


Food system resilience requires moving beyond zero-sum growth-defense frameworks

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ABSTRACT

Agricultural systems are increasingly challenged by climatic instability, pest outbreaks, and pressure to reduce dependence on external inputs. However, agricultural evaluation systems remain strongly focused on productivity under optimal conditions, with less emphasis on resilience and adaptive capacity. One driver of this bias is the longstanding assumption that plant growth and defense are inherently antagonistic. Although plant biology now shows that growth and defense are dynamically coordinated rather than strictly competitive, this vision remains poorly integrated into agronomic evaluation and policy. In this Perspective we argue that persistent zero-sum interpretations of growth-defense relationships may constrain how resilience, stress tolerance, and sustainability are integrated into agricultural evaluation systems. Reframing growth-defense antagonism as a systems and policy problem may help align agricultural evaluation frameworks with the multifunctional demands imposed by climate change and sustainable food production.

1. The growth-defense antagonism: from biological insight to dominant narrative

The idea that plants face a trade-off between growth and defense is one of the most enduring concepts in plant biology (Herms and Mattson, 1992; He et al., 2022). For decades, growth-defense antagonism was framed as a resource constraint, in which carbon, nitrogen, and energy invested in defense were assumed to constrain vegetative growth and potentially reduce reproductive performance and yield (Huot et al., 2014). In this see-saw model, growth and defense are antagonistically linked by the assumption that any nutrient flux directed toward defense removes resources that could otherwise be allocated to growth or biomass production, and vice-versa.

Accumulating evidence now suggests that growth-defense relationships are more flexible and context dependent than predicted by simplistic resource-allocation or zero-sum models (Kliebenstein, 2016; Ballaré and Austin, 2019; Campos, 2025; Hurtado et al., 2025). Studies on light signaling and jasmonate-mediated defense pathways have demonstrated that growth and defense responses can be genetically and

physiologically uncoupled under certain conditions, allowing plants to maintain competitive growth while preserving inducible defenses (Campos et al., 2016; Cerrudo et al., 2017; Fernández-Milmanda et al., 2020). More recent ecological evidence further indicates that some species can simultaneously sustain competition-related growth and herbivore resistance depending on life-history strategy and environmental context (Mueller et al., 2026). Together, these findings support a framework in which growth and defense function as integrated developmental programs whose coordination can optimize performance across environmental contexts (Kliebenstein, 2016).

Despite growing acceptance of this perspective within plant biology, its implications have been slower to permeate agronomy and policy. As conceptualized in Fig. 1, the persistence of a zero-sum interpretations of growth and defense extends beyond biological oversimplification and increasingly shapes how agricultural performance is evaluated and translated into policy priorities. In this Perspective, we argue that the problem is not the recognition that trade-offs can occur, but the continued treatment of growth-defense antagonism as an inevitable and universally limiting constraint in crop production systems. This

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assumption contributes to evaluation and policy frameworks that prioritize maximum yield under optimal conditions while undervaluing resilience-related traits, stress tolerance, yield stability, and reduced dependence on external inputs (e.g. pesticide and fertilizer applications). Because food security increasingly depends on crops capable of maintaining performance under environmental and economic volatility, how growth and defense are conceptualized has direct implications for food production systems.

2. When biological trade-offs become evaluation frameworks

Agricultural systems are major sources of environmental pressure worldwide, and agricultural policy has long been shaped by the assumption that improving resistance to pests or abiotic stress necessarily comes at the expense of growth and productivity (Derbyshire et al., 2024). This assumption has become embedded in evaluation frameworks that prioritize peak yield under standardized trials, often discounting yield stability, input-use efficiency, and risk buffering as secondary outcomes.

International assessments indicate that agricultural support remains largely oriented toward production-linked objectives and aggregate output indicators, with comparatively limited investment in innovation and agricultural knowledge systems needed to sustain long-term productivity and resilience within food production systems (OECD, 2025).

Reductions in pesticide or fertilizer dependence are frequently undervalued in cost-benefit analyses, while sustainability and resilience objectives are often addressed through parallel or compensatory policy instruments rather than integrated into core productivity metrics (Pappo et al., 2023; Sgarbi and Nadeu, 2023; Granda and Muñoz, 2025). Reviews of agricultural policy frameworks consistently highlight a persistent reliance on productivity and economic performance indicators and call for stronger integration of resilience, sustainability, and adaptive capacity metrics into policy evaluation (DeBoe, 2020; Grigorieva et al., 2023; Pawłowska, 2025; Prigoreanu et al., 2025).

