Acta Botanica Brasilica, 2025, 39: e20250002
doi: https://doi.org/10.1590/1677-941X-ABB-2025-0002

On the plant growth versus defense antagonism: Past, present and future

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ABSTRACT

One of the most fascinating aspects of the plant immune system is the growth versus defense antagonism. This phenomenon describes a physiological condition where the activation of defense mechanisms suppresses growth, and vice-versa. This trade-off has profound implications in natural and agronomical ecosystems, making it a critical focus of research in plant biology. In this viewpoint, I offer a historical perspective our understanding of the growth versus defense antagonism in plants, highlighting a significant paradigm shift in the field. Traditionally, this negative correlation was attributed to limited resources, which plants must allocate either to growth or to defense. However, recent discoveries of the genetic components governing the balance between plant growth and defense revealed that this tradeoff is a strategic adaptation for fitness optimization in varying environments. I also share personal insights into the current challenges and emerging opportunities in this research area. By exploring the past, present, and future of growth versus defense antagonism, this article aims to contribute to the development of innovative strategies that enhance plant resilience and productivity. Such advances are critical for transforming agriculture in the face of increasing pest and pathogen pressures and the mounting challenges of climate change.

Keywords: Growth versus defense antagonism, plant enemies, jasmonates, plant immune system, plant development, trade-offs

Received January 19, 2025; Accepted June 20, 2025
Editor-in-Chief: Thaís Elias Almeida; Associate Editor: Moemy Moraes

Data availability:
All data is available from the main author upon request.

How to cite:
Campos ML. 2025. On the plant growth versus defense antagonism: Past, present and future. Acta Botanica Brasilica 39: e20250002. doi: 10.1590/1677-941X-ABB-2025-0002

Introduction

For millions of years, plants have been dealing with relentless attacks by pests and pathogens that try to exploit their tissues as a source of nutritional needs. This long-standing battle has driven the evolution of a sophisticated and multi-layered defense network known as the plant immune system (Jones & Dangl, 2006; Campos *et al.*, 2014; Jones *et al.*, 2024). This defense system operates through a hierarchical series of mechanisms, ranging from preformed physical and chemical barriers to inducible responses triggered upon enemy recognition (Campos *et al.*, 2014; Bentham *et al.*, 2020). The efficacy of the plant immune system is evidenced in the widespread resistance of plants to the vast majority of existing enemies. This resilience is a fundamental reason why terrestrial ecosystems remain predominantly green, as plants susceptibility to pests and pathogens are the exception, not the rule (Bar-On *et al.*, 2018; Panstruga & Moscou, 2020; Pinheiro *et al.*, 2024).

An intriguing aspect of the plant immune system is the inherent antagonism between growth and defense. This well-documented phenomenon indicates that the activation of plant immune responses often suppresses growth (Herms & Mattson, 1992; Huot *et al.*, 2014; Cipollini *et al.*, 2018; Guo *et al.*, 2018a; Gao *et al.*, 2024). Conversely, rapid plant growth is frequently associated with diminished defense capability (Izaguirre *et al.*, 2006; Yang *et al.*, 2012). This negative correlation imposes plants into a physiological dilemma with significant implications for both natural and agronomical ecosystems (Cope *et al.*, 2021; Fernandez *et al.*, 2021; Giolai & Laine, 2024). For this reason, studies on growth versus defense antagonism have gained attention recently, with potential implications for conservation and for the development of crop varieties that combine robust growth with enhanced resilience to biotic stressors (Gao *et al.*, 2024).

