

## Feature Review

Functional trait effects on ecosystem stability:  
assembling the jigsaw puzzle

Francesco de Bello,<sup>1,2,3,\*</sup> Sandra Lavorel,<sup>4,5</sup> Lauren M. Hallett,<sup>6</sup> Enrique Valencia,<sup>7</sup> Eric Garnier,<sup>8</sup> Christiane Roscher,<sup>9,10</sup> Luisa Conti,<sup>2,11</sup> Thomas Galland,<sup>1,2</sup> Marta Goberna,<sup>12</sup> Maria Májeková,<sup>1,13,14</sup> Alicia Montesinos-Navarro,<sup>3</sup> Juli G. Pausas,<sup>3</sup> Miguel Verdú,<sup>3</sup> Anna E-Vojtkó,<sup>1,2</sup> Lars Götzenberger,<sup>1,2</sup> and Jan Lepš<sup>1,15</sup>

Under global change, how biological diversity and ecosystem services are maintained in time is a fundamental question. Ecologists have long argued about multiple mechanisms by which local biodiversity might control the temporal stability of ecosystem properties. Accumulating theories and empirical evidence suggest that, together with different population and community parameters, these mechanisms largely operate through differences in functional traits among organisms. We review potential trait-stability mechanisms together with underlying tests and associated metrics. We identify various trait-based components, each accounting for different stability mechanisms, that contribute to buffering, or propagating, the effect of environmental fluctuations on ecosystem functioning. This comprehensive picture, obtained by combining different puzzle pieces of trait-stability effects, will guide future empirical and modeling investigations.

### Biotic mechanisms of stability: a jigsaw puzzle

As biodiversity is declining at an unprecedented rate, a particularly urgent scientific challenge is to understand and predict the consequences of biodiversity loss on multiple ecosystem functions [1–3]. Temporal stability of the functioning of ecosystems is critical to both intrinsic and human purposes (Box 1, Figure 1). Temporal stability can be defined as the ability of a system to maintain, through time, multiple **ecosystem properties** (see Glossary) in relation to reference conditions. Key elements of stability (Box 1 and Figure 1) are, for example, inter-annual **constancy** in ecosystem properties, but also **resistance and recovery** from environmental change and **perturbation**. Stability is maintained by populations, communities, and ecosystems that can buffer the effects of environmental variation, thus retaining ecosystem functions such as productivity, carbon sequestration, pollination, etc. The idea that greater biodiversity stabilizes natural communities and ecosystems (i.e., diversity begets stability [4,5]) has led to a long-running debate on the relationship between species diversity and stability [6,7].

At the same time, the understanding that the functioning of ecosystems depends on species' functional traits, rather than only on species diversity *per se*, is becoming a dominant paradigm [1,8–10]. Trait-based approaches, in combination with classical taxonomic approaches, have been developed to unravel species coexistence mechanisms [11–13] and predict ecosystem functions and services at a given point in time [1,14]. The mechanisms by which biodiversity affects temporal stability (Box 2) also operate through differences between organisms in terms of their functional traits (Figure 1). However, scattered evidence and diverse methods exploring these links have prevented a more complete view of the complex relationships between traits and stability. One potential limitation is that the concepts of stability and their drivers remain a major source of Babylonian confusion and disagreement among scientists today [15]. Stability, including its underlying mechanisms, is a multifaceted concept (Boxes 1 and 2) and

### Highlights

The main mechanisms by which biodiversity affects the stability of ecosystem functions (dominant species, compensatory dynamics, and insurance effects) all act through the functional traits of organisms that form local communities.

These mechanisms can be assessed using different components of trait value distributions within and between species [collectively referred as trait probability density (TPD)].

Variation in local populations can result in overall changes in community structure, which may or may not be propagated into changes in ecosystem functions. The extent of such propagation depends on: (i) the extent of TPD shifts, and (ii) the overlap between response and effect traits, and these effects will vary depending on the biotic mechanisms being assessed.

<sup>1</sup>Department of Botany, Faculty of Science, University of South Bohemia, 37005 České Budějovice, Czech Republic

<sup>2</sup>Institute of Botany of the Czech Academy of Sciences, 37901 Třeboň, Czech Republic

<sup>3</sup>Centro de Investigaciones sobre Desertificación (CSIC-UV-GV), 46113, Valencia, Spain

<sup>4</sup>Laboratoire d'Ecologie Alpine, CNRS – Université Grenoble Alpes – Université Savoie Mont-Blanc, 38058 Grenoble, France

<sup>5</sup>Manaaki Whenua Landcare Research, Lincoln, 7608, New Zealand

<sup>6</sup>Environmental Studies Program and Department of Biology, University of Oregon, Eugene, OR, 97403-5289, USA



**Box 1. Stability components**

The term stability is frequently used and misused in ecology [15]. This term is generally associated with either the ability of an ecosystem to minimize the variability over time of one of its elements or recover it quickly after a perturbation. While specific ecosystem functions or services are most often assessed, stability also includes a species' population size or community composition. Scholars have either focused on ecosystem fluctuations around some 'equilibrium' condition, under stochastic environmental fluctuations, or ecosystem response to specific perturbations. This distinction underpins the debate on how to classify and quantify different stability components [7, 18]. Among multiple approaches, scholars have identified three main types of stability components (Figure 1), which can be further refined [19–21].

The first component is temporal variability or constancy. Constancy describes the extent of natural fluctuations of an ecosystem property when environmental conditions and disturbance levels fluctuate within historical ranges and without the occurrence of extreme events. In these conditions, ecosystem properties fluctuate around a reference condition ('baseline'). Constancy can be measured by the inverse of the coefficient of variation (CV) of an ecosystem property. Other approaches avoid the confounding effects of long-term temporal trends on CV, which can arise due to directional species' temporal turnover [22, 23]. This is often the case when ecosystems are subjected to long-term environmental change (e.g., increasing drought).

The second component is resistance, the ability to maintain a given ecosystem function when subjected to a perturbation by a substantial environmental stress or disturbance. It can be quantified as the (inverse of the) deviation from the reference level of the ecosystem function of interest. Resistance can be also estimated as the ability of an ecosystem to buffer long-term environmental changes [24].

The third component is recovery, the ability of an ecosystem property to return to its reference condition after being subjected to a perturbation. This can be quantified in different ways, for instance, as the time required by an ecosystem property to return to a baseline [21] or the extent of recovery at a given time after perturbation. More definitions of stability components exist, together with different quantification methods. For example, **resilience** includes both resistance and recovery, although in some cases it is equated only with recovery [6, 16, 20, 21].

It should be noted that most studies on stability have investigated only one or a few ecosystem properties, especially biomass production (see [10, 14] for reviews). However, the relationship between biodiversity and stability should be relevant to multiple ecosystem functions, such as nutrient cycling or pollination [1, 14, 25]. An increasing number of studies have demonstrated that biodiversity is playing a role in multifunctionality [26, 27].

understanding it requires connecting a wide variety of drivers across various scales. Some seminal works have paved the road for future research [16, 17], but connecting these scattered puzzle pieces remains an essential step for developing comprehensive conceptual and quantitative trait-based frameworks. In this review, we analyze the main pieces of the biodiversity- and trait-stability puzzle and explore connections between these pieces that can generate integrative conceptual and quantitative approaches for future research (Figures 1 and 2).

**Puzzle piece 1: effects of dominant species' traits**

According to the 'mass-ratio hypothesis' [36], dominant species in a community, through their traits, exert the strongest effect on ecosystem functions at a given time (called 'immediate' effects). Such **dominant species' traits** do not have only immediate effects. One of the two main drivers of constancy is how stable populations are within a community, expressed as average species-level population stability weighted by species' relative abundances [28]. The constancy of species populations has been related to species traits [37–39]. Moreover, resistance and recovery of community biomass after perturbation have been related to the functional traits of the dominant species in a community, rather than to species diversity itself [29]. As such, variation in trait values of dominant species in a community can bridge the gap between temporal population dynamics, community properties and ecosystem stability.