In the European context, reforms to the Common Agricultural Policy (CAP) have introduced environmental measures, yet incentives still struggle to align productivity targets with environmental and climate objectives, reflecting persistent gaps in how success is defined and measured. As a result, inputs and practices that enhance resistance are often evaluated through a narrow lens: do they reduce yield penalties under stress, and if so, at what cost to growth under “normal” conditions? This zero-sum evaluation framework fails to capture performance in managed fields, where the timing, inducibility, and reversibility of defense responses allow growth and defense to be coordinated rather than traded permanently (Gao et al., 2024).

Reframing growth-defense antagonism: biological coordination and policy consequences

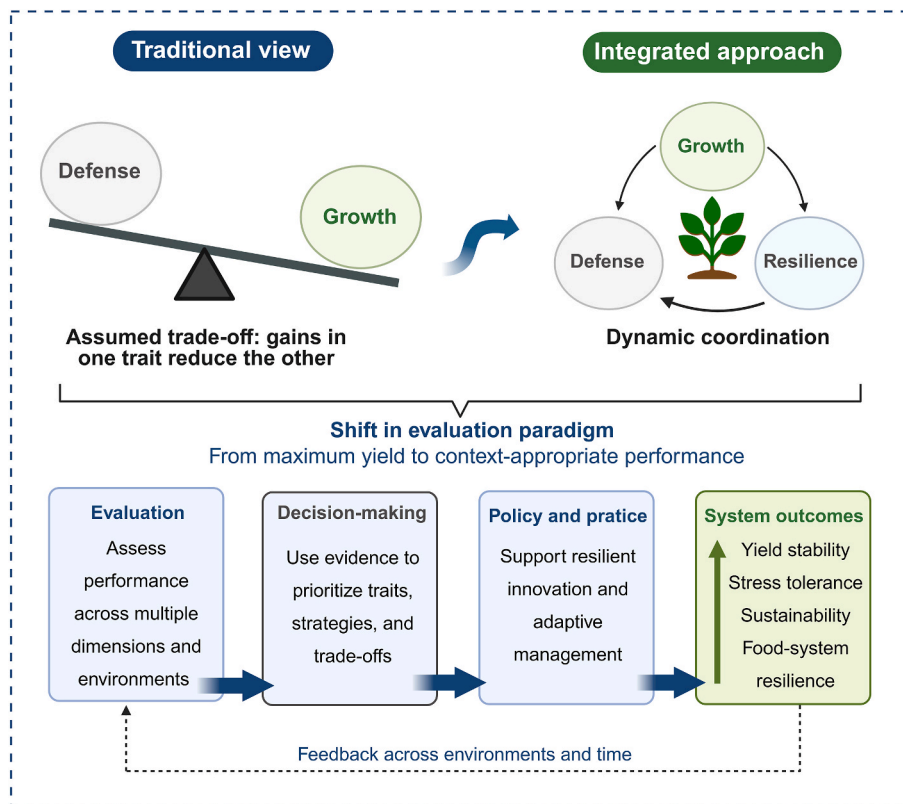


Fig. 1. Reframing plant growth-defense antagonism as a food-system evaluation problem. The traditional view treats defense investment as a constraint on vegetative growth and yield potential, reinforcing a zero-sum framework in which crop performance is often assessed primarily under optimal or low-stress conditions. This binary framing can shape both biological interpretation and agricultural evaluation metrics by prioritizing maximum yield over context-dependent performance. An integrated perspective recognizes that growth, defense, and resilience can be dynamically coordinated across time and environments, generating multifunctional outcomes such as yield stability, stress tolerance, sustainability, and food-system resilience. When translated into agricultural evaluation, decision-making, policy, and practice, this reframing shifts the emphasis from maximum yield toward performance across variable conditions, supporting production systems that better align productivity with resilience and sustainability. The feedback loop indicates that system outcomes should inform future evaluation criteria across environments and over time.