Plant growth-defense tradeoffs have traditionally been explained as a consequence of limited resources that must be allocated to growth or defense, making the investment in one come at the expense of the other (Herms & Mattson, 1992; Huot *et al.*, 2014). However, a series of findings in the last two decades are challenging this 'resource allocation' theory in favor of an alternative 'fitness optimization' model, where plants adjust their growth and defense strategies in response to environmental cues, aiming to optimize overall fitness (Campos *et al.*, 2016; Guo *et al.*, 2018b; Fernández-Milmanda *et al.*, 2020; Li *et al.*, 2022; Saura-Sánchez *et al.*, 2023; Hurtado *et al.*, 2025; Zhou *et al.*, 2025). In this viewpoint, I explore the historical context and the conceptual development that has led to this significant paradigm shift. My objective is not to provide a comprehensive review of the topic (for that, please refer to Huot *et al.*, 2014; Züst & Agrawal, 2017; Guo *et al.*, 2018a; Ballaré & Austin, 2019; Figueroa-Macías *et al.*, 2021; Monson *et al.*, 2022; Sestari & Campos, 2022), but rather to highlight key evidence supporting the 'fitness optimization' model as a more comprehensive and reliable explanation for the growth versus defense antagonism. I also share some personal perspectives on the potential future directions of research on this topic. Considering that biotic stresses remain among the primary threats to global food security (Savary *et al.*, 2019), understanding how plants balance growth and defense is more crucial than ever.

Past: A resource-centered plant's dilemma

Since the advent of agriculture around 12,000 years ago, mankind has been aware that diseases and insect infestations interfere with plant development and reduce productivity. But what exactly causes growth reduction when plants are dealing with enemies? Early documentation that plant growth loss is proportional to the extent of leaf defoliation caused by enemies (Minott & Guild, 1925) provided empirical foundations to the idea of 'limitation of resources': as pests and pathogens consume the green tissues, the plants' capacity to acquire carbon via photosynthesis is diminished, leading to reduced growth. This theory gained traction in the 1930s, with Walter E. Loomis' 'growth-differentiation balancing hypothesis' (GDBH). According to the GDBH, plant development can be divided into cell growth and differentiation. While growth results from cell enlargement and division, differentiation involves chemical modifications that change the structure and function of existing cells (Loomis, 1932).

The GDBH establishes the foundations for the 'resource allocation' theory by articulating two core principles. First, it proposes that limitations in resource availability create physiological tradeoffs, since both growth and differentiation are resource-demanding processes, they compete for the same internal reserves. Second, it explains the antagonism between growth and defense: many defense traits (e.g. the production of secondary metabolites, trichomes, and cuticles) are outcomes of differentiation and therefore draw from the same limited resource pool needed for growth (Coley *et al.*, 1985; Simms & Rausher, 1987). For instance, rapidly growing plants tend to exhibit lower levels of defense compounds because the export of resources to support rapid leaf production leaves little available for the synthesis of secondary metabolites. Evidence supporting the GDBH includes: (1) observations that periods of rapid growth are associated with diminished investment in secondary metabolites (Mooney & Chu, 1974); (2) findings that growth- and defense-related metabolites share biosynthetic precursors and intermediates, thus competing for common substrates (Margna *et al.*, 1989), and (3) modeling studies demonstrating that defensive compounds are metabolically costly to produce (Gershenzon, 1994; Bekaert *et al.*, 2012). GDBH also provides a compelling explanation for why many plant defenses are inducible rather than constitutive: since defense responses are energetically costly and may suppress growth, they are more efficiently deployed only when needed (Harvel, 1990; Züst & Agrawal, 2017).

Although the original outline of GDBH proposed by Loomis provided a conceptual model to describe patterns of resource allocation in plants, it was Herms & Mattson (1992) who expanded this hypothesis. They framed it as a broader evolutionary explanation for how selective forces (namely competition and enemy attack) influence plant investment in growth and defense. In what is arguably the most influential manuscript on the topic, Herms and Mattson (1992) popularized the idea that the dilemma between growth and defense manifests as a product of physiological and ecological constraints. Across both local and evolutionary timescales, the allocation of limited resources depends on the level of plant-plant competition and stress from pests and pathogens. While competition selects growth-dominated strategies, enemy interaction drives plants towards defense-dominated strategies (Stamp, 2003). In their words, "(plants) must grow fast enough to compete, and yet maintain the physiological adaptations (defenses) necessary for survival in the presence of herbivores and pathogens" (Herms & Mattson, 1992).