Recent studies have shown that key trade-offs in functional traits between species, such as the leaf economics spectrum [10], or dormancy [39–41] in plants, can help predict both community and population stability [37, 42]. One extreme of the leaf economics spectrum trade-off comprises

<sup>7</sup>Departamento de Biología y Geología, Física y Química Inorgánica, Escuela Superior de Ciencias Experimentales y Tecnología, Universidad Rey Juan Carlos, 28933, Móstoles, Spain

<sup>8</sup>CEFE, CNRS, Univ Montpellier, EPHE, IRD, Univ Paul Valéry Montpellier 3, 34293, Montpellier, France

<sup>9</sup>Department of Physiological Diversity, UFZ – Helmholtz Centre for Environmental Research, Permoserstrasse 15, Leipzig, 04318, Germany

<sup>10</sup>German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Puschstrasse 4, Leipzig, 04103, Germany

<sup>11</sup>Faculty of Environmental Sciences, Czech University of Life Sciences Prague, Praha, Czech Republic

<sup>12</sup>Department of Environment and Agronomy, Centro Nacional Instituto de Investigación y Tecnología Agraria y Alimentaria (INIA, CSIC). Carretera La Coruña km 7.5, 28040, Madrid, Spain

<sup>13</sup>Plant Ecology Group, Institute of Evolution and Ecology, University of Tübingen, Tübingen, Germany

<sup>14</sup>Department of Soil Science, Faculty of Natural Sciences, Comenius University in Bratislava, Bratislava, Slovak Republic

<sup>15</sup>Biology Research Centre, Czech Academy of Sciences, Institute of Entomology, 37005, České Budějovice, Czech Republic

\*Correspondence: fradebel@ext.uv.es (F. de Bello).

species with faster relative growth rate and faster acquisition of resources (acquisitive species). The other extreme defines species with slower growth but, potentially, a greater ability to store resources and thus better withstand extreme events and stressful periods (conservative species). It remains unclear, however, whether above-ground trade-offs such as the leaf economics spectrum are mirrored by dormancy or below-ground trade-offs [43]. Below-ground storage organs, including nonstructural carbohydrate reserves [44], could help buffer population growth (i.e., where species accumulate resources in more favorable years and use them to compensate growth in less favorable years [12]). Similarly, seed dormancy, as a bet-hedging strategy, increases population constancy by reducing short-term reproductive success in favor of longer-term risk reduction [40]. Expanding trade-off mechanisms to various organisms, the classic  $r/K$  selection theory [45] already predicted a general differentiation between  $r$ -type species, with higher relative growth rate, colonization, and dispersion but with lower temporal population stability, and  $K$ -type species, with lower relative growth rate but more stable populations.

Based on these trade-offs, it is expected that communities dominated by slow-growing, conservative species are more stable over time and will be more resistant to extreme events [7,46,47]. First, the few existing results generally confirm the expectations that more conservative species have more stable populations [41,48], for example, characterized by higher leaf dry matter content (LDMC) and lower relative growth rates [37]. Second, communities dominated by plant species with greater LDMC are more stable, in terms of both composition and overall biomass [42,49]. A global meta-analysis on sown biodiversity experiments showed that the increase in fast-growing species (with an acquisitive leaf economy) destabilizes community biomass through time [17]. These studies showed the relevance of **community weighted mean (CWM)** traits (Box 3) (i.e., average of trait values weighted by species abundance) and hence of dominant species [50].

### Puzzle piece 2: compensatory dynamics through species dissimilarity

Constancy is also influenced by the **synchrony** in the fluctuations of different populations within communities [28]. While it is generally accepted that a decrease in species synchrony increases stability of ecosystem properties, the mechanisms generating synchrony, or a lack thereof, are more controversial. Synchrony between species is generally attributed to similar species responses to environmental fluctuations [51,52]. Hence, species with similar adaptations to the environment (i.e., similar response traits; see 'Puzzle piece 4') should fluctuate synchronously and species with different adaptations can fluctuate independently or compensate for each other [3,11]. Note that **compensatory dynamics** are sometimes broadly associated with any deviation from a perfect synchrony between species due to independent fluctuations (sometimes called **asynchrony**), while compensation exceeding averaging effects arises from negative (sum of) covariance between species (**antisynchrony**).

A pattern of compensatory dynamics could result also from biotic interactions, a hypothesis that has caused controversy. For example, competition among functionally similar species could create a pattern where two species prevail over each other in an alternating fashion [53]. This effect could destabilize individual populations [e.g., increasing community coefficient of variation (CV)]. However, the potentially negative covariance between species due to competition could compensate this effect and even result in an increased constancy at the community level [12,54]. Competition might also generate compensatory dynamics through environment–species interactions; for example, environmental conditions that shift species' competitive abilities will decrease synchrony among functionally dissimilar species [55]. Facilitation, especially in severe environments, can increase constancy when some plants buffer microhabitat environmental

### Glossary

**Asynchrony:** deviation from a perfect synchrony in species' fluctuations.

**Antisynchrony:** prevailing negative covariance between species' fluctuations (i.e., negative synchrony).

**Averaging/portfolio effect:** link between an increase in species number and the decrease in the coefficient of variation (CV) of community abundance in the case of independent species fluctuations.

**Buffering:** the ability of a system to maintain given ecosystem functions, even despite species turnover. It is the opposite of propagation.

**Community weighted mean (CWM):** the average of trait values weighted by the relative abundance of each species in a community.

**Compensatory dynamics:** the changes in the relative abundance of some species that are offset, or compensated for, by changes in the relative abundance of other species.

**Constancy:** a stability component describing how invariable (i.e., as inverse of temporal variability) ecosystem properties are in a given period without particularly extreme events.

**Dominant species' traits:** the effect exerted by the dominance of species with particular traits, which governs how a community as a whole responds to environmental fluctuations and affects ecosystem functioning. It is linked to the mass–ratio hypothesis. It can be quantified by the community weighted mean (CWM).

**Ecosystem property:** broadly defined as any measurable component of an ecosystem or its constituent components, including ecosystem functioning, population abundances, species composition, species diversity, etc.

**Effect traits:** any characteristic of an organism that has repercussions for environmental conditions, community properties, ecosystem processes, or functions.

**Functional diversity:** the extent of trait differences among a set of organisms. It is commonly quantified with multiple indices reflecting, for example, average trait dissimilarity or the volume of trait space occupied by a set of species.

**Insurance effect:** a system's ability to buffer the effect of perturbations on community or ecosystem processes by the replacement of species by others

fluctuations for other plants [56]; however, its role in synchrony between populations remains to be clarified. Compensatory dynamics could be also driven by other biotic interactions, such as **intransitive competition** [57] (i.e., in a rock–paper–scissors game between species with different traits).

The relationship between species synchrony and species **pairwise trait dissimilarity** (Box 3), could provide a mechanistic view on the drivers of compensatory dynamics (Box 2). There is increasing empirical evidence that greater trait similarity between species is associated with greater synchrony [3,58–60]. As such, an increase in community **functional diversity** (Box 3) should lead to greater constancy. Support for a decrease in synchrony with increasing functional diversity has been found in beetle communities [61] and in manipulated plant communities [55,62]. The recent study by Craven *et al.* [17] failed to detect any marked effect of plant functional diversity, expressed only for the leaf economics spectrum, on synchrony, but detected an effect of phylogenetic diversity, as in Cadotte *et al.* [63]. This is possibly because the relationship between pairs of species and their synchrony is better appreciated on the basis of **multiple traits** [3,61]. Phylogenetic diversity can be considered as a proxy of multi-trait diversity and unmeasured traits [64]. It should be noted that classic species coexistence theories, like limiting similarity and niche complementarity, also predict that multi-trait dissimilarity could allow species coexistence by decreasing competition for similar resources and improve ecosystem multifunctionality [13]. In a temporal context, multi-trait dissimilarity could cause, beside these effects, compensatory dynamics.

### Puzzle piece 3: redundancy and the insurance effect

The **'insurance effect'** requires the presence of multiple species with a similar effect on ecosystem functioning but different sensitivities to specific perturbations. Authors have thus stressed the importance of functional **redundancy** (i.e., the presence of multiple species with a similar effect on a given ecosystem function) as an important recovery and resistance mechanism [16]. A quick recovery can be obtained, for example, when a subordinate species, with similar effects on ecosystem functioning, but different environmental sensitivity, rapidly replaces lost dominant species [33]. For instance, a conservative stress-tolerant species could replace a more acquisitive species during an extreme drought event, thus maintaining equal ground cover and soil stabilization. Likewise, a generalist pollinator species could maintain pollination, usually realized by a specialist species, after an unusually early spring or a fire [65]. These species replacements would not count as regular alternation of dominant species (compensatory dynamics), but long-term compositional changes following a given perturbation, including extinction events. Another important difference between insurance and compensatory dynamics is the selection of relevant functional traits. While, as we saw earlier, compensatory dynamics reflect adaptation to both multiple abiotic and biotic conditions, for which a multivariate trait dissimilarity (or phylogenetic distance) between species is important, insurance can be ideally tested by selecting species' adaptation to a specific perturbation.

There is evidence that low functional redundancy in fish communities increases ecosystem vulnerability to environmental changes [66]. It is also expected that greater diversity in resource use between species lowers the requirement for multiple species in order to maintain stability in each ecological function [67] (i.e., a lower number of species is required to maintain redundancy if these species have sufficiently different environmental sensitivities).

Although these effects seem very promising, there are methodological difficulties in quantifying functional redundancy. Functional redundancy should ideally reflect how many different species there are for a given functional role in a community and it is thus not fully covered by measures

with similar effect traits. It depends on functional redundancy.

**Intransitive competition:** interactions among species in a community in which they do not follow a linear hierarchy but a 'rock-paper-scissors' game without a single best competitor.

**Pairwise trait dissimilarity:** functional trait differences between pairs of species in terms of given traits or multiple traits. Sometimes a phylogenetic distance (e.g., length of branches connecting two species in a phylogenetic tree) is used as well.