3. What current metrics fail to capture in real agricultural systems

The relationship between growth and defense is highly context dependent. Rather than operating as a fixed resource-based trade-off, growth and defense are dynamically coordinated across physiological, ecological, and management conditions. Nutrient availability, microbial interactions, environmental variability, and temporal regulation all influence how plants allocate resources and maintain performance across environments (Campos, 2025). As a result, resistance, vegetative growth, and yield outcomes are not necessarily linked through fixed antagonistic relationships, particularly under field conditions where stress responses are often inducible, reversible, and strongly shaped by environmental context. Field-based strategies increasingly demonstrate that resilience-enhancing interventions can stabilize productivity without imposing persistent growth penalties. Approaches involving microbiome management, silicon fertilization, targeted nutrient regimes, and coordinated genetic regulation illustrate how stress tolerance, resource-use efficiency, and crop performance may be simultaneously improved under variable environments (Campos et al., 2016; Bastias et al., 2021; Rajput et al., 2021; Houmani et al., 2024; Panigrahi and Rout, 2025). What many current evaluation systems fail to capture is that these interventions may enhance performance stability and reduce dependence on external inputs even when they do not maximize yield under optimal conditions. Long-term agricultural resilience depends less on maximizing short-term yield and more on maintaining stable performance across fluctuating conditions.

This disconnect becomes increasingly consequential as agriculture faces overlapping climatic, environmental, and economic pressures. Productivity is still commonly assessed through average yield under standardized conditions rather than through metrics that capture resilience, risk buffering, or long-term stability (Martín-García et al., 2025). Under highly variable environments, however, resilience-related traits increasingly contribute to realized productivity and production security. Treating defense investment as an unavoidable drag on growth therefore oversimplifies how crops perform in real agricultural systems and may constrain the adoption of strategies better aligned with climate-resilient food production. In practice, farmers operating under climatic and economic uncertainty frequently prioritize yield reliability and risk reduction over maximum productivity under ideal conditions.

4. When defensive traits are misclassified as productivity costs

This misalignment becomes particularly evident when examining how specific classes of defensive traits are evaluated and categorized in practice. Structural investments, in particular, reveal how the persistence of growth-defense framing continues to distort breeding priorities and policy assessments. Traits such as thicker leaves, increased silicification, enhanced cuticular waxes, or denser trichomes are frequently classified as “defensive”, even though many of these features also improve water-use efficiency, mechanical stability, and photosynthetic longevity (Konrad et al., 2014; Blumenthal et al., 2020; Tunstad et al., 2024; Kumar et al., 2025).

In practice, cultivar registration protocols, breeding pipelines, and cost-benefit assessments increasingly recognize the importance of resilience-related traits, but these traits are often still evaluated primarily in relation to their effects on yield performance under relatively optimized conditions. In many breeding and official evaluation systems, varieties are primarily assessed under relatively optimized management conditions, which may unintentionally favor genotypes expressing high productivity under favorable environments while underestimating traits whose agronomic value emerges predominantly under climatic variability, biotic stress, or resource limitation. Consequently, resilience-associated defensive or structural traits may remain comparatively undervalued when their benefits are context dependent and insufficiently captured by conventional performance metrics. As a result,

breeding programs and performance tests may still disproportionately favor conventional productivity indicators, even as resilience-oriented traits receive growing attention within crop improvement frameworks (Lopes, 2023; Mastretta-Yanes et al., 2024). Policy and breeding frameworks have repeatedly been criticized for emphasizing yield-centric objectives while insufficiently integrating resilience and adaptive traits into breeding goals and regulatory criteria (Lopes, 2023; Climent et al., 2024; Mastretta-Yanes et al., 2024). Consequently, structural defense traits are often deprioritized not because they reduce agronomic performance, but because they fall outside conventional growth-defense and yield-centric evaluation frameworks.

5. Why the growth-defense binary persists

One reason the binary growth or defense narrative persists is its strong grounding in controlled experimental systems. Under such conditions, sustained activation of defense pathways predictably suppresses growth, reflecting real regulatory tensions between partially incompatible developmental programs. Plants therefore possess mechanisms that gate immune activation in time and space, precisely to limit the growth costs of defense (Guo et al., 2018; Zhou et al., 2025). What controlled experiments often fail to capture is not the existence of antagonism, but the field-relevant factors that modulate how it is expressed in managed systems, including soil heterogeneity, microbiomes, structural investments, and temporal separation between growth and defense phases (Gao et al., 2024). Defense signaling pathways are often associated with growth suppression, yet their effects depend strongly on timing, intensity, and interaction with other signaling pathways (Chan, 2022; Li et al., 2022). In practice, plants often activate defenses transiently and reversibly, minimizing long-term growth costs once the threat subsides.