The work by Herms & Mattson (1992) marked a pivotal shift in the history of GDBH. Their research not only reframed the original concept but also inspired numerous subsequent studies on growth versus defense antagonism, extending the GDBH to encompass broader ecological and evolutionary contexts. This included redefining the concept of limiting resources beyond carbon (photoassimilates) and nitrogen to include factors such as water, mineral nutrients in the soil, and physical space (Matyssek *et al.*, 2012; Siemens *et al.*, 2012). Field experiments have lent support to these ideas. For example, the experimental removal of natural enemies has been shown to rapidly reduce defensive traits in plants (Mauricio & Rausher, 1997), underscoring the role of enemy pressure in shaping defense investment.

Herms and Mattson's framework prompted researchers to recognize that the shift between growth and defense is not strictly binary but exists along a continuum. This idea gained traction with the discovery that some metabolites and transcriptional programs serve dual functions in both growth and defense (e.g. Arnold & Targett, 2003; Attaran *et al.*, 2014). The expanded GDBH also emphasized the idea that resource limitations are mediated both internally and externally, including plant interaction with beneficial microbes (Matyssek *et al.*, 2005). These conceptual advances allowed the GDBH to integrate principles from other theories, such as the 'carbon-nutrient balance theory' and the 'optimal defense theory' (Herms & Mattson, 1992; Matyssek *et al.*, 2012; Cipollini *et al.*, 2018). By the early 2000s, the GDBH had evolved far beyond its original formulation, emerging as a comprehensive and multi-conceptual paradigm for understating resource allocation in plants – a status recognized by many as making it the "most theoretically mature of the hypotheses of plant defense" (Stamp, 2004) (Figure 1A).

Present: The 'fitness optimization' paradigm

The study of jasmonates (JAs) marked a pivotal turning point in understanding the growth versus defense antagonism in plants. First identified in 1962 as the key aromatic compounds in jasmine flowers (Demole *et al.*, 1962), JAs were initially regarded merely as fragrant metabolites. However, their role in plant biology expanded dramatically in 1971, when fungal-derived JAs were proven to be potent plant growth inhibitors (Aldridge *et al.*, 1971). By the 1980s, it became evident that JAs were more than just perfumes, as these molecules were found to be produced by a wide range of plant species, with numerous biological activities, including the promotion of senescence and attraction of pollinators (Ueda & Kato, 1980). A breakthrough occurred in the 1990s with the discovery of JAs as master regulators of the plant immune system (reviewed in Campos *et al.*, 2014). The importance of JAs for plant immunity was largely demonstrated by JA-impaired mutants, which are rendered almost defenseless against pest and pathogen attacks (Campos *et al.*, 2014; Pinheiro *et al.*, 2024). Further research in the 1990s and 2000s elucidated the molecular mechanisms of JA synthesis and signaling, solidifying their status as bona fide plant hormones (reviewed in Gasperini & Howe, 2024).

As plant scientists were uncovering the role of JAs in plant development, emerging evidence began to challenge the traditional resource allocation theory behind the growth versus defense antagonism, showing that the GDBH was just a piece of a large and more complex puzzle. Notably, JAs were found to act not only as potent activators of plant defenses but also as strong repressors of growth (e.g. Campos *et al.,* 2016; Guo *et al.,* 2018b; Liu *et al.*, 2021). These findings indicated that plants do not merely respond passively to resource limitations but actively regulate the balance between growth and defense through an endogenous regulator. This hypothesis has been robustly supported by studies on mutants with constitutively activated JA responses. These plants typically exhibit enhanced defense responses but suffer from stunted growth and developmental delays (McGurl *et al.*, 1994; Campos *et al.*, 2016; Major *et al.*, 2017; Guo *et al.*, 2018b; Liu *et al.*, 2021). Conversely, JA-deficient mutants, which are unable to properly activate defense responses under stress, often display enhanced growth (Zhang & Turner, 2008; Yang *et al.*, 2012; Cunha *et al.*, 2023). Together, these findings strongly suggest that JAs evolved as central, evolutionarily conserved regulators of the growth versus defense antagonism. Additional evidence comes from the observation that JA-deficient plants fail to alter their growth in response to stressors like mechanical wounding of leaves, which potentially reduce the plant's capacity to produce photoassimilates and trigger a defensive shift (Zhang & Turner, 2008; Cunha *et al.*, 2023).