**Perturbation:** a relatively sudden change in environmental conditions or in the disturbance regime beyond the range of the historical variability (e.g., exceptional fire, flood, or drought).

**Propagation:** the process by which species turnover is directly translated into changes in ecosystem function.

**Recovery:** the ability for a population, community, or ecosystem function to reorganize and return to its reference condition after it has been affected by a perturbation.

**Redundancy:** the degree to which species perform similar functions. Communities with high redundancy are expected to be able to lose species without great changes in ecosystem functions due to replacement of dominant species by subordinate species with similar effect traits.

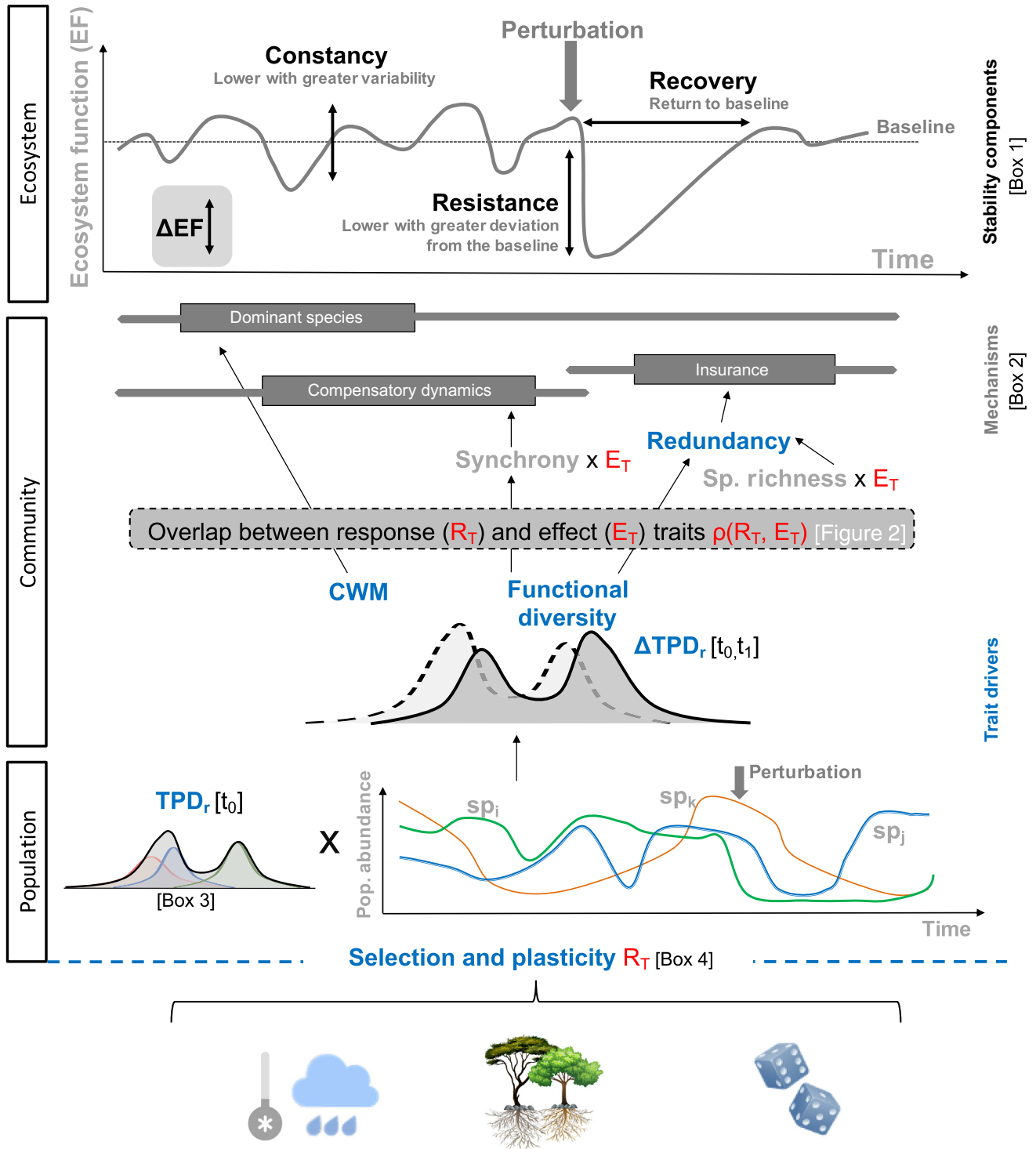
**Resilience:** the degree to which an ecosystem function can resist or recover rapidly from perturbations.

**Resistance:** the ability of an ecosystem to remain unchanged when being subjected to a perturbation. It is inversely proportional to vulnerability.

**Synchrony:** the pattern that occurs when most of the species in a community respond in the same manner to variation in abiotic and biotic conditions, leading to concordant species fluctuations.

**Trait probability density (TPD):** distribution of trait values of an ecological unit, from the individual to ecosystem level, in a given functional space. Such trait distributions can be the basis of multiple indices and components.

**Turnover:** the rate or magnitude of change in species composition (e.g., replacement of species and changes in their abundances in space or time).



Trends in Ecology & Evolution  
(See figure legend at the bottom of the next page.)



### Box 2. Stability mechanisms

The hypothesis that biodiversity can increase ecosystem stability has generated a great debate in ecology [5,6]. Biotic effects are expected to modulate various components of stability within a given trophic level via several ecological mechanisms. Three distinct mechanisms involve functional traits: (i) dominant species, (ii) compensatory dynamics, and (iii) insurance. These mechanisms are expected to be differently associated with different components of stability (see Figure 1 in main text). The first two mechanisms have been related to constancy [28]. However, the effect dominant species have also been related to resistance and recovery after perturbations, together with the insurance effect [6,16,29]. Other mechanisms operate, for example, at the landscape level [16,30], but local biodiversity effects, addressed here, are arguably the first crucial link.

The dominant species effect reflects the effect of communities' most abundant species through their overwhelming influence on multiple ecosystem functions. The coefficient of variation (CV) in total community productivity (i.e., inverse of constancy [28,31]), reflects fluctuations of individual species' populations and can be influenced directly by the weighted average of the CVs of individual species' abundances.

Compensatory dynamics occur when temporal fluctuations in the abundance of some species are offset by fluctuations of others [6,32]. Compensatory dynamics decrease synchrony among species and can be interpreted as the effect of varying species-specific responses to environmental fluctuations, species interactions, and stochastic events. The positive effect of species richness on stability, increasing with independent fluctuations and lower synchrony between species, is called the 'averaging' or 'portfolio' effect [6,32].

Differing species-specific environmental sensitivities can also underpin the insurance effect. Various definitions of the insurance effect exist. Here, following McCann [6], we first distinguish the insurance effect from compensatory dynamics by whether pronounced perturbation events are considered (Box 1) where an insurance effect characterizes the ability of an ecosystem to resist and recover after a perturbation. A perturbation can cause a decline or loss in some dominant species. The insurance effect implies the presence of some subordinate species being 'redundant' (i.e., with similar ecosystem effects but differing sensitivity to perturbations; see 'Puzzle piece 3') with the declining dominant species [20,33,34]. These 'redundant' species can replace the formerly dominant species and maintain ecosystem functioning. Note that this directional substitution is distinguishable from a regular fluctuation between dominant species expected under compensatory dynamics, which also do not necessarily follow perturbations. Redundancy can support both higher resistance and recovery. In practice, distinguishing perturbations from historical variability and environmental stochasticity in local conditions can be arbitrary, but the identification of any specific perturbation is essential for assessing mechanisms of resistance and recovery [35].

of functional diversity alone [68–70]. Measures of the functional role of rare species, in this sense, are increasingly getting attention [71]. A common approach is to define the number of species within functional groups (e.g., [16,33]). However, this depends on the definition of functional groups in a community [34,66]. While in some cases (e.g., nitrogen-fixing species) their delineation is rather straightforward, assigning species to separate groups is often unfeasible or context-dependent since traits often vary continuously rather than supporting any division into clear-cut groups [72,73]. New approaches have therefore been proposed to quantify functional redundancy without defining functional groups. However, problems remain with existing metrics as they correlate too tightly with measures of species diversity or functional diversity, raising doubts on their actual value [68–70]. Future developments for quantifying functional redundancy are thus required, especially to account for the potential of subordinate species to replace dominant species in a community in the face of specific perturbations.

Figure 1. Changes in population abundance, in response to deterministic and stochastic events, build up into different changes at the community level [e.g., trait probability density (TPD), species richness, synchrony] and affect different components of ecosystem stability (variation of a given ecosystem function in time, i.e.,  $\Delta EF$ , with higher  $\Delta EF$  implying lower stability). The effects of biodiversity can be summarized as three main biotic mechanisms together with their corresponding set of trait-related measures. The response to deterministic and stochastic events can be expressed in terms of response traits ( $R_T$ ) and translates into changes in community trait structure (broadly defined as ' $\Delta TPD_R$ ', i.e., community TPD in terms of response traits). The overlap between response and effect traits ( $E_T$ ) will result in changes in different stability components and in changes in different biotic stability mechanisms. Details about several elements of the figures can be found in specific sections of the manuscript (e.g., Box 1, etc.). Drawings at the bottom of the figure are from [freepik.com](https://www.freepik.com). Abbreviation: CWM, community weighted mean.