Consistent with this view, plants possess multiple endogenous safeguards that evolved to prevent chronic overinvestment in defense, which would otherwise lead to severe developmental penalties (Rodríguez et al. 2018, 2023; Wang et al., 2025; Zhou et al., 2025). In these cases, the apparent “trade-off” reflects dynamic regulation rather than a permanent reallocation of resources. Policies and evaluation frameworks that assume static, cumulative costs therefore miss this temporal dimension entirely.

6. From biological simplification to policy misalignment

These biological nuances have direct and measurable consequences for agricultural policy. Pest management strategies that rely primarily on chemical suppression of herbivores externalize the cost of defense, often at the expense of environmental health and long-term resistance management (Brzozowski and Mazourek, 2018). By contrast, approaches that enhance plant-intrinsic defenses, when appropriately matched to crop genotype, environment, and management, can reduce pest pressure without imposing chronic growth penalties. Yet because many policy frameworks continue to equate defense investment with yield loss, such strategies struggle to achieve broad adoption.

The same logic applies to climate adaptation. As heat waves, droughts, and pest outbreaks become more frequent and overlapping, crops are increasingly exposed to compound stresses rather than isolated challenges (Pascual et al., 2022). Under these conditions, maximizing productivity under ideal environments becomes less relevant than maintaining function under suboptimal ones. Yield stability, not peak yield, emerges as the critical performance metric, particularly in regions where farmers face high climatic variability, limited access to inputs, and increasing exposure to market and environmental shocks. Under increasing climatic variability, the ability of crops to maintain stable production across environments becomes directly linked to food-system resilience and long-term food security. However, many agricultural policies still reward inputs and practices that optimize short-term productivity, while overlooking resilience traits that safeguard production

over time. This mismatch leaves food production systems poorly equipped to cope with the very stresses that policy instruments increasingly seek to address.

7. Reframing growth-defense antagonism as a systems problem

The growth-defense trade-off also intersects with how success is measured in agriculture. Yield remains the dominant evaluation benchmark in many agricultural systems, while reduced losses, lower input requirements, and improved stress tolerance are often treated as secondary benefits (Breure et al., 2024). This bias may reinforce the perception that defense-related traits are secondary to productivity gains, even though preventing losses can be as valuable as increasing potential yield, particularly under increasing climatic uncertainty. Reframing growth-defense antagonism as a policy issue does not mean abandoning biological principles. It means recognizing that biological trade-offs operate within systems shaped by management practices, incentive structures, and governance. Plants evolved under constraints very different from those imposed by modern agriculture (Qaim and Parlasca, 2025). When policy ignores this mismatch, it locks farming systems into rigid strategies that perform well only under narrow and increasingly unrealistic conditions.

What would change if policy treated growth-defense antagonism as a systems problem? First, evaluation criteria would shift from average yield under optimal conditions to performance across stress gradients. Inputs and practices would be assessed by their capacity to maintain function and reduce risk, not solely by their ability to maximize output. Second, regulatory frameworks would better accommodate multifunctional traits and inputs that contribute simultaneously to growth, defense, and resource-use efficiency. Third, funding priorities would favor integrative research spanning physiology, agronomy, and socio-economic outcomes, rather than isolating defense biology from productivity goals.

A transition toward resilience-oriented agricultural systems would also require new performance indicators capable of integrating productivity with resilience outcomes. Metrics such as yield stability across climatic variability, input-use efficiency, resistance durability, and reduced dependence on pesticides or fertilizers could complement traditional yield-based assessments. Incorporating these dimensions into breeding programs, subsidy structures, crop insurance models, and sustainability certification systems would allow agricultural policies to better reflect the multifunctional nature of crop performance under climate uncertainty.

