers learners and stakeholders alike to engage more critically, fostering informed dialogue about what should count in conservation and why.

Make better policy decisions

Finally, treating diversity as an ECC has implications for the science-policy interface. Conservation recommendations often carry moral weight and political consequences. Recognizing the contested nature of diversity ensures that policy decisions are not presented as the inevitable result of a single, value-free calculation but rather as reasoned judgments that balance different dimensions and commitments. This honesty does not undermine conservation; it strengthens its legitimacy by aligning scientific practice with democratic ideals of transparency, deliberation, and accountability.

In summary, the lesson for ecologists and conservation biologists is not to eliminate contestation over diversity, but to engage with it thoughtfully and constructively. Working with diversity should mean embracing its multiplicity, making explicit the normative foundations that underlie different approaches, and using that awareness to guide more transparent, pluralistic, and context-sensitive science, conservation actions, and policies. Rather than treating diversity's constested nature as problem, we argue that it should be recognized as a strength.

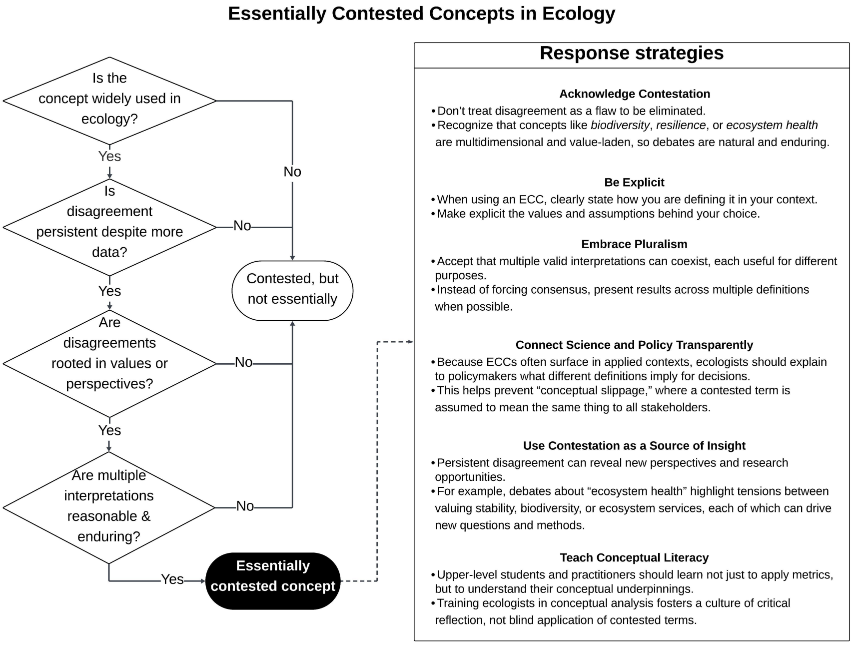
5 | SYNTHESIS AND CONCLUSIONS

Biodiversity matters deeply to science, policy, and society, yet our understanding of what counts as *diverse* remains diverse itself, shaped by differing values, assumptions, and priorities, even if these are not always explicitly acknowledged. This plurality underlies ongoing debates over how biodiversity should be defined, measured, and prioritized, with real implications for ecological research, conservation strategies, and policy decisions. Our paper bridges the abstract theory of *essentially contested concepts* (ECC) with concrete real-world challenges faced in empirical analysis of biodiversity, conservation science, and biodiversity policy.

We argue that the proliferation of diversity metrics is not merely a technical or methodological issue, but a reflection of the deeper reality that *diversity* is itself an ECC. Like "justice" or "democracy," *diversity* resists closure because it is internally complex, value-laden, and continually reinterpreted as scientific tools and social priorities evolve. Far from being a weakness, diversity's contested status can be harnessed as a resource for conceptual clarity, methodological innovation, public engagement, and more transparent policymaking.

Figure 3 offers a practical lens for working with *any* ecological concept that qualifies as an ECC. It highlights two key moves. First, diagnosis: is disagreement persistent, rooted in values, and resistant to resolution by more data? If so, the concept should be treated as essentially contested. Second, response: rather than forcing consensus, ecologists can adopt strategies such as acknowledging contestation, making assumptions explicit, embracing pluralism, and connecting scientific choices more transparently to policy and management contexts. These strategies reposition disagreement not as a barrier but as a generative force for dialogue across disciplines and concerned groups.

In the case of *diversity*, framing it as an ECC helps explain why no single metric can be definitive. Different indices, whether based on species richness, evenness, or rarity, prioritize distinct ecological dimensions and reflect underlying normative commitments. Collapsing taxonomic diversity into a single value risks obscuring both the ecological complexity of communities and the value judgments embedded in the choice of metric. Instead, presenting full diversity profiles, Hill number curves (see e.g., Figure 1), or complementary multi-metric summaries, along with a clear explanation of their underlying normative assumptions, offers a more transparent and informative view of biodiversity. This pluralistic approach not only captures the multifaceted structure of species assemblages but also aligns more directly with diverse conservation priorities, whether the goal is to maximize species counts, safeguard rare taxa, or preserve balanced community composition.



Response strategies

Acknowledge Contestation
- Don't treat disagreement as a flaw to be eliminated.
- Recognize that concepts like *biodiversity*, *resilience*, or *ecosystem health* are multidimensional and value-laden, so debates are natural and enduring.

Be Explicit
- When using an ECC, clearly state how you are defining it in your context.
- Make explicit the values and assumptions behind your choice.

Embrace Pluralism
- Accept that multiple valid interpretations can coexist, each useful for different purposes.
- Instead of forcing consensus, present results across multiple definitions when possible.

Connect Science and Policy Transparently
- Because ECCs often surface in applied contexts, ecologists should explain to policymakers what different definitions imply for decisions.
- This helps prevent "conceptual slippage," where a contested term is assumed to mean the same thing to all stakeholders.

Use Contestation as a Source of Insight
- Persistent disagreement can reveal new perspectives and research opportunities.
- For example, debates about "ecosystem health" highlight tensions between valuing stability, biodiversity, or ecosystem services, each of which can drive new questions and methods.

Teach Conceptual Literacy
- Upper-level students and practitioners should learn not just to apply metrics, but to understand their conceptual underpinnings.
- Training ecologists in conceptual analysis fosters a culture of critical reflection, not blind application of contested terms.

FIGURE 3 Identifying and responding to essentially contested concepts in ecology.

The implications extend beyond ecology. Policymakers must recognize that "areas of high biodiversity importance" cannot be reduced to a uniform definition; governments and industry must engage transparently with the diversity metrics used in impact assessments; Indigenous and local communities should be empowered to articulate the forms of diversity that matter most *to them*; and education must cultivate conceptual literacy so that future ecologists are trained to see metrics not as neutral tools but as *value-inflected choices*, i.e., normative commitments. In all these contexts, and many others, Figure 3 provides a simple heuristic: once a concept is diagnosed as essentially contested, the task is not to eliminate disagreement but to navigate it constructively.

In closing, treating diversity as an essentially contested concept reframes long-standing disputes as opportunities for pluralism, reflexivity, and innovation. Our goal was to demonstrate that acknowledging diversity as an essentially contested concept is not a weakness of ecological thought, but a prompt for more reflective, inclusive, and responsible research, teaching, and policy. Diversity's very elusiveness is what makes it powerful: it invites ecologists, policymakers, and citizens alike to reflect on what they value in the living world and to be explicit about how those values shape science and decision-making. Acknowledging the contested nature of biodiversity, and embracing transparency and pluralism in how it is defined and measured, can help ensure that conservation lives up to both its scientific ambition and its ethical promise.

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