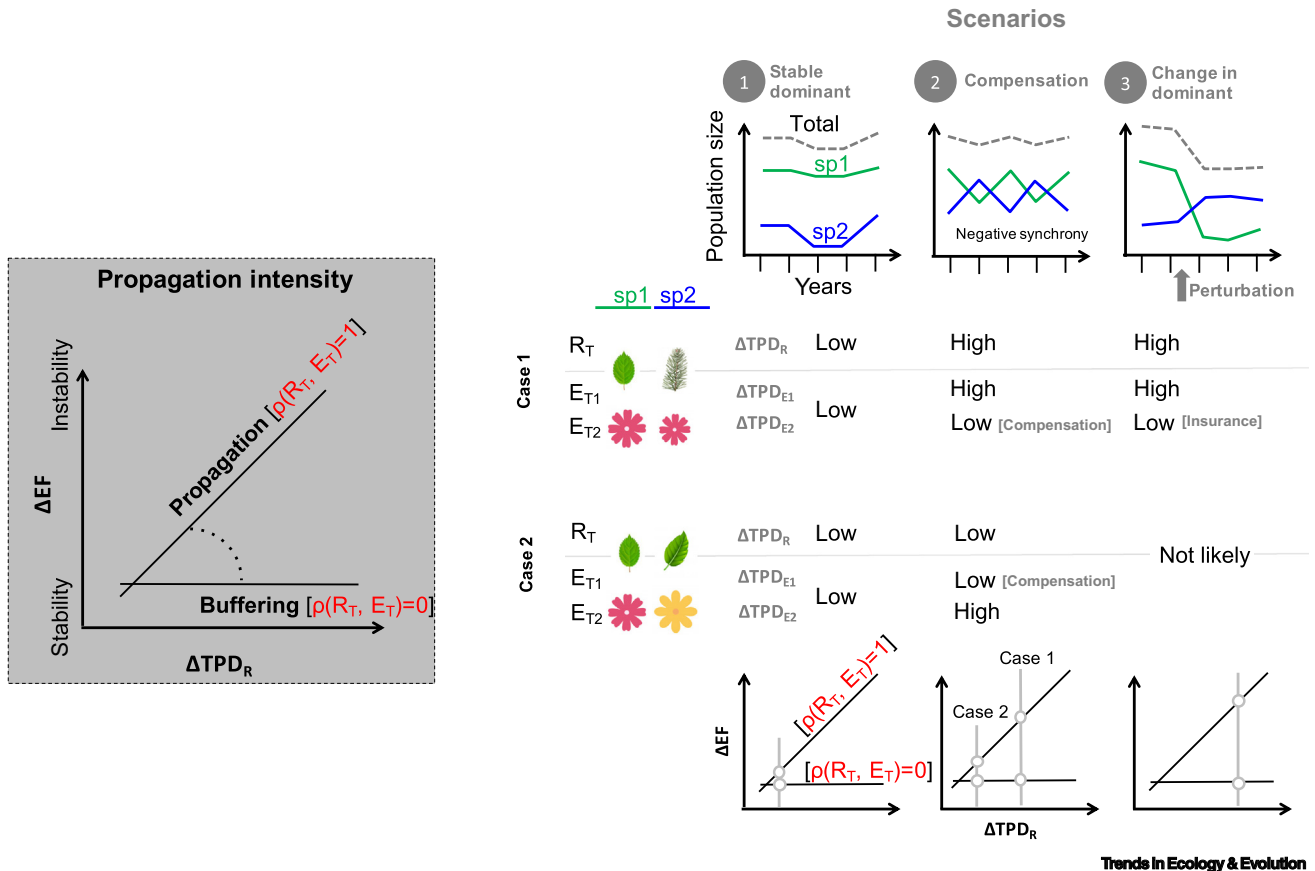


Figure 2. Effect of the overlap between response and effect traits, expressed as their covariation [i.e.,  $\rho(R_T, E_T)$ ], on the modulation of different biotic effects that control ecosystem function stability. Variation in response traits at the community level [ $\Delta TPD_R$  changes in community trait probability density (TPD) in terms of response traits] may or may not result (propagating versus buffering, respectively) in changes in ecosystem function ( $\Delta EF$ ), increasing the chance of greater  $\Delta EF$ . Three scenarios are considered (see section ‘The puzzle comes together: buffering versus propagating’ for details) and each one results in different species composition changes [i.e., fluctuations of two species in time (sp1 and sp2) and their sum (Total)]. In the ‘stable dominant’ scenario (scenario 1) the dominant species remains stable after some environmental change or perturbation, while the subordinate species decreases and then recovers. In the ‘compensation’ scenario (scenario 2) the two species alternate regularly in dominance. In the ‘change of dominant’ scenario (scenario 3), related to an insurance effect, the subordinate species replaces the dominant species after a perturbation causing long-term compositional changes. Within each scenario we consider two cases: (1) one in which the two species have different response traits [ $R_T$ , e.g., one species has high leaf dry matter content (LDMC) and another has low LDMC], and (2) one in which the two species in a community have similar response traits. Within each of these two cases, species can have both similar or different effect traits ( $E_T$ ) for different ecosystem functions; referring to the example in this figure, leaf type and flower would be traits associated with different functions (e.g., decomposition rate and pollination rate). For each scenario, a specific projection of the propagation intensity scheme is reported in the lower part of the figure (vertical lines in panels at the bottom of the figure indicate how Case 1 and 2 affect stability; Case 1 and 2 have different effects only in scenario 2). The labels ‘low’ and ‘high’ summarize the extent of  $\Delta TPD$  components. See details in the main text. Drawings of leaves and flowers are from [freepik.com](https://www.freepik.com).

#### Puzzle piece 4: response and effect traits

A decisive puzzle piece modulating different trait–stability mechanisms is the trait response–effect framework [77], as originally suggested by Oliver *et al.* [16]. Which species will increase or decrease in response to both environmental fluctuations, including disturbances, and biotic interactions depends on their ‘response traits’ (i.e., traits that affect the fitness of species for given ecological conditions, including prevailing interactions) [10]. For example, plant traits related to drought tolerance, such as succulence [73] or the ability to retain water in isopods [78], are traits associated with greater fitness of species in drier conditions [79,80]. Similarly, species with traits associated with a higher intrinsic relative growth rate will recover more quickly from environmental perturbations [16] but will also be less constant in abundance over time [29,37].

Some functional traits also have the potential to affect other trophic levels and multiple ecosystem functions [10,14,25]. **Effect traits** are therefore those traits of an organism that impact prevailing ecosystem processes and functions. For example, mandible strength will determine the extent and type of food consumed in grasshoppers [81]. Flammability traits in plants modify the fire regime and generate eco-evolutionary feedback [82]. Secondary compounds in leaves not only offer defense against herbivory but might slow down litter decomposition [83], while floral traits will affect pollination [25].

The covariation, or the overlap, between response and effect traits has been identified as the key mechanism by which environmental changes can be translated into ecosystem function changes [77,84]. The response–effect framework, however, has been only rarely assessed in the context of stability [16]. For example, accounting for both response and effect traits has been advocated as an important aspect in estimating functional redundancy [34]; however, empirical tests are scarce (but see [85]). More broadly, with greater trait overlap between response and effect traits, changes in environmental conditions will more likely propagate into ecosystem functions, thus decreasing stability. This effect, however, will depend on the stability mechanisms under consideration and the trait probability density (TPD) components considered (Figure 2 and see later).

It should be noted that it can be difficult to understand to what extent a trait is purely a response or an effect trait, or both. Whether a given trait operates as a response or effect trait depends on the environmental context and ecosystem functions of interest. Traits that are related to the processing of resources (e.g., gas exchange, water and nutrient uptake in plants, or body size in animals) will be likely both response and effects traits for corresponding functions of biogeochemical cycling. But these traits will not affect, at least directly, some other ecosystem functions. For example, leaf traits associated with several functions of resource use do not directly affect pollination, which depends on flower traits, although they might be correlated through phylogeny [25].

### The puzzle comes together: buffering versus propagating

Oliver *et al.* [16] already stressed the central importance of the interplay between response and effect traits for the insurance effect. Here, by expanding this, we illustrate how this interplay represents the centerpiece for translating, via TPD, population and community changes to ecosystem functioning, integrating different stability components and their underlying mechanisms. The central concept bringing this puzzle together is that environmental fluctuations and perturbations cause changes in population abundances, and possibly intraspecific phenotypic variation (Box 4), modifying the local TPD for response traits ( $\Delta\text{TPD}_R$ ; Figure 1).