Greater realism in how agricultural solutions are framed is equally important. Rather than promising universal gains or technological silver bullets, policies could prioritize strategies that maintain performance across variable environments and uncertain conditions. The growth-defense trade-off will remain a central concept in plant biology. However, when treated as an immutable rule rather than a conditional and context-dependent outcome, it becomes a barrier to innovation in agricultural systems. In a world where agri-food systems must simultaneously deliver food security, climate resilience, and environmental sustainability, continued reliance on simplified trade-offs risks reinforcing structural vulnerabilities within food production systems. Recognizing growth-defense antagonism as a systems and policy problem is therefore a necessary step toward building agricultural systems that are productive, resilient, and capable of sustaining food security under increasing environmental uncertainty.

Ethics approval and consent to participate

Not applicable.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to improve readability and language accuracy. After using the tool, the authors carefully reviewed and edited the content as necessary and take full responsibility for the final version of the publication.

CRediT authorship contribution statement

Raul Antonio Sperotto: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – original draft. **Luana Vanessa Peretti Minello:** Methodology, Software, Writing – review & editing. **Thainá Pereira da Silva Cabral:** Methodology, Software, Writing – review & editing. **Maria Luísa Neri Campos:** Methodology, Software, Writing – review & editing. **Felipe Augusto Queiroz de Almeida:** Methodology, Software, Writing – review & editing. **Marcelo Lattarulo Campos:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

References

- Ballaré, C.L., Austin, A.T., 2019. Recalculating growth and defense strategies under competition: key roles of photoreceptors and jasmonates. *J. Exp. Bot.* 70, 3425–3434. <https://doi.org/10.1093/JXB/ERZ237>.
- Bastías, D.A., Gianoli, E., Gundel, P.E., 2021. Fungal endophytes can eliminate the plant growth-defense trade-off. *New Phytol.* 230, 2105–2113. <https://doi.org/10.1111/nph.17335>.
- Blumenthal, D.M., Mueller, K.E., Kray, J.A., et al., 2020. Traits link drought resistance with herbivore defence and plant economics in semi-arid grasslands: the central roles of phenology and leaf dry matter content. *J. Ecol.* 108, 2336–2351. <https://doi.org/10.1111/1365-2745.13454>.
- Breure, T.S., Estrada-Carmona, N., Petsakos, A., et al., 2024. A systematic review of the methodology of trade-off analysis in agriculture. *Nat. Food* 5, 211–220. <https://doi.org/10.1038/s43016-024-00926-x>.
- Brzozowski, L., Mazourek, M., 2018. A sustainable agricultural future relies on the transition to organic agroecological Pest management. *Sustainability* 10, 2023. <https://doi.org/10.3390/su10062023>.
- Campos, M.L., 2025. On the plant growth versus defense antagonism: past, present and future. *Acta Bot. Bras.* 39, e20250002. <https://doi.org/10.1590/1677-941X-ABB-2025-0002>.
- Campos, M.L., Yoshida, Y., Major, I.T., et al., 2016. Rewiring of jasmonate and phytochrome B signalling uncouples plant growth-defense tradeoffs. *Nat. Commun.* 7, 12570. <https://doi.org/10.1038/ncomms12570>.
- Cerrudo, I., Caliri-Ortiz, M.E., Keller, M.M., et al., 2017. Exploring growth-defense trade-offs in arabidopsis: phytochrome B inactivation requires JAZ10 to suppress plant immunity but not to trigger shade-avoidance responses. *Plant Cell Environ.* 40, 635–644. <https://doi.org/10.1111/pce.12877>.
- Chan, C., 2022. Progress in salicylic acid-dependent signaling for growth-defense trade-off. *Cells* 11, 2985. <https://doi.org/10.3390/cells11192985>.
- Climent, J., Alía, R., Karkkainen, K., et al., 2024. Trade-offs and trait integration in tree phenotypes: consequences for the sustainable use of genetic resources. *Current Forestry Reports* 10, 196–222. <https://doi.org/10.1007/s40725-024-00217-5>.