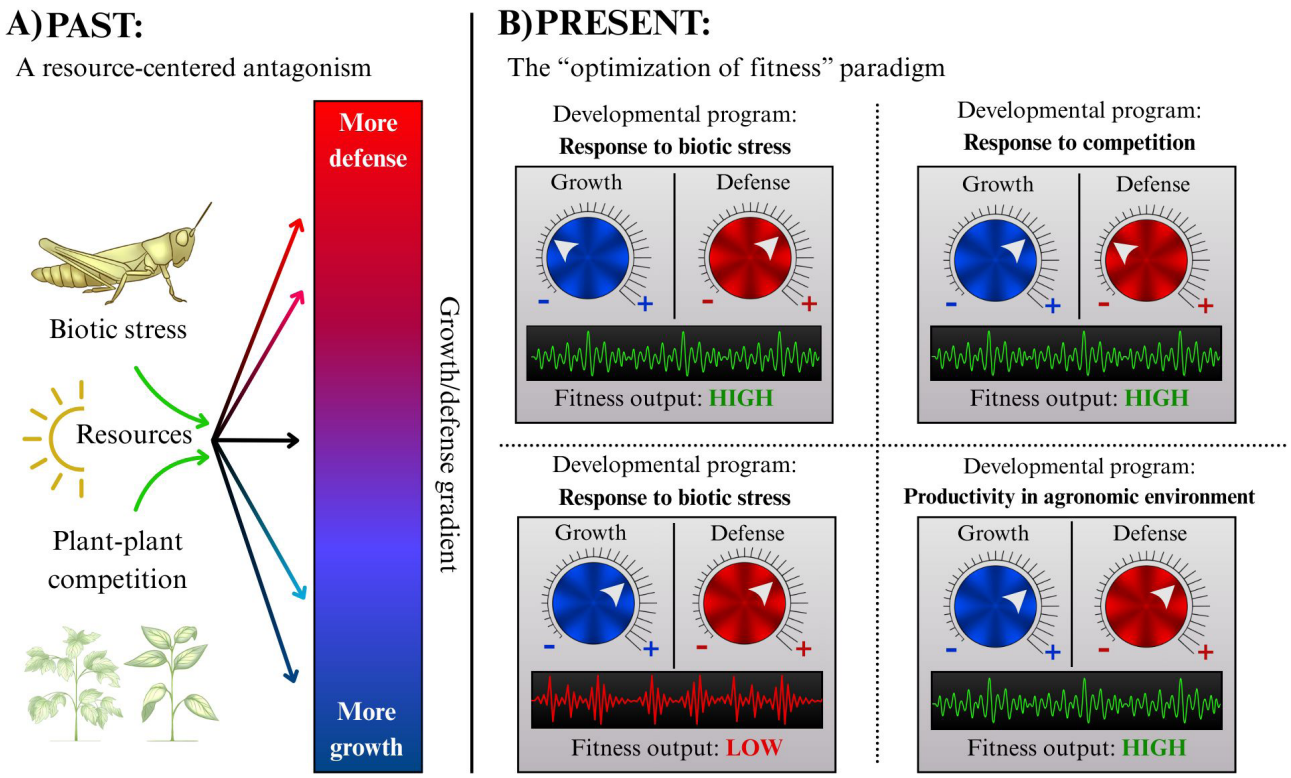

Figure 1. Evolving perspectives on the plant growth versus defense antagonism. A) Traditionally, the balance between growth and defense in plants was viewed through a 'resource-centered' perspective. In this model, ecological factors (such as plant-plant competition and biotic stress), are considered external factors that influence how plants allocate limited internal resources. Scarcity of resources imposes physiological constraints, forcing plants to adjust development along a continuous growth-defense spectrum. B) Recent findings support a shift toward a 'fitness optimization' model, where growth and defense can be independently regulated to maximize overall fitness. For instance, under biotic stress (top left in B), plants may strategically suppress growth not due to resource limitation but to reduce visibility to herbivores, while enhancing defense mechanisms. Although simultaneous upregulation of both processes is physiologically feasible, it may reduce fitness in such a scenario (bottom left in B). In contrast, under high competition (top right in B), the optimal response favors increased growth while reducing defense. In managed agricultural systems (bottom right in B), where external inputs support both processes, plants that maintain high growth and robust defense will achieve maximal fitness.

Such results further undermine the resource allocation theory and highlight the active, hormone-driven nature of the growth-defense balance in plants.

Characterization of JA-related mutants also provides evidence that overcommitting to either growth or defense can have catastrophic consequences for plants. For instance, while a strong and constitutive activation of the JA signaling pathway results in robust activation of defenses (e.g. production of toxic metabolites and higher resistance to insect herbivory), these mutant plants also suffer from severe growth penalties including tissue necrosis, poor reproductive output and even lethality (Guo *et al.*, 2018b; Liu *et al.*, 2021). Conversely, plants impaired in light perception, which exhibit exaggerated growth due to constitutive activation of the shade avoidance syndrome and suppression of JA responses, show heightened susceptibility to pests and pathogens (Izaguirre *et al.*, 2006; Yang *et al.*, 2012; Campos *et al.*, 2016). These findings offer compelling support for our current understanding of the growth versus defense antagonism: rather than operating as a rigid trade-off, the relationship between growth and defense has been evolutionary tailored as a strategy to optimize plant fitness. In this scenario, growth and defense are not engaged in a simple zero-sum game where investment in one leads to suppression of the other. Instead, they participate in an integrative, dynamic 'dialogue', modulated by hormone signaling pathways, that enable plants to adjust their strategies in response to environmental contexts (Kliebenstein, 2016). Indeed, genetic and evolutionary studies in natural ecosystems indicate that the ability to finely balance growth and defense is a key determinant of plant fitness, shaping not only species distribution but also interactions with competitors, and natural enemies (Agrawal *et al.*, 2012; Züst *et al.*, 2012; Cope *et al.*, 2021).

