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Trends in
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Opinion

# Plant defense strategies against attack by multiple herbivores

Maite Fernández de Bobadilla [1,3] Alessia Vitiello [1,3] Matthias Erb [2,3] and Erik H. Poelman [1,3,*]

**Plants may effectively tailor defenses by recognizing their attackers and reprogramming their physiology. Although most plants are under attack by a large diversity of herbivores, surprisingly little is known about the physiological capabilities of plants to deal with attack by multiple herbivores. Studies on dual herbivore attack identified that defense against one attacker may cause energetic and physiological constraints to deal with a second attacker. How these constraints shape plant plasticity in defense to their full community of attackers is a major knowledge gap in plant science. Here, we provide a framework for plant defense to multiherbivore attack by defining the repertoire of plastic defense strategies that may allow plants to optimize their defenses against a multitude of stressors.**

## Highlights

Virtually all plants are under attack by a species-rich community of antagonists. A response to one attacker should be balanced with the costs that this response may entail toward defense against other attackers.

Reprogramming of plant physiology to counteract herbivory is typically studied under single or dual attack. Often these studies identify antagonistic interactions that limit plants in their ability to resist a second attacker. The emerging physiological concepts may lead to a mismatch with the adaptive nature of plant responses in community context.

Identifying plants' plasticity to deal with their full community of attackers is key in understanding plant defense strategies and requires unified terminology to illustrate the repertoire of plant plasticity matching ecological patterns of attack.

## Plants are under selection to defend against multiherbivore attack

Plants interact with a large diversity of organisms in antagonistic or mutualistic relationships. For many plant species, insect herbivores are some of the most prominent and diverse antagonists that often have a direct or indirect negative impact on **plant fitness** (see Glossary) [1]. To maximize their fitness, plants use **tolerance** and **resistance** strategies [2,3]. An important asset of the defense repertoire in plants is that they can recognize the specific attacker [4–6] and mount **induced responses** to tailor resistance to the type of attacker. Such induced responses are likely a cost-saving strategy [7]. Typically, responses of plants to herbivores are studied by isolating responses to individual stressors. These studies yielded extensive knowledge on plant perception, recognition, and regulation of responses to insect attack (Box 1). Over the past few decades, studies on dual herbivore attack also uncovered interactions between gene regulatory networks involved in response to individual stressors, resulting in distinct responses to sequential or simultaneous attack by two herbivore species [8–10]. Importantly, these studies documented that antagonistic cross-communication between these networks may impair plants in maximizing resistance to individual stressors [11–16]. Although these results represent a step forward to understand defense responses in an herbivore community context, they do not yet capture the full dynamics occurring in nature, where plants are simultaneously or sequentially attacked by a multitude of organisms [17]. In theory, plants should optimize their defense strategies to deal with **communities of attackers** [18–20]. However, clear examples and a framework for plant defense optimization toward herbivore communities from a physiological perspective are currently missing. Here, we provide a framework to understand plant adaptive responses to multiherbivore attack.

## Plasticity to match community context

From an adaptive point of view, plants should balance their investment in defense with maintaining competitiveness for light and nutrients [21–23]. Optimal defense theory predicts in this context that plants may save costs of defense in the absence of herbivory and especially by defending the most valuable tissues, such as young leaves, the tap root, and reproductive tissues [24,25]. As plants are attacked by communities of herbivores, these tissues are attacked by various herbivore species that differ in where and when they feed, how they damage plants, and how they are affected by

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### Box 1. Plant perception, recognition, and response to herbivores

To deal with multiple attackers, which may all require different **defensive traits**, plants have evolved mechanisms to recognize specific attackers they are facing [2,4]. Plants perceive herbivory via binding and recognition of specific molecules. These molecules may originate from disrupted cell walls that provide general information on plant damage (damage-associated molecular patterns, or DAMPS) or provide more specific information on herbivore identity by herbivore-associated molecular patterns (HAMPs), such as those contained in herbivore saliva. Perception and recognition of specific attackers result in mobilization of resistance through phytohormonal signaling and broad transcriptional reprogramming [2,4,6]. Each attacker elicits a unique signature of responses involving several phytohormones. In general, responses to leaf-chewing herbivores such as caterpillars and necrotrophic pathogens are predominately mediated by jasmonic acid (JA), abscisic acid (ABA) and ethylene (ET). Phloem-feeding herbivores such as aphids or biotrophic pathogens typically induce responses that are mediated by salicylic acid (SA) induction [6,33].