To what extent do these changes cause a modification in ecosystem functioning ( $\Delta\text{EF}$ )? For the sake of simplicity, we will distinguish two extreme situations (Figure 2): (i) communities ‘**buffering**’ the effect of environmental change (i.e., with very small consequences for ecosystem functions, small  $\Delta\text{EF}$ , greater stability) versus (ii) communities ‘**propagating**’ environmental change effects on ecosystem functions, (a large  $\Delta\text{EF}$ , lower stability). In general terms, a community will be buffering, or conversely propagating, a given environmental change, depending on the extent of change in response traits. A small change in TPD for response traits ( $\Delta\text{TPD}_R$ ) will likely result in small changes in ecosystem functions (small  $\Delta\text{EF}$ ) because of limited changes in effect traits. The larger the  $\Delta\text{TPD}_R$ , the greater the chance that some effect traits will change as well and, hence, increase the change in ‘**propagation**’ effects (marked  $\Delta\text{EF}$ ). Further, this propagation will be stronger with a tighter overlap between response and effect traits [i.e., a high  $\rho(R_T, E_T)$ ]. Let us consider now a few scenarios as examples of the flow from population abundances to  $\Delta\text{EF}$ , depending on the magnitude of  $\Delta\text{TPD}_R$  and  $\rho(R_T, E_T)$ . In the following we unpack how



these scenarios determine how much communities buffer or propagate effects of environmental changes on ecosystem functions and, thus, how the different puzzle pieces can come together.

### Stable dominants

The first scenario is when small changes in composition within a local community follow a given environmental change (scenario 1, [Figure 2](#)). This could happen both under natural environmental variability in an ecosystem at equilibrium or following a perturbation. An example of this pattern was observed in plant communities dominated by conservative species after an extreme drought event [29]. These communities were able to buffer (i.e., high resistance) environmental variations [86], likely because of the buffered population growth of the dominant species. Buffered population growth is a key mechanism of coexistence in fluctuating environments, also described as the 'storage effect' [12], where conservative species can withstand unfavorable years, for example, due to resource storage [87]. We can thus expect small changes in all facets of TPD, and thus stability, in multiple ecosystem functions (low  $\Delta EF$ ), independently of whether species have overlapping response and effect traits.

### Compensatory dynamics

Compensatory effects are usually considered to be a key mechanism of constancy [6] but may also destabilize ecosystem functioning. Constancy in ecosystem functioning can be obtained when 'inconstant' populations of species with similar effect traits periodically (for example, on a yearly basis) 'compensate' for each other (scenario 2, in [Figure 2](#)), that is, they negatively covary in time (antisynchrony). As we discussed earlier, theoretical [11] and empirical evidence [3,58–61] suggests that antisynchrony will occur between species with different response traits, moderate to high  $\Delta TPD_R$ , and overall high functional diversity in a community; case 1 in [Figure 2](#)), reflecting different environmental preferences. Constancy in ecosystem functioning will then occur only if effect traits and response traits are dissociated (high functional diversity in response traits, low in effect traits). Otherwise, changes in species composition will propagate into changes in effect traits and cause  $\Delta EF$ . Imagine a case where the ecosystem function of interest is pollination and two antisynchronous species have different response traits (e.g., different LDMC) and also different effect traits (e.g., flower types with access to different pollinators; case 2 in [Figure 2](#)), that is, high  $\rho(R_T, E_T)$ . In this case we can expect a periodic change in  $\Delta EF$  both in decomposability and pollination. Antisynchrony could also occur between functionally similar species (low  $\Delta TPD_R$ ) after temporal changes in the competition hierarchy ([3,11]; case 2 in scenario 2, [Figure 2](#) [57]). In this case, buffering is more likely, especially if effect and response traits overlap.

### Insurance effect

The insurance effect can be particularly important in the case of replacement of a dominant species by an otherwise subordinate species following some exceptional perturbation (e.g., fire or drought [88]). Such directional species replacements (different from periodic replacement in compensatory effects, earlier) are expected between species with different adaptations to given perturbations (and, likely, a high  $\Delta TPD_R$  in specific traits; a replacement between species with similar response traits following an extreme climatic or disturbance event is not likely). An insurance effect is again possible only if response and effect traits are dissociated (case 1, scenario 3, [Figure 2](#)). It should be noted that greater species diversity should increase the odds that more species will have different adaptations to perturbations [52]. At the same time the greater the diversity in  $\Delta TPD_R$ , the lower the species richness needed to buffer an ecosystem process [67]. For this reason, functional redundancy between dominant species and subordinate species, key for the insurance effect, is expected to reflect the interplay of both species diversity and functional diversity across species. Note also that in scenario 3, [Figure 2](#), it can happen that some functional traits may exert some insurance effects, but the total population abundance can still decrease.

Some ecosystem functions, such as soil stability and formation, could be thus affected by the perturbation, simply as a consequence of reduced plant cover (see next section).

### Connecting the pieces with TPD: data analysis considerations

Connecting different biotic drivers of stability is a tall challenge and remains a critical gap in our understanding of trait effects on ecosystem stability. Approaches similar to path analysis can provide a way forward for testing causal and cascading connections among the functional make-up of populations and communities and those of communities and ecosystem properties [17,31,55,61,89]. Existing studies have already considered a selection of TPD components to explain specific components of stability [3,17,31,55,61,89]. It is thus important to select predictors and tests based on the mechanism(s) of stability considered (Figure 1) and the specific scale of interest (Box 3 for specific tests). As discussed earlier, trait selection is also a key step that depends on the stability mechanism under evaluation (response traits) and the ecosystem function considered (effect traits). A useful set of trait-based predictors includes: (i) CWM for studies on dominant species and insurance effects; (ii) functional dissimilarity between dominant species (i.e., for functional diversity) for compensatory dynamics; and (iii) functional redundancy between sets of dominant and subordinate species for an insurance effect.

In these approaches it is important to connect TPD components with key predictors that are usually considered when assessing the biodiversity–stability puzzle [17,28,31,61]; this also depends on the biotic mechanisms of stability being tested (Boxes 1 and 2). As we saw earlier, key measures are synchrony between species for compensatory dynamics and population CV for dominant species effects. The overall community CV is the most frequently used measure for compensatory dynamics. For compensatory dynamics, under certain conditions, the number of species in a community is mathematically associated with the CV of total community abundance (**averaging/portfolio effect** [6]). Evenness in species' abundances, or the relationship between species' abundances and their variability (mean-variance scaling), can both indirectly affect the CV of total community abundance in different ways [28]. Total community abundance and overyielding (i.e., species in mixtures being more productive than in monocultures, thus increasing total abundance) both affect CV. These, and other predictors and interdependencies, are essential for appropriately modeling biodiversity effects on constancy, even if they do not reflect ecological mechanisms *per se* [28].

In biodiversity experiments manipulating species number, species richness can appear as an important direct driver of multiple components of TPD and stability [17]. In natural conditions, however, both species richness and TPD can be rather seen as a result of assembly mechanisms determined by local conditions. In these cases, compensatory dynamics is related to synchrony, and underlying trait dissimilarity [3], rather than to species richness itself [32,90]. On the contrary, the case of the insurance effect shows the relevance of directly considering indices such as species richness together with TPD dimensions [70]. Combining species richness and functional diversity can thus be useful to estimate functional redundancy while new indices of functional redundancy are being developed.

Different parameters of population abundances are other important drivers in the causal relationships between biodiversity and stability of ecosystem functions. For example, either mean population variability or total abundance, and sometimes both, are considered in causal relationships. Both the ranking in population abundances and average population stability vary, depending on species' response traits within the local species pool, and these traits directly affect indices such as CWM and functional diversity. Moreover, some ecosystem functions will also depend directly on the total abundance of local populations, for example, through its effect on

**Box 3. Trait probability density**

Trait-related stability mechanisms can be assessed by using different facets of trait-abundance distributions within and across species. Trait-abundance distributions are broadly referred to as trait probability density (TPD). The TPD reflects the relative abundance of trait values at a given study scale. It can be described by the different statistical 'moments' of trait distributions (e.g., mean, variance, skewness, kurtosis) on multiple scales, from individuals to ecosystems. A great variety of measures exist to characterize multiple TPD components, which is not bound to given mathematical approaches [68,74,75].

By integrating species abundances and traits, TPD has the potential for connecting population and community dynamics and thus scaling up temporal variations in species populations to ecosystem functioning and its stability (see Figure 1 in main text). TPD in a local community is the result of both random and deterministic processes governing changes in species' relative abundances from the local species pool [76] (see Figure 1 in main text) and trait variability within species (Box 4). Temporal changes in TPD components can thus affect stability and can be assessed together with taxonomy-based measures such as species richness and evenness or synchrony between species, which are also known to influence stability [28,31] (see 'Connecting the pieces with TPD: data analysis considerations'). Changes in TPD build up from population to community trait structure and different tests can be run, at different scales, to track the effect of these changes on stability (Figure 1).