In the late 2010s, during my graduate studies in Dr. Gregg Howe's lab at Michigan State University, I was

involved in the characterization of an *Arabidopsis thaliana* mutant constitutively activated in the JA signaling pathway, known as *jazQ* (Campos *et al.*, 2016). As anticipated, *jazQ* exhibited strong activation of defense responses alongside delayed growth. Taking advantage of the mutant's easily observable phenotypes (e.g. accumulation of anthocyanins in the petioles as a marker of induced defense and small rosette size and a marker of suppressed growth), we performed an ethyl methanesulfonate mutagenesis screen in an attempt to uncover new molecular components involved with the regulation of growth and defense. To our surprise, we identified several mutant lines that displayed both increased rosette size and persistent high anthocyanin levels, suggesting that growth and defense processes were simultaneously activated in these lines (Campos *et al.*, 2016). We named these mutants *suppressors of jazQ* (*sjq*). One such line, *sjq11* was found to carry a null mutation in the phytochrome B (*PHYB*) gene, a key light receptor. Reconstitution of this double mutant in pure lines (*jazQphyB*) confirmed that growth and defense processes can be uncoupled via genetic rewiring of plant JA and PHYB pathways (Campos *et al.*, 2016). This discovery laid the foundation for the hypothesis that the antagonism between growth and defense arises from conserved transcriptional networks designed to attenuate growth in the activation of defenses or vice-versa. This concept has since been supported by additional studies, which have revealed the involvement of multiple plant hormone pathways – including auxins, gibberellins, brassinosteroids and salicylic acid – in modulating this trade-off (Yang *et al.*, 2012; Campos *et al.*, 2016; Guo *et al.*, 2018b; Fernández-Milmanda *et al.*, 2020; Li *et al.*, 2022; Saura-Sánchez *et al.*, 2023; Ortega *et al.*, 2024; Zhou *et al.*, 2025). The ability to uncouple growth from defense has important applications in biotechnology and agronomy, offering a path toward developing plant cultivars that combine vigorous growth and high productivity with enhanced resilience to pests and pathogens. Interestingly, we also previously demonstrated that hormonal rewiring can produce the opposite outcome, with plants with short growth and reduced defense (Campos *et al.*, 2009) supporting the idea that the growth-defense relationship is not strictly limited by resource allocation, but is, instead governed by regulatory network architecture.