Crosstalk between signal transduction pathways allows plants to fine-tune responses to multiple attackers [11,12]. Crosstalk between the signal transduction pathways is strongly regulated by the NPR1 proteins and WRKY transcription factors that link the JA and SA pathways [61]. Signal transduction in the SA pathway has antagonistic effects on JA regulation [14]. The JA/ET pathway is activated by JASMONATE ZIM-DOMAIN (JAZ) proteins that regulate JA activity and thereby transcriptional activators. The JA pathway has two branches. The MYC2 branch activates wound-induced responses through transcription of *LOX*. The ERF branch is connected to JA and ET signaling and activates transcription of *PDF1.2*, which is primarily involved in responses to necrotrophic pathogens [61,62]. Signaling through one branch has antagonistic effects on the other branch. SA accumulates after attack by sap-sucking herbivores and regulates *NPR1* and its downstream WRKY and TGA transcription factors. These activate defense gene expression such as those that encode for pathogenesis-related proteins (*PR1*).

### Glossary

**Communities of attackers:** multiple species of plant antagonists that arrive simultaneously or sequentially.
**Direct defense:** plant traits that increase the resistance of plants to insect herbivores resulting in reduction of plant fitness loss by herbivory.
**Indirect defense:** plant traits that enhance top-down control of herbivores by natural enemies resulting in reduction of plant fitness loss by herbivory.
**Induced responses:** defense trait that is activated upon herbivore attack and recognition.
**Metabolic costs:** energy and resources required for the production and maintenance of defenses.
**Plant defensive trait:** plant trait that increases the fitness of plants upon herbivore attack.
**Plant fitness:** contribution of an individual plant to the gene pool of the next generation.
**Resistance:** plant traits that reduce pathogen, herbivore performance, or herbivore food plant acceptance.
**Tolerance:** ability of a plant to compensate fitness losses by herbivory without preventing the attack.

plant defenses. This implies that plant responses to one attacker should be balancing the costs and benefits of the response to their suite of attackers to maximize fitness [18,20,26]. These defense strategies may represent advanced risk management strategies to deal with a multitude of stressors [19,20].

## Specific or generalized responses to herbivory

Plants that are apparent to herbivores, such as long-lived trees, shrubs, or perennial weedy species, often heavily invest in broadly effective defenses [27]. When herbivore pressure is high, plants express *constitutive defenses* (Box 2) to reduce herbivory at high maintenance costs [23]. Under high and predictable herbivore pressure, such plants may also use a *general induced response* that targets all potential attackers at once (Figure 1A). Several studies have shown that individual herbivores induce similar suites of defense compounds, where activity of individual compounds may only effectively target a single herbivore species [28,29]. This suggests that either these plant species are not capable of recognizing the specific attacker and thus mount a broad spectrum of defenses or that individual plants are predictably attacked by most of the herbivore species in the pool of potential attackers [20,30]. The costs associated with synthesizing a broad palette of defense compounds may be reduced when compounds are highly *multifunctional* and are involved in **direct** and **indirect defense** as well as other metabolic functions [31,32].

Less apparent plants, such as short-lived species part of early successional stages, may invest in defenses that are tailored to specific specialized herbivores [27]. There is substantial evidence that these plants recognize and differentially respond to specific herbivores. Plants recognize herbivore feeding guilds by their type of damage (e.g., piercing-sucking or leaf chewing) and food plant specialization of herbivores by the organs or tissues they attack (e.g., root, shoot, or flowers), and they can also identify specific herbivores through associated elicitors [2,4,6] (Box 1). However, there is also considerable overlap in core transcription profiles after herbivore attack and little evidence that the expressed phenotype specifically targets the current attacker [33]. Limited specificity may be particularly adaptive under high and predictable herbivore pressure. When herbivore attack patterns are unpredictable, adaptive plant defense strategies may favor specific responses to individual attackers [7]. Theoretically, a more specific response maximizes resistance to the current attacker and reduces investment costs to only the specific defenses needed [7]. However, a

## Box 2. Plant strategies

In the context of the multitude of attackers arriving on plants in various ecological settings, a number of defense strategies can be defined. Many of these include advanced risk management strategies that are reflected in physiological responses of plants to herbivory.