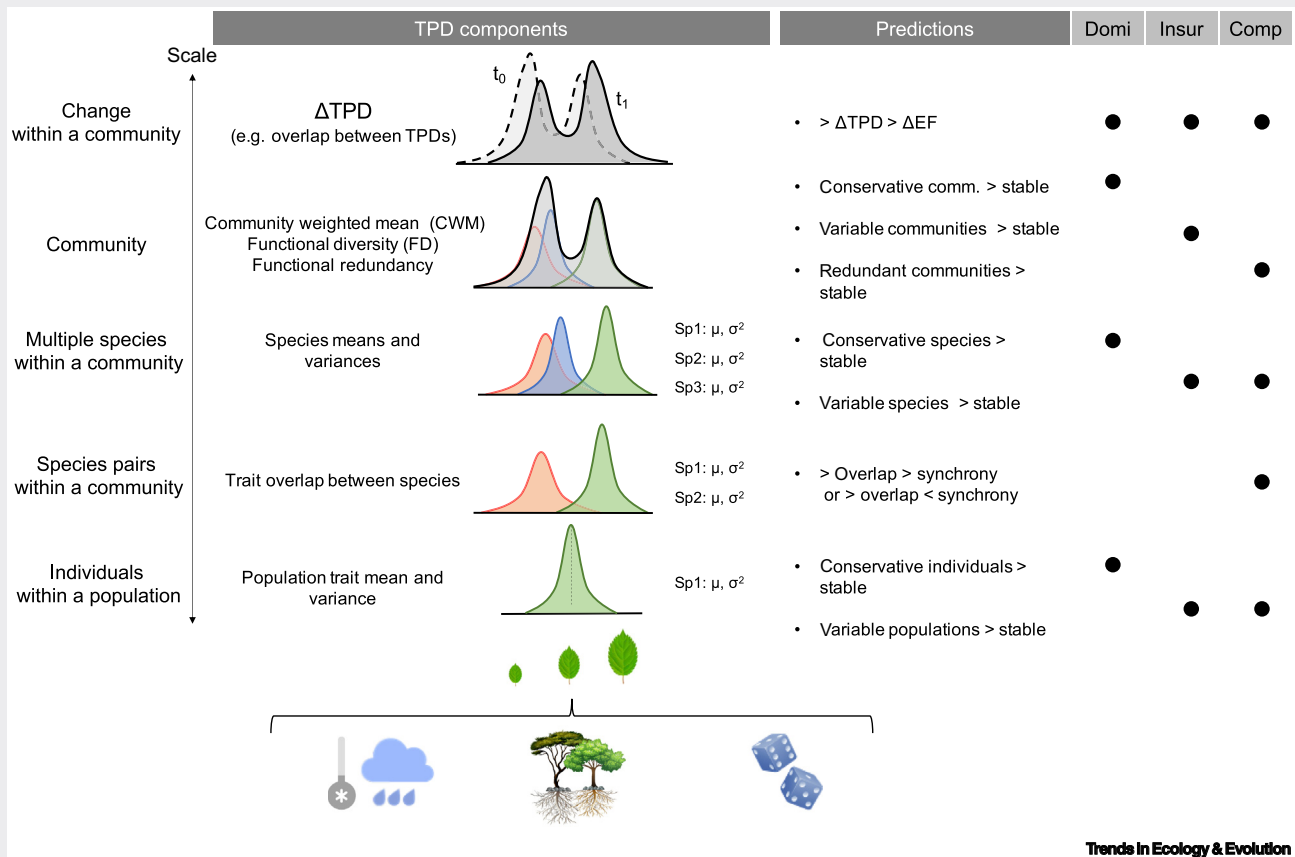


Figure 1. Different components of trait probability density (TPD), at different scales, with reference to their potential test and possible stability mechanisms. Note that spatial TPD changes within a site or landscape can be also visualized similar to the case of 'Change within a community'; in that case, however, spatial heterogeneity in TPD ( $\Delta$ TPD) should result in an overall more stable ecosystem functioning [16,30]. Abbreviations: Comp, compensatory dynamics effect; Domi, dominant species effect; Insur, insurance effect.

the denominator of CV. Two communities with identical distributions of trait values could have very different total abundances of individuals, especially since TPD is generally based on species relative abundances [68]. A greater absolute abundance in one community, while keeping all other TPD components fixed, could imply direct effects on ecosystem functions, for instance, greater resource use, greater productivity, etc. Total population abundance can thus modulate ecosystem stability directly, or even indirectly via changes in TPD components.

Environmental conditions might also modulate ecosystem functioning directly, not only indirectly through changes in TPD components. For example, in their meta-analysis across biodiversity experiments manipulating sowing species diversity, Craven *et al.* [17] showed the direct effects of environmental conditions (both their mean and heterogeneity) on stability of productivity, independently of the biotic predictors considered. However, within given locations, environmental effects may primarily operate indirectly through changes in TPD components.

An important practical decision when using taxonomic or functional components of diversity as predictors of stability is at what point in time they should be computed. Authors usually consider an average species richness, or an average functional diversity, across the studied period when assessing constancy through CV [3,17,61]. The accumulated species richness, or overall functional diversity, across the whole period, has also been considered, although they tend to be correlated with average values [3]. These correlations, however, might be weak when communities undergo gradual species **turnover**, or after a strong perturbation, which would change species composition and species richness over time [91]. In these cases, detrending methods should be considered [23,92]. For resistance and recovery, the optimal approach is to compute biodiversity indices before and at various stages after the perturbation under study.

### Concluding remarks

Several biotic mechanisms affect the different components of ecosystem stability. Theoretical and empirical evidence is accumulating suggesting that these biotic mechanisms are affected by different components of the trait-probability distributions within local species pools. Future studies therefore need to consider differences in trait values within and between species when assessing how different biotic mechanisms affect stability (see [Outstanding questions](#)). We argue that conceptual and terminological clarity would provide a more complete picture of the effects of biodiversity on stability by connecting the pieces of the trait-stability puzzle.

Different tests are possible depending on the ecological scale considered ([Box 3](#)), and the interplay between population dynamics and community properties ([Figure 2](#)) is key in determining biodiversity effects on the stability of ecosystem functioning. Comprehensive frameworks testing biodiversity effects on ecosystem properties need to combine multiple types of metrics ([Figure 1](#)), not necessarily trait-based, which are also selected depending on the stability mechanisms under scrutiny. Variation in the local populations can result in overall changes in community structure, which may, or may not, propagate into changes in ecosystem functioning. The strength of this propagation depends on the extent of trait changes and the degree of overlap between response and effect traits, an idea which has, so far, not been fully incorporated in analyses linking biodiversity and stability. Including response and effect trait analyses can also help to improve the quantification of functional redundancy, which is essential for testing the insurance effect. In the future, attention should also be paid to the potential for intraspecific trait variability (ITV) in affecting local population stability, via intraspecific adjustments ([Box 4](#)). While here we have reviewed mechanisms of stability within given trophic levels, trait mechanisms acting across trophic levels will be central to future developments for assessing the stability of multi-trophic ecosystem functions. Finally, the framework and concepts synthesized in this review should be applicable to different types of environments and under different global-change scenarios. This will enable us to assess to what degree the effects of different biotic mechanisms of stability vary along gradients of habitat severity and habitat heterogeneity and in response to different types of perturbations.

### Outstanding questions

What is the relative effect of different components of trait value distributions within communities ([Box 3](#)) on various components of stability ([Box 1](#))? To what extent does the effect of different biotic mechanisms of stability change along gradients of habitat severity and habitat heterogeneity?

How much do (i) selection of genotypes, and (ii) phenotypic plasticity (including epigenetic variation and transgenerational plasticity) affect population fluctuations? What is the relative effect of such mechanisms on the stability of communities and ecosystem functions?

To what extent can the overlap between response and effect traits affect the potential of communities to buffer changes in environmental conditions on ecosystem function stability? To what extent are temporal trade-offs in the stability of multiple ecosystem functions connected with the overlap between response and effect traits across trophic levels?

#### Box 4. Future puzzle pieces: intraspecific trait variability (ITV)

Most of the examples and studies reviewed so far refer to the effect of species diversity and trait dissimilarity between species, including trait trade-offs between species. However, most of the mechanisms act first on the variability of local populations and therefore cause phenotypic differences within and between populations of a species. ITV could theoretically affect stability [16]. At the same time, it is important to differentiate between 'spatial' ITV (among individuals) and 'temporal' ITV (between seasons or years, including plasticity and micro-evolutionary processes). Both these expressions of ITV are components of TPD [68]. Changes in time, or space, in TPD can be caused by ITV and species turnover, or more frequently by both [93].

ITV caused by genetic variation within the population can affect its stability [94,95]. For example, individuals within a population with more conservative traits could have more stable growth or reproduction over time, while individuals with less conservative strategies would be less resistant, but exhibit faster recovery [96]. Hence a population with both 'types' could be maintained, overall more constantly in time, in fluctuating conditions. Wright *et al.* [97] hypothesized that higher ITV could confer greater stability within species, possibly through an insurance mechanism, although compensatory mechanisms between different genotypes could also occur [98].