So, what is the current paradigm to explain the apparent antagonism between growth and defense in plants? While the traditional view of the GDBH emphasized a rigid tradeoff governed by limited resources, contemporary theories have shifted toward a more integrative framework that still acknowledges resource constraints but places greater emphasis on the role of signaling networks (Yang *et al.*, 2012; Guo *et al.*, 2018a; Ballaré & Austin, 2019; Figueroa-Macías *et al.*, 2021; Monson *et al.*, 2022; Sestari & Campos, 2022). In this view, growth and defense are co-regulated by a complex web of endogenous signaling networks, which allow plants to make context-dependent decisions rather than simply respond to a zero-sum allocation of resources. These signaling networks are highly dynamic and sensitive to both internal and external cues, enabling plants to optimize fitness across a range of ecological scenarios. In this sense, the relationship between growth and defense is shaped by both short-term responses and long-term selective pressures, making the antagonism highly flexible rather than fixed (Agrawal *et al.*, 2012; Züst *et al.*, 2012; Campos *et al.*, 2016: Guo *et al.*, 2018a; Ballaré & Austin, 2019; Cope *et al.*, 2021; Sestari & Campos, 2022; Giolai & Laine, 2024; Hurtado *et al.*, 2025).

Within this framework, growth and defense can be conceptually visualized as adjustable 'dials' that plants can modulate, via interconnected signaling modules, to control the intensity of each process (as illustrated in Figure 1B). Although these dials are not inherently linked, meaning that both processes can be up- or downregulated independently, plants must continuously fine-tune them to optimize fitness. Growth and defense should not be seen as competing processes but rather as integrative developmental outputs that enable plants to respond precisely to their environment. For instance, when a plant is attacked by herbivores or pathogens, plants often suppress growth not merely due to limited resources, but as a strategic, signal-mediated shift in developmental programs – a hallmark of the broader 'defense syndrome' (Ballaré & Austin, 2019). Indeed, a recent meta-analysis study indicates that the availability of nutrients in the soil is not a factor limiting the concomitant upregulation of growth an defense in plants (Hurtado *et al.*, 2025). Reducing vegetative growth in such contexts may serve to minimize visible or metabolically active tissues that could attract or sustain further attack (Fig. 1B, top left inset). In this scenario, the simultaneous upregulation of growth would be maladaptive (e.g. reduced fitness), enhancing the susceptibility by increasing palatable tissues (Fig. 1B, bottom left inset). Conversely, in competitive environments, maximizing growth is essential, and dialing down defense can function as a growth-promoting strategy (Fig. 1B, top right inset). For example, some metabolites produced during immune responses may be toxic to the plant, reducing leaf expansion and stem elongation (Sestari & Campos, 2022). In this sense, reduced defense is not merely a compromise but a proactive developmental choice. In agronomic environments, where resource inputs and selective breeding decouple many natural constraints, the upregulation of both growth and defense processes is likely the best configuration to enhance plant fitness (Fig. 1B, bottom right inset). This dual enhancement leads to increased productivity and better protection against specialized pests and pathogens common in monocultures.

In summary, the growth versus defense antagonism reflects an evolutionarily tuned balance governed not simply by resource availability, but also by sophisticated signaling networks that coordinate plant responses to environmental challenges. These networks allow plants to adjust their

developmental programs through flexible regulation of growth and defense dials to maximize overall fitness (Fig. 1 B). This view highlights that plants are extremely adaptable organisms, constantly adjusting their growth and defense strategies to thrive in complex and often hostile environments.