### Constitutive defense

Plants express their defenses independently of actual herbivore attack [3,7].

### General induced response

The induced response against the first attacker is also effective against all subsequent attackers (e.g., cell wall thickening, trichome density, broad spectrum of chemical defenses) [7] (see Figure 1A in main text).

### Multifunctional defense traits

Plants use the same compound to defend against various attackers or with different purposes [16].

### Switching

The plant has the ability to always adapt the response to the current attacker and tailor the defense phenotype to the identity of the stressor (Figure 1B).

### Canalization

The first herbivore attacking the plant has a large impact on the plant defense phenotype. The induced phenotype cannot be changed to respond against subsequent attackers, and it determines how the plant interacts with other members of the insect community [39] (Figure 1C).

### Integration

Plants activate a defense response every time a new attacker arrives and integrate this response into a defense phenotype that is effective against the full suite of attackers but is suboptimal to each individual attacker [47,48] (Figure 1D).

### Prioritization

Upon damage by the most ravaging herbivore species, plants target their defense to the specific attacker, with a cost of becoming more susceptible to other attackers (Figure 1E).

### Vaccination

Induced response to an herbivore species that can be tolerated with the benefit of reduced attack by a more ravaging herbivore [49].

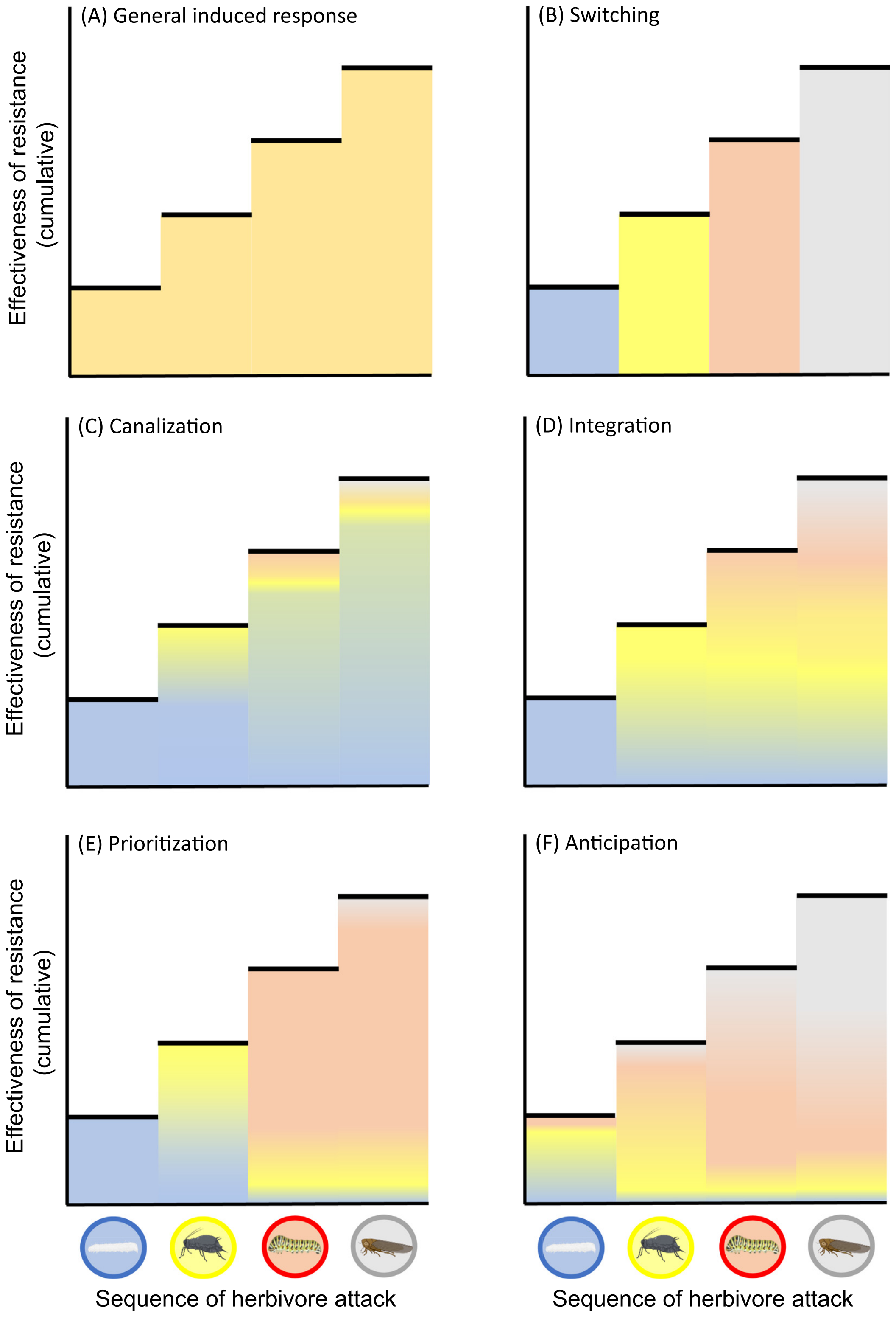
### Anticipation

Plants anticipate the arrival of other herbivores based on cues or the presence of specific herbivores. In their response to the current attacker, the plant already mobilizes defenses for likely forthcoming attack [20,26,53] (Figure 1F).

specific response to one herbivore may impair plants in maximizing resistance or even result in susceptibility to other herbivores, thus compromising fitness. For some plant species, for example, induction of plant defenses to aphids has been shown to reduce resistance to caterpillars [12,34–36]. Similarly, an induced increase in plant family–specific defense chemistry in response to a generalist herbivore may make the plant more susceptible to attack by specialists [37]. Recent studies further identify that cross-resistance or susceptibility via induced responses may be highly specific for the interacting herbivore species pair [26,38]. How specificity in response to individual herbivores and physiological constraints of dealing with a multitude of attackers is reflected in plant defense strategies is poorly defined and underexplored.