- DeBoe, G., 2020. Impacts of agricultural policies on productivity and sustainability performance in agriculture: a literature review. In: OECD Food, Agriculture and Fisheries Papers, vol. 141. OECD Publishing, Paris. <https://doi.org/10.1787/bbc916e7-en>.
- Derbyshire, M.C., Newman, T.E., Thomas, W.J.W., et al., 2024. The complex relationship between disease resistance and yield in crops. *Plant Biotechnol. J.* 22, 2612–2623. <https://doi.org/10.1111/pbi.14373>.
- Fernández-Milmanda, G.L., Crocco, C.D., Reichelt, M., et al., 2020. A light-dependent molecular link between competition cues and defence responses in plants. *Nat. Plants* 6, 223–230. <https://doi.org/10.1038/s41477-020-0604-8>.
- Gao, M., Hao, Z., Ning, Y., et al., 2024. Revisiting growth-defence trade-offs and breeding strategies in crops. *Plant Biotechnol. J.* 22, 1198–1205. <https://doi.org/10.1111/pbi.14258>.
- Granda, L.E.S., Muñoz, R.C.R., 2025. Comprehensive approaches in agricultural policies for sustainability: a literature review. In: Crowther, D., Seifi, S. (Eds.), *Equalizing the Three Pillars of Sustainability. Approaches to Global Sustainability, Markets, and Governance*. Springer, Singapore. https://doi.org/10.1007/978-981-96-5719-3_5.
- Grigorieva, E., Livenets, A., Stelmakh, E., 2023. Adaptation of agriculture to climate change: a scoping review. *Climate* 11, 202. <https://doi.org/10.3390/cli11100202>.
- Guo, Q., Yoshida, Y., Major, I.T., et al., 2018. JAZ repressors of metabolic defense promote growth and reproductive fitness in *arabidopsis*. *Proceedings of the National Academy of Sciences of the USA* 115, e10768–e10777. <https://doi.org/10.1073/pnas.1811828115>.
- He, Z., Webster, S., He, S.Y., 2022. Growth-defence trade-offs in plants. *Curr. Biol.* 32, R589–R683. <https://doi.org/10.1016/j.cub.2022.04.070>.
- Herms, D.A., Mattson, W.J., 1992. The dilemma of plants: to grow or defend. *Q. Rev. Biol.* 67, 283–335. <https://doi.org/10.1086/417659>.
- Houmani, H., Debez, I.B.S., Turkan, I., et al., 2024. Revisiting the potential of seed priming to improve stress resilience and nutritive value of cereals in the context of current global challenges. *Agronomy* 14, 1415. <https://doi.org/10.3390/agronomy14071415>.
- Huot, B., Yao, J., Montgomery, B.L., et al., 2014. Growth-defence tradeoffs in plants: a balancing act to optimize fitness. *Mol. Plant* 7, 1267–1287. <https://doi.org/10.1093/mp/ssu049>.
- Hurtado, A.C., Prado, R.M., Campos, M.L., 2025. Challenging the “resource allocation” paradigm: a meta-analysis on how nitrogen fertilization balances plant growth and defense against insects. *Theor. Exp. Plant Physiol.* 37, 35. <https://doi.org/10.1007/s40626-025-00382-3>.
- Kliebenstein, D.J., 2016. False idolatry of the mythical growth versus immunity tradeoff in molecular systems plant pathology. *Physiol. Mol. Plant Pathol.* 95, 55–59. <https://doi.org/10.1016/j.pmpp.2016.02.004>.
- Konrad, W., Burkhardt, J., Ebner, M., et al., 2014. Leaf pubescence as a possibility to increase water use efficiency by promoting condensation. *Ecohydrology* 8, 480–492. <https://doi.org/10.1002/eco.1518>.
- Kumar, A., Choudhary, A., Kaur, H., et al., 2025. Exploring the role of silicon in enhancing sustainable plant growth, defense system, environmental stress mitigation and management. *Discov. Appl. Sci.* 7, 406. <https://doi.org/10.1007/s42452-025-06866-w>.
- Li, C., Xu, M., Cai, X., et al., 2022. Jasmonate signaling pathway modulates plant defense, growth, and their trade-offs. *Int. J. Mol. Sci.* 23, 3945. <https://doi.org/10.3390/ijms23073945>.
- Lopes, M.A., 2023. Rethinking plant breeding and seed systems in the era of exponential changes. *Cienc. E Agrotecnol* 47, e0001R23. <https://doi.org/10.1590/1413-70542023470001R23>.