Future: Challenges and opportunities in the research of plant growth versus defense antagonism

We are living in a golden age of research into plant growth versus defense antagonism. Over the past two decades, significant progress has been made in unraveling the genetic framework that governs this complex balance (e.g. Campos *et al.,* 2016; Guo *et al.,* 2018b; Giolai & Laine, 2024). Thanks to the advances in molecular techniques, like -omics studies and gene editing, we can now envision a near future where precise manipulation of molecular components could allow us to fine-tune the dials of growth and defense to suit environmental conditions and improve fitness for specific ecological and agronomical demands. In this section, I explore the future of research in this field, providing some personal insights into the key challenges and opportunities that lie ahead. Addressing these issues will be critical for developing innovative solutions that can transform agriculture and ensure sustainable food security on the brink of climatic challenges.

As discussed in the previous section, the identification of the molecular players involved in plant growth versus defense tradeoffs represents a monumental breakthrough, reshaping foundational paradigms and paving the way for the development of genetic tools aimed at decoupling these two antagonistic processes in plants. However, most of the molecular players identified so far are central hubs of plant signaling networks. These include key regulators such as light receptors (Cerrudo *et al.*, 2012; Campos *et al.*, 2016; Guo *et al.*, 2018b), core components of hormonal signaling pathways (Campos *et al.*, 2009; Yang *et al.*, 2012; Campos *et al.*, 2016, Major *et al.*, 2017; Li *et al.*, 2022; Feiz *et al.*, 2024), and key genes involved with pest and pathogen perception (Giolai & Laine, 2024; Gao *et al.*, 2024; Zhou *et al.*, 2025). While genetic modifications of these broad regulators have allowed us to envision plant genotypes with enhanced growth and defense capacities, the widespread pleiotropic effects associated with altering such central nodes underscore that genetic uncoupling remains, for now, a compelling proof of concept rather than a practical solution ready for deployment. The next phase of research must therefore focus on identifying and manipulating molecular players that specifically and exclusively modulate the growth-defense balance, without broadly disrupting other physiological functions. Several promising avenues are already available for that purpose. These include the rational design and synthesis of hormone agonists capable of selectively activating parts of defense pathways without triggering growth inhibition (or vice-versa, e.g. Takaoka *et al.*, 2018). In addition, mining large-scale transcriptomics and metabolomics datasets, and performing coexpression network analysis, particularly on high-order mutants described in recent studies (Campos *et al.*, 2016; Guo *et al.*, 2018b; Zhang *et al.*, 2020), offer powerful strategies to identify novel tradeoff-specific regulators.

The trade-off between plant growth and defense can be mitigated through associations with specific microorganisms, which provide mechanisms to promote growth while simultaneously improving resistance to biotic stresses (Pangesti *et al.*, 2013; Bastías *et al.*, 2021). For instance, *Epichloë* fungal endophytes have been shown to stimulate the production of growth- and defense-related hormones (such as gibberellins, auxins, and JAs), while also supplying microbial-derived bioactive metabolites that enhance host protection, thus allowing plants to grow and defend concomitantly (Bastías *et al.*, 2017; Bastías *et al.*, 2021; Mathew *et al.*, 2023). Another promising strategy involves the manipulation of defense priming, a phenomenon where, following pathogen exposure, plants develop resistance to future attack. A pre-treatment with specific microorganisms that can elicit the plant immune system (such as *Trichoderma* and *Bacillus* isolates) can allow plants to be primed for defense while also promoting plant development and productivity (Leibman-Markus *et al.*, 2023). Unlike transgenic approaches, which face regulatory hurdles and public skepticism, microbial-based solutions offer a scalable and readily deployable alternative for sustainable agriculture. Their non-GMO status facilitates regulatory approval and intellectual property processes, accelerating adoption. In regions where GMO remain prohibited, microbial inoculants may represent the only feasible approach to sustainably optimizing crop productivity with improved biotic stress resilience.