## Defining plastic defense strategies to match multiherbivore attack

Here, we define the repertoire of plastic defense strategies that may allow plants to use specific responses in a multiherbivore context (Box 2 and Figure 1). A strong, specific, induced response to a first attacker may limit the potential to respond to other stressors. Several plants show such *canalization* in their response and cannot deploy a full response to subsequent stressors [39]. The



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reduced potential to respond to a second attacker may come from prioritizing defense to the first attacker over growth, which reduces the available energy to mount defenses against subsequent attackers [15,16], and/or antagonistic cross-communication between signal transduction pathways triggered by different herbivores [12,34–36]. The systemic canalization strategy may be adaptive if the first attacker is the most damaging or if the new plant phenotype has broad cross-resistance to subsequent attackers [28,29]. The costs of canalized responses in terms of impaired resistance to subsequent attackers or negative effects on interactions with beneficial organisms [12,40] may be reduced when plants have tissue-specific defense responses and defense allocation [41]. Adopting a *tissue-specific canalization* where each plant organ specifically responds to its first attacker may be adaptive when each organ is attacked by only a few organ-specific herbivore species.

Plants may adopt a *switching* strategy if resistance to each herbivore requires very different responses and the costs of switching phenotype are low. The costs do not only entail metabolic investment in the new resistance traits; if the former attacker is still present, the switch will lead to vulnerability to the first attacker [42]. Thus, completely switching defense phenotype may especially be advantageous when herbivore species do not temporally overlap in when they feed on the host plant [43,44] (e.g., plants growing at high altitude or in very dry ecosystems with herbivore species–poor communities). The **metabolic costs** of switching may be reduced when biosynthetic enzymes and intermediates are shared between pathways that regulate resistance to each individual attacker [16], such as through remobilization of resources from secondary to primary metabolisms and *vice versa* or reabsorbing secondary metabolites to synthesize new chemicals needed for a different response. The switching strategy also implies that plants may reconfigure gene networks involved in crosstalk between pathways to avoid antagonistic crosstalk or switch resistance downstream by, for example, converting secondary chemistry into different components matching the type of attacker or by resource allocation strategies [15,16].