Another mechanism concerning the effect of ITV on stability is phenotypic variation across generations. This can be caused by either selection of different phenotypes over time or transgenerational plasticity. Zuppinger-Dingley *et al.* [99] and Latzel *et al.* [100] highlighted the importance of within-species trait variability and year-to-year trait-adjustment effects on ecosystem stability and the influence of both selection and transgenerational plasticity on ITV. Ultimately, selection across generations can increase functional diversity in a community [99]. Interactions between species within a given season can stabilize communities via transgenerational effects in plant traits in the following growing seasons [101]. Thus, these within-species adjustments seem to be an important, yet largely unexplored, component of the stability of communities. However, the empirical testing of ITV effects on stability will be challenging, particularly if we are not able to separate the cause of phenotypic variation. We should be also aware that high ITV might be a consequence, instead of the cause, of population instability. For example, seasonal drought will probably have a spatially nonhomogenous effect on plants, causing high levels of intraspecific variability in some traits and, at the same time, this will also affect the population size, causing temporal variability.

#### Acknowledgments

This study is the result of an international workshop financed by the Valencian government in Spain (Generalitat Valenciana, reference AORG/2018/) and was supported by Spanish Plan Nacional de I+D+i (project PGC2018-099027-B-I00). E.V. was supported by the 2017 program for attracting and retaining talent of Comunidad de Madrid (no. 2017-T2/AMB-5406).

#### Declaration of interests

No interests are declared.

#### References

- Diaz, S. *et al.* (2007) Incorporating plant functional diversity effects in ecosystem service assessments. *Proc. Natl. Acad. Sci. U. S. A.* 104, 20684–20689
- de Mazancourt, C. *et al.* (2013) Predicting ecosystem stability from community composition and biodiversity. *Ecol. Lett.* 16, 617–625
- Lepš, J. *et al.* (2018) Stabilizing effects in temporal fluctuations: management, traits, and species richness in high-diversity communities. *Ecology* 99, 360–371
- Tilman, D. and Downing, J.A. (1994) Biodiversity and stability in grasslands. *Nature* 367, 363–365
- Isbell, F. *et al.* (2015) Biodiversity increases the resistance of ecosystem productivity to climate extremes. *Nature* 526, 574–577
- McCann, K.S. (2000) The diversity–stability debate. *Nature* 405, 228–233
- Lepš, J. (2013) Diversity and ecosystem function. In *Vegetation Ecology* (2nd edn) (van der Maarel, E. and Franklin, J., eds), pp. 308–346. Wiley
- Hooper, D.U. *et al.* (2005) Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. *Ecol. Monogr.* 75, 3–35
- Cernansky, R. (2017) The biodiversity revolution. *Nature* 546, 22–24
- Garnier, E. *et al.* (2016) *Plant Functional Diversity. Organism Traits, Community Structure, and Ecosystem Properties*. Oxford University Press
- Adler, P.B. *et al.* (2013) Trait-based tests of coexistence mechanisms. *Ecol. Lett.* 16, 1294–1306
- Chesson, P. (2000) Mechanisms of maintenance of species diversity. *Annu. Rev. Ecol. Syst.* 31, 343–366
- Kraft, N.J.B. *et al.* (2015) Plant functional traits and the multidimensional nature of species coexistence. *Proc. Natl. Acad. Sci. U. S. A.* 112, 797–802
- de Bello, F. *et al.* (2010) Towards an assessment of multiple ecosystem processes and services via functional traits. *Biodivers. Conserv.* 19, 2873–2893
- Van Meerbeek, K. *et al.* (2021) Unifying the concepts of stability and resilience in ecology. *J. Ecol.* Published online March 19, 2021. <https://doi.org/10.1111/1365-2745.13651>
- Oliver, T.H. *et al.* (2015) Biodiversity and resilience of ecosystem functions. *Trends Ecol. Evol.* 30, 673–684
- Craven, D. *et al.* (2018) Multiple facets of biodiversity drive the diversity–stability relationship. *Nat. Ecol. Evol.* 2, 1579–1587
- Gross, K. *et al.* (2014) Species richness and the temporal stability of biomass production: a new analysis of recent biodiversity experiments. *Am. Nat.* 183, 1–12
- Grimm, V. and Wissel, C. (1997) Babel, or the ecological stability discussions: an inventory and analysis of terminology and a guide for avoiding confusion. *Oecologia* 109, 323–334
- Elmqvist, T. *et al.* (2003) Response diversity, ecosystem change, and resilience. *Front. Ecol. Environ.* 1, 488–494
- Ingrisch, J. and Bahn, M. (2018) Towards a comparable quantification of resilience. *Trends Ecol. Evol.* 33, 251–259