The balance between plant growth and defense should be evaluated under the scope of the circadian clock. Circadian regulation represents a quintessential adaptation to fluctuating environmental conditions, not only for the plants but also for their associated pests and pathogens. In plants, the circadian clock regulates at least one-third of the genes, with growth regulators and stress responses being notably overrepresented among those under clock control (Covington *et al.*, 2008; Panter *et al.*, 2019). While it is well established that the circadian clock modulates the plant immune system (reviewed in Butt *et al.*, 2020), as well as the plant's ability to growth under different environmental conditions (Dantas *et al.*, 2021) and even the time of pest and pathogen attack (Goodspeed *et al.*, 2012; Fan *et al.*, 2014), few integrative studies have addressed how the growth versus defense antagonism is regulated from a chronobiology perspective. Future research should explore how growth and defense mechanisms are regulated by different stressors across various times of the

day. Preliminary data from my research group suggests that environmental cues activating the plant immune system can trigger distinct signaling cascades depending on the time of the day that the stress occurs. It is not only about what happens but also when it happens.

Finally, while significant advances have been made in understanding the molecular framework of the growth versus defense antagonism and in identifying strategies to uncouple these processes, it is now crucial to translate this knowledge from the controlled environment of the laboratory to the complexity of the field. Despite the enormous potential of crops engineered for both enhanced growth and robust defense still, to my knowledge, no commercial cultivar has yet been fully realized using these concepts. This translational gap reflects several challenges, including the unpredictable nature of field conditions, the high variability among the genetics of cultivars, and the regulatory constraints surrounding the testing and commercialization of transgenic plants. Moving forward, research on the growth versus defense trade-off must increasingly reflect the multifaceted realities of ecological and agronomic systems. Beyond the well-studied effects on traits like plant competition, emerging evidence suggests that many species exhibit compensatory growth following stress – a response that, under classical trade-off expectations, should impair their ability to mount effective defenses against subsequent biotic threats (Agrawal, 2000; Pinheiro *et al.*, 2024). A recent meta-analysis indicates that overcompensation is a widespread phenomenon in plant-insect interactions (Garcia & Eubanks, 2019) and that it can be used as an unconventional strategy to increase crop production and plant resilience (Poveda *et al.*, 2018). Such findings highlight the importance of studying trade-offs not in totally controlled conditions, but in the context of sequential or combined stress exposures, which are common in nature and agriculture alike. Understanding how plants prioritize and reconfigure their responses under these dynamic scenarios will likely shape the next frontier in growth versus defense antagonism.

This shift also demands a 'farm-to-lab-to-farm' model of innovation, where ecologists, geneticists, physiologists, farmers, and even consumers co-create knowledge and solutions tailored to specific environmental and agronomic situations (Rhee *et al.*, 2024). To support this process, laboratory studies must embrace the complexity of real-world, multi-stress environments. At the same time, great emphasis must be placed on public engagement and science communication. Rather than relying solely on sharing their findings via hard-to-understand scientific papers, researchers should adopt inclusive, transparent strategies that build public trust and support for new technologies. Such efforts are essential for fostering regulatory frameworks that enable the development and acceptance of novel cultivars designed to thrive under increasingly variable conditions (Nisbet & Scheufele, 2009; Rhee *et al.*, 2024).

Acknowledgments

I thank the two anonymous reviewers for their insightful comments and the editorial board of Acta Botanica Brasilica for the invitation to publish this work, which was partially presented as a poster and oral presentation at the 74º Brazilian Congress of Botany. I also thank Sam Generoso for helping with the preparation of the figures. Work on the plant growth versus defense antagonism in the CamposLab is supported by Instituto Serrapilheira (grant number 7755/2023), Fundação de Amparo à Pesquisa do Estado de Mato Grosso (grant number FAPEMAT-PRO.000274/2023), and Conselho Nacional de Desenvolvimento Científico e Tecnológico (grant number: 303757/2023-0)

Author contributions

MLC conceptualized the ideas for the manuscript, wrote the text, and prepared the figure.

Conflicts of Interest

The author declares no conflicts of interest.

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