Many plant species find themselves in ecological settings where stressors occur simultaneously. Plants that face multiple abiotic and biotic stressors at the same time need an *integrating* defense response that balances the severeness of each of the stresses. Responses to abiotic and biotic stress share the same signaling pathways and, through crosstalk between the signal transduction pathways plants, may integrate a response to multiple stressors. The plant phenotype thus compromises resistance potential to each individual attacker but yields a net benefit of resistance in perspective of the full attacker community [45–48]. The costs of an integrated response may arise when plants are not able to effectively deal with the most ravaging herbivore species in terms of their effect on plant fitness. Such costs are likely to be countered by *prioritizing* responses to the most damaging herbivores. Thus, plants may integrate responses to multiple attackers but, upon attack by a key herbivore, redirect their resistance to particularly deal with that attacker. The costs emerging from prioritizing resistance to one attacker is suboptimal resistance against other attackers. Thus, such strategies are likely to arise only when fitness costs of attack by herbivore species substantially differ. Under these conditions, we may also find plants to

Figure 1. Strategies of plant-induced responses upon attack by multiple herbivores to acquire cumulative resistance to attack by the full herbivore community. In response to sequential attack by insect herbivores, a general induced response (A) to the first herbivore may be broadly effective against subsequent herbivores. The plant does not favor resistance to one herbivore above others. To reach the same goal to herbivores that widely differ in how they respond to resistance traits, a plant may switch its resistance phenotype according to the type of the attacker (B). In canalized responses (C), the plant response to the first herbivore limits the response to subsequent attack and dominates the resistance phenotype of the plant, reducing resistance to subsequent attack. To tailor the resistance phenotype to multiherbivore attack, plants may integrate and build on their responses to initial herbivore attack (D). Alternatively, a plant may prioritize its response to the most ravaging herbivore and have a vigorous response to this particular herbivore in the sequence of attack (E). Finally, when arrival patterns of herbivores are predictable, plants may respond to initial herbivore attack by already mobilizing resistance traits to forthcoming herbivores and anticipate herbivore attack (F). Colors in bars represent the induced response phenotype to its identically colored herbivore. This figure was created using BioRender (https://biorender.com/).

tolerate particular herbivore species that themselves may not inflict large fitness costs but with their presence reduce the likelihood that the plant will be colonized by more ravaging herbivores [18]. One may even speculate that such *vaccination* strategies lead to plants' recruiting specific herbivores that reduce overall costs of herbivory in a community context [49].

In a community context, plants may use advanced strategies that match predictable patterns of herbivore attack. When arrival of one herbivore species predicts the odds of arrival of subsequent species, plants may evolve *anticipation* strategies [20,26]. In such strategies, the induced response to one herbivore includes a trait expression that prepares for future attack. Examples of this strategy include oviposition-induced resistance to the caterpillars that hatch from these eggs [50,51], plants responding to snail cues and becoming more resistant to later arriving insect herbivores [52], or leaf herbivory enhancing resistance to herbivores feeding on reproductive organs [53]. Anticipatory strategies may only persist under high predictability of herbivore co-occurrence and order of attack [20].

### Using one or multiple strategies

Adaptiveness of each of these strategies largely depends on community context, and it is evident that many plant species are part of communities that are highly stochastic in terms of local dynamics of herbivore and pathogen attack. This means not only that within plant populations frequency-dependent selection may maintain large diversity in (plastic) defense strategies [54] but also that individual plants may be selected to carry out context-dependent strategies [20,55]. Within one plant, the optimal defense strategy to use may depend on attack intensity. This may entail that, depending on the severity of attack by a particular herbivore, plants may either integrate a response to multiple attackers at low density of each attacker or prioritize responses to one attacker when it reaches a damage threshold. Per plant organ, plants may adopt different strategies when leaves are under attack by a large diversity of herbivores, but reproductive tissues are under attack by one herbivore. The effectiveness of each strategy may also largely differ with plant ontogeny, especially when the costs of defense in trade-off with growth and the likelihood of attack vary across plant age [43,44]. This implies that individual plants may exhibit ontogeny-determined plastic responses to multiherbivore attack. Abiotic conditions may limit the potential to deploy particular strategies by resource limitation or by physiological interactions in dealing with abiotic and biotic stress [56].