22. Fernández-Martínez, M. *et al.* (2018) The consecutive disparity index, D: a measure of temporal variability in ecological studies. *Ecosphere* 9, e02527
23. Lepš, J. *et al.* (2019) Accounting for long-term directional trends on year-to-year synchrony in species fluctuations. *Ecography* 42, 1728–1741
24. Kéfi, S. *et al.* (2019) Advancing our understanding of ecological stability. *Ecol. Lett.* 22, 1349–1356
25. Lavorel, S. *et al.* (2013) A novel framework for linking functional diversity of plants with other trophic levels for the quantification of ecosystem services. *J. Veg. Sci.* 24, 942–948
26. Moullot, D. *et al.* (2011) Functional structure of biological communities predicts ecosystem multifunctionality. *PLoS One* 6, e17476
27. Le Bagousse-Pinguet, Y. *et al.* (2019) Phylogenetic, functional, and taxonomic richness have both positive and negative effects on ecosystem multifunctionality. *Proc. Natl. Acad. Sci. U. S. A.* 116, 8419–8424
28. Thibaut, L.M. and Connolly, S.R. (2013) Understanding diversity–stability relationships: towards a unified model of portfolio effects. *Ecol. Lett.* 16, 140–150
29. Lepš, J. *et al.* (1982) Community stability, complexity and species life history strategies. *Vegetatio* 50, 53–63
30. Wang, S. and Loreau, M. (2016) Biodiversity and ecosystem stability across scales in metacommunities. *Ecol. Lett.* 19, 510–518
31. Hallett, L.M. *et al.* (2014) Biotic mechanisms of community stability shift along a precipitation gradient. *Ecology* 95, 1693–1700
32. Valencia, E. *et al.* (2020) Synchrony matters more than species richness in plant community stability at a global scale. *Proc. Natl. Acad. Sci. U. S. A.* 117, 24345–24351
33. Walker, B. *et al.* (1999) Plant attribute diversity, resilience, and ecosystem function: the nature and significance of dominant and minor species. *Ecosystems* 2, 95–113
34. Laliberté, E. *et al.* (2010) Land-use intensification reduces functional redundancy and response diversity in plant communities. *Ecol. Lett.* 13, 76–86
35. Smith, M.D. (2011) An ecological perspective on extreme climatic events: a synthetic definition and framework to guide future research. *J. Ecol.* 99, 656–663
36. Grime, J.P. (1998) Benefits of plant diversity to ecosystems: immediate, filter and founder effects. *J. Ecol.* 86, 902–910
37. Májeková, M. *et al.* (2014) Plant functional traits as determinants of population stability. *Ecology* 95, 2369–2374
38. Metz, J. *et al.* (2010) Plant survival in relation to seed size along environmental gradients: a long-term study from semi-arid and Mediterranean annual plant communities. *J. Ecol.* 98, 697–704
39. Angert, A.L. *et al.* (2009) Functional tradeoffs determine species coexistence via the storage effect. *Proc. Natl. Acad. Sci. U. S. A.* 106, 11641–11645
40. Venable, D.L. (2007) Bet hedging in a guild of desert annuals. *Ecology* 88, 1086–1090
41. Campetella, G. *et al.* (2020) Plant functional traits are correlated with species persistence in the herb layer of old-growth beech forests. *Sci. Rep.* 10, 1–13
42. Polley, H.W. *et al.* (2013) Plant functional traits improve diversity-based predictions of temporal stability of grassland productivity. *Oikos* 122, 1275–1282
43. Bergmann, J. *et al.* (2020) The fungal collaboration gradient dominates the root economics space in plants. *Sci. Adv.* 6, eaba3756
44. Janeček, Š. and Klimešová, J. (2014) Carbohydrate storage in meadow plants and its depletion after disturbance: do roots and stem-derived organs differ in their roles? *Oecologia* 175, 51–61
45. Pianka, E.R. (1970) On r- and K-Selection. *Am. Nat.* 104, 592–597
46. MacGillivray, C.W. *et al.* (1995) Testing predictions of the resistance and resilience of vegetation subjected to extreme events. *Funct. Ecol.* 9, 640–649
47. Karłowsky, S. *et al.* (2018) Land use in mountain grasslands alters drought response and recovery of carbon allocation and plant-microbial interactions. *J. Ecol.* 106, 1230–1243
48. Pausas, J.G. and Keeley, J.E. (2014) Evolutionary ecology of resprouting and seeding in fire-prone ecosystems. *New Phytol.* 204, 55–65
49. Cholle, S. *et al.* (2014) Combined effects of climate, resource availability, and plant traits on biomass produced in a Mediterranean rangeland. *Ecology* 95, 737–748
50. Garnier, E. *et al.* (2004) Plant functional markers capture ecosystem properties during secondary succession. *Ecology* 85, 2630–2637
51. Ives, A.R. *et al.* (1999) Stability and variability in competitive communities. *Science* 286, 542–544
52. Loreau, M. and de Mazancourt, C. (2013) Biodiversity and ecosystem stability: a synthesis of underlying mechanisms. *Ecol. Lett.* 16, 106–115
53. Tilman, D. *et al.* (1998) Diversity–stability relationships: statistical inevitability or ecological consequence? *Am. Nat.* 151, 277–282
54. Allan, E. *et al.* (2011) More diverse plant communities have higher functioning over time due to turnover in complementary dominant species. *Proc. Natl. Acad. Sci. U. S. A.* 108, 17034–17039
55. Hallett, L.M. *et al.* (2017) Functional diversity increases ecological stability in a grazed grassland. *Oecologia* 183, 831–840
56. Butterfield, B.J. (2009) Effects of facilitation on community stability and dynamics: synthesis and future directions. *J. Ecol.* 97, 1192–1201
57. Levine, J.M. *et al.* (2017) Beyond pairwise mechanisms of species coexistence in complex communities. *Nature* 546, 56–64
58. Vergnon, R. *et al.* (2009) Niches versus neutrality: uncovering the drivers of diversity in a species-rich community. *Ecol. Lett.* 12, 1079–1090
59. Rocha, M.R. *et al.* (2011) Functionally similar species have similar dynamics. *J. Ecol.* 99, 1453–1459
60. Karp, D.S. *et al.* (2011) Resilience and stability in bird guilds across tropical countryside. *Proc. Natl. Acad. Sci. U. S. A.* 108, 21134–21139
61. Klink, R. *et al.* (2019) Functional differences stabilize beetle communities by weakening interspecific temporal synchrony. *Ecology* 100, e02748
62. Roscher, C. *et al.* (2011) Identifying population- and community-level mechanisms of diversity–stability relationships in experimental grasslands. *J. Ecol.* 99, 1460–1469
63. Cadotte, M.W. *et al.* (2012) Phylogenetic diversity promotes ecosystem stability. *Ecology* 93, S223–S233
64. de Bello, F. *et al.* (2017) Decoupling phylogenetic and functional diversity to reveal hidden signals in community assembly. *Methods Ecol. Evol.* 8, 1200–1211
65. García, Y. *et al.* (2018) Differential pollinator response underlies plant reproductive resilience after fires. *Ann. Bot.* 122, 961–971
66. Moullot, D. *et al.* (2014) Functional over-redundancy and high functional vulnerability in global fish faunas on tropical reefs. *Proc. Natl. Acad. Sci. U. S. A.* 111, 13757–13762
67. Yachi, S. and Loreau, M. (1999) Biodiversity and ecosystem productivity in a fluctuating environment: the insurance hypothesis. *Proc. Natl. Acad. Sci. U. S. A.* 96, 1463–1468
68. Carmona, C.P. *et al.* (2016) Traits without borders: integrating functional diversity across scales. *Trends Ecol. Evol.* 31, 382–394
69. Ricotta, C. *et al.* (2016) Measuring the functional redundancy of biological communities: a quantitative guide. *Methods Ecol. Evol.* 7, 1386–1395
70. Galland, T. *et al.* (2020) Are redundancy indices redundant? An evaluation based on parameterized simulations. *Ecol. Indic.* 116, 106488
71. Violle, C. *et al.* (2017) Functional rarity: the ecology of outliers. *Trends Ecol. Evol.* 32, 356–367
72. Westoby, M. (1998) A leaf-height-seed (LHS) plant ecology strategy scheme. *Plant Soil* 199, 213–227
73. Diaz, S. *et al.* (2004) The plant traits that drive ecosystems: evidence from three continents. *J. Veg. Sci.* 15, 295–304
74. Pavoine, S. and Bonsall, M.B. (2011) Measuring biodiversity to explain community assembly: a unified approach. *Biol. Rev.* 86, 792–812

75. Gross, N. *et al.* (2017) Functional trait diversity maximizes ecosystem multifunctionality. *Nat. Ecol. Evol.* 1, 0132
76. de Bello, F. *et al.* (2012) Functional species pool framework to test for biotic effects on community assembly. *Ecology* 93, 2263–2273
77. Lavorel, S. and Gamier, E. (2002) Predicting changes in community composition and ecosystem functioning from plant traits: revisiting the Holy Grail. *Funct. Ecol.* 16, 545–556
78. Dias, A.T.C. *et al.* (2013) Traits underpinning desiccation resistance explain distribution patterns of terrestrial isopods. *Oecologia* 172, 667–677
79. Wright, A.J. *et al.* (2017) Plants are less negatively affected by flooding when growing in species-rich plant communities. *New Phytol.* 213, 645–656
80. Veldhuis, M.P. *et al.* (2019) Large herbivore assemblages in a changing climate: incorporating water dependence and thermoregulation. *Ecol. Lett.* 22, 1536–1546
81. Ibanez, S. *et al.* (2013) Herbivory mediated by coupling between biomechanical traits of plants and grasshoppers. *Funct. Ecol.* 27, 479–489
82. Pausas, J.G. *et al.* (2017) Flammability as an ecological and evolutionary driver. *J. Ecol.* 105, 289–297
83. Chomel, M. *et al.* (2016) Plant secondary metabolites: a key driver of litter decomposition and soil nutrient cycling. *J. Ecol.* 104, 1527–1541
84. Suding, K.N. and Goldstein, L.J. (2008) Testing the Holy Grail framework: using functional traits to predict ecosystem change. *New Phytol.* 180, 559–562
85. Kohler, M. *et al.* (2017) Plant functional assemblages as indicators of the resilience of grassland ecosystem service provision. *Ecol. Indic.* 73, 118–127
86. Smith, M.D. and Knapp, A.K. (2003) Dominant species maintain ecosystem function with non-random species loss. *Ecol. Lett.* 6, 509–517
87. Moreira, B. *et al.* (2012) To resprout or not to resprout: factors driving intraspecific variability in resprouting. *Oikos* 121, 1577–1584
88. Battlori, E. *et al.* (2019) Compound fire-drought regimes promote ecosystem transitions in Mediterranean ecosystems. *J. Ecol.* 107, 1187–1198
89. Doležal, J. *et al.* (2020) Determinants of ecosystem stability in a diverse temperate forest. *Oikos* 129, 1692–1703
90. Blüthgen, N. *et al.* (2016) Land use imperils plant and animal community stability through changes in asynchrony rather than diversity. *Nat. Commun.* 7, 10697
91. Dornelas, M. *et al.* (2014) Assemblage time series reveal biodiversity change but not systematic loss. *Science* 344, 296–299
92. Hillebrand, H. *et al.* (2018) Decomposing multiple dimensions of stability in global change experiments. *Ecol. Lett.* 21, 21–30
93. Lepš, J. *et al.* (2011) Community trait response to environment: disentangling species turnover vs intraspecific trait variability effects. *Ecography* 34, 856–863
94. Mueller, L.D. *et al.* (2000) Does population stability evolve? *Ecology* 81, 1273–1285
95. Koji, S. and Nakamura, K. (2002) Population dynamics of a thistle-feeding lady beetle *Epilachna niponica* (Coccinellidae: Epilachninae) in Kanazawa, Japan. 1. Adult demographic traits and population stability. *Popul. Ecol.* 44, 103–112
96. Jung, V. *et al.* (2014) Intraspecific trait variability mediates the response of subalpine grassland communities to extreme drought events. *J. Ecol.* 102, 45–53
97. Wright, J.P. *et al.* (2016) The more things change, the more they stay the same? When is trait variability important for stability of ecosystem function in a changing environment. *Philos. Trans. R. Soc. B Biol. Sci.* 371, 20150272
98. Fridley, J.D. and Grime, J.P. (2010) Community and ecosystem effects of intraspecific genetic diversity in grassland microcosms of varying species diversity. *Ecology* 91, 2272–2283
99. Zuppinge-Dingley, D. *et al.* (2014) Selection for niche differentiation in plant communities increases biodiversity effects. *Nature* 515, 108–111
100. Latzel, V. *et al.* (2013) Epigenetic diversity increases the productivity and stability of plant populations. *Nat. Commun.* 4, 1–7
101. Puy, J. *et al.* (2018) Improved demethylation in ecological epigenetic experiments: testing a simple and harmless foliar demethylation application. *Methods Ecol. Evol.* 9, 744–753