- Martín-García, J., Gómez-Limón, J.A., Menor-Campos, A., 2025. Farms' economic resilience: assessment, drivers and policy-making. *Environ. Sustain. Indic.* 27, 100740. <https://doi.org/10.1016/j.indic.2025.100740>.
- Mastretta-Yanes, A., Tobin, D., Bellon, M.R., et al., 2024. Human management of ongoing evolutionary processes in agroecosystems. *Plant People Planet* 6, 1190–1206. <https://doi.org/10.1002/ppp3.10521>.
- Mueller, M.B., Chen, X., Philbin, C.S., et al., 2026. Functional uncoupling of the induced defense-competitive growth trade-off. *New Phytol.* 250, 2586–2598. <https://doi.org/10.1111/nph.71058>.
- Panigrahi, L.L., Rout, G.R., 2025. Mechanistic insights into micro and nanosilicon for environmental stress mitigation in plant. *Discovery Nano* 20, 208. <https://doi.org/10.1186/s11671-025-04387-4>.
- Pappo, E., Wilson, C.H., Pitts, J.J., et al., 2023. Toward a new perspective on evaluating climate change resilience of agroecosystems. *Ecosphere* 14, e4594. <https://doi.org/10.1002/ecs2.4594>.
- Pascual, L.S., Segarra-Medina, C., Gómez-Cadenas, A., et al., 2022. Climate change-associated multifactorial stress combination: a present challenge for our ecosystems. *J. Plant Physiol.* 276, 153764. <https://doi.org/10.1016/j.jplph.2022.153764>.
- Pawłowska, A., 2025. Has the “green” transformation of the common agricultural policy affected the environmental sustainability of farms? *PLoS One* 20, e0333703. <https://doi.org/10.1371/journal.pone.0333703>.
- Prigoreanu, I., Grigore-Sava, A., Avarvarei, S.C., et al., 2025. Agricultural sustainability in the European union: a review of concepts, policies and economic perspectives. *Frontiers in Agronomy* 7, 1714297. <https://doi.org/10.3389/fagro.2025.1714297>.
- Qaim, M., Parlasca, M.C., 2025. Agricultural economics and the transformation toward sustainable agri-food systems. *Agric. Econ.* 56, 327–335. <https://doi.org/10.1111/agec.70023>.
- Rajput, V.D., Minkina, T., Feizi, M., et al., 2021. Effects of silicon and Silicon-based nanoparticles on rhizosphere microbiome, plant stress and growth. *Biology* 10, 791. <https://doi.org/10.3390/biology10080791>.
- Rodríguez, J., Calbi, M., Roiloa, S.R., et al., 2018. Herbivory induced non-local responses of the clonal invader *Carpobrotus edulis* are not mediated by clonal integration. *Sci. Total Environ.* 633, 1041–1050. <https://doi.org/10.1016/j.scitotenv.2018.03.264>.
- Rodríguez, J., Novoa, A., Sotes, G., et al., 2023. Variation in defensive traits against herbivores of native and invasive populations of *Carpobrotus edulis*. *Biol. Invasions* 25, 1149–1164. <https://doi.org/10.1007/s10530-022-02970-9>.
- Sgarbi, F., Nadeu, E., 2023. Resilience and Sustainability in Food Systems Research: a Review of the Main Issues and Knowledge Gaps. Institute for European Environmental Policy (IEEP). Available at: https://ieep.eu/wp-content/uploads/2023/11/Resilience-and-sustainability-in-food-systems_Test-ESAD-IEEP-2023-.pdf. Accessed on December 18th.
- Tunstad, S.A., Bull, I.D., Rands, S.A., et al., 2024. The cuticular wax composition and crystal coverage of leaves and petals differ in a consistent manner between plant species. *Open Biol.* 14, 230430. <https://doi.org/10.1098/rsob.230430>.
- Wang, L., Maier, L.P., Pham, N., et al., 2025. A receptor antagonist counterbalances multiple systemin phytochemicals in tomato. *Cell* 188, 6509–6518.e12. <https://doi.org/10.1016/j.cell.2025.07.044>.
- Zhou, K., Wu, F., Deng, L., et al., 2025. Antagonistic systemin receptors integrate the activation and attenuation of systemic wound signaling in tomato. *Dev. Cell* 60, 535–550. <https://doi.org/10.1016/j.devcel.2024.11.005>.