## Concluding remarks and future outlook

Plant defense strategies against herbivores evolve under the complexity of multiherbivore attack but have been largely studied in isolation over the past decades. Very few studies have moved beyond challenging plants with two stressors [47,48,57,58], and we are only beginning to understand how plants match their phenotype with natural encounters by a large diversity of herbivores [36]. Two important challenges are to identify plant limitations in dealing with their natural numbers and sequences of stressors and to test our current insights of defense plasticity to multiple attackers in an ecologically relevant context. In many of the plastic defense strategies we describe here, specific ecological settings may select against induced plant responses that lead to impaired defense to future attack. We may anticipate that plants adapt their plasticity to match patterns in stress sequences. They should either reduce antagonistic crosstalk between signaling pathways, correct antagonisms in downstream signal transduction, or balance energetic costs of defense responses to multiple attackers. Evidence for such adaptations may be found in plant species that do not have an induced susceptibility to sequential attack that is predicted from antagonistic signal transduction crosstalk [26,35,38].

To understand the physiological strategies and limitations that plants have in dealing with multiherbivore attack, we should challenge plants with simultaneous and sequential attack by

### Outstanding questions

To what extent does recognition of attack by specific herbivores lead to specificity in plant defense phenotypes?

What are the physiological limitations of plant responses to multiple attacks?

What role does crosstalk play in mediating plant responses to multiple herbivores?

Is predictability in the order and timing of attack reflected in plastic plant defense strategies?

Does attack by multiple herbivores lead to diffuse evolution of defense traits?

more than two herbivores. Here we should address in controlled experiments how plants deal with variation in the density, order, and timing of arrival of herbivores; the organs that they attack; and the dissimilarity in traits of the herbivores (e.g., leaf chewer, phloem feeder, cell content feeder; specialist, generalist). We should design these experiments by comparing patterns of attack that differ only in one of these aspects at the time to evaluate the importance of each individual parameter [58]. Because comparisons of various species combinations and order of arrival easily built to treatment numbers beyond feasibility, we should dare to make compromises in treatment numbers to include only those that are critical for the narrow question we may address per experiment [36]. These challenges will especially arise when studying plant transcriptomic responses to scenarios of multiherbivore attack due to the essential comparison with plant responses to each herbivore in isolation. Although in such studies there is a tendency to combine stressors that differ in the signal transduction pathways they induce, we still lack studies that combine herbivores that induce similar signal transduction pathways. Importantly, multiherbivore attack should eventually be placed in an ecological context. This can be done by challenging plants with natural sequences of herbivore attack potentially in comparison with nonoccurring or rare orders of arrival to study what parts of plant plasticity are adaptive to patterns of attack found in nature [26]. Ultimate evidence for adaptive strategies should be supported by measuring strong proxies for Darwinian fitness, such as seed set [3], and placing the antagonistic interactions in community context that includes mutualistic interactions with pollinators and natural enemies.

Comparing physiological strategies of different plant species with multiple herbivores will provide novel insights into macroevolutionary patterns of defense plasticity. We may predict that selection by several herbivores on plant defenses leads to diffuse evolution in specific traits such as chemical and structural defenses [59,60]. However, predictability of patterns of attack by multiple herbivores may combine selective agents into promoting natural selection for plasticity traits such as inducible defenses, ability to integrate multiple stressors, and balancing growth–defense trade-offs [20]. Transition to sustainable agriculture urges us to identify traits that make plants resilient to multistress conditions. With reduced pesticide use, multiherbivore attack will become more common again for many crops (see Outstanding questions).

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## Declaration of interests

The authors have no interests to declare.

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