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SYMPOSIUM INTRODUCTION

Introduction to Plant–Pollinator Interactions in a Changing Landscape: Embracing Integrative Approaches Across Scales

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The coevolutionary relationship between angiosperms and their animal pollinators has driven striking speciation and produced remarkable adaptations in morphology, behavior, and chemical ecology in both plants and animals, while also being critically important in supporting crop productivity and agricultural systems (Senapathi et al. 2021). Plant–pollinator relationships are critical to ecological health in terrestrial biomes (Fig. 1), as they facilitate stability of both plant and pollinator populations, which in turn form the lower tiers of many trophic pyramids. Degradation of these populations could disrupt the integrity of ecological communities and have downstream ecosystem impacts, e.g., on population declines in primary and secondary consumers (Rafferty and Cosma 2024; Tobajas et al. 2024). In addition, almost paradoxically, the agricultural systems that rely on pollination are contributing to pollinator declines through actions such as the use of insecticides and landscape simplification (Outhwaite et al. 2022). Conservation of plant–pollinator networks are critical to both terrestrial ecosystem health and sustainable agriculture efforts (Lichtenberg et al. 2017). Thus, understanding the interactions between plants and pollinators is critical to supporting biodiversity and human wellbeing under rapid anthropogenic environmental change.

While recent decades have seen an enormous surge in research on the effects of global change on the health of pollinators, plants, and their interactions, this research has underscored the enormous challenge of predicting responses of these complex systems to changing environments. For example, early models for the impacts of climate-driven phenological mismatches on plant–pollinator communities predicted severe effects on community stability and extinction (Memmott et al. 2007). However, subsequent decades of work have shown the effects of phenological shifts to be much more complex and nuanced, with plant–pollinator communities showing substantial resilience to mismatches (Gérard et al. 2020). In part, this is a result of the central role of complex, organismal factors (e.g., behavioral flexibility or developmental plasticity) in driving resilience and sensitivity of plant–pollinator systems change. The enormous complexity of species' interactions is reflected in pollination biology, and makes plant–pollinator interactions an ideal model system for understanding dynamic community responses to global environmental change in the Anthropocene. Interactions between plants and pollinators are models for ecological networks (especially mutualistic ones), interspecies signalling and communication, physiology, and behavior.

Addressing these grand challenges in plant–pollinator interactions—and their resilience and stability under global change—will require developing a deeper, more integrative understanding of these inter-

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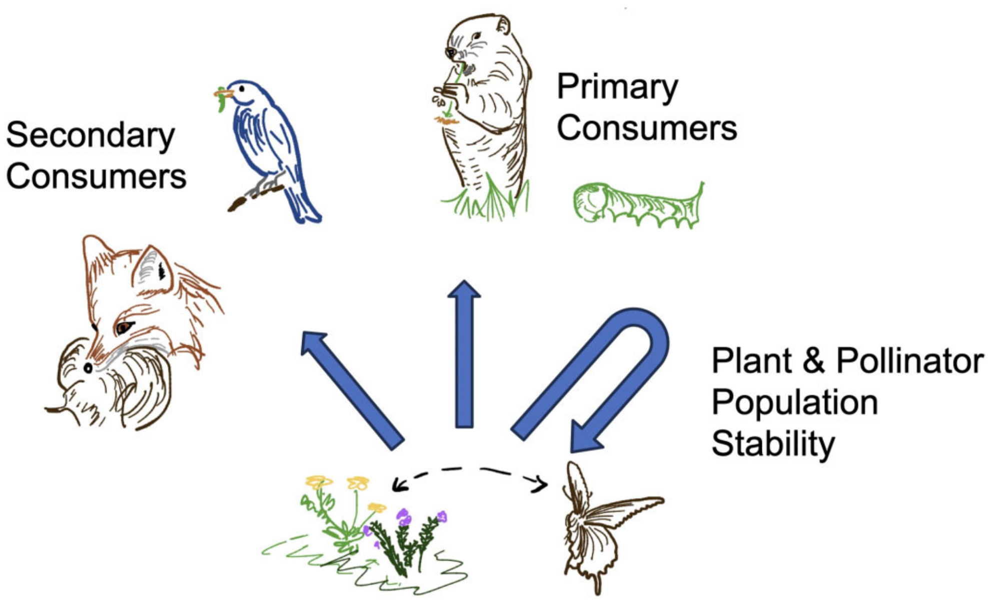

Fig. 1 Plant–pollinator relationships facilitate trophic stability.

actions across taxa and scales of biological organization. Examples of these challenging questions include: How does pollution disrupt the sensory physiology of pollinators, and what are the impacts on species interactions and floral reproduction? What are the physiological responses of plants to drought, and what are the behavioral responses of insects? Integrative and organismal biology—i.e., developing a holistic perspective on organisms and how they interact with each other and the environment—provides an ideal framework for addressing these critical knowledge gaps. The symposium "Pollinator-plant interactions in a changing landscape: embracing integrative approaches across scales" held at the 2025 annual Society for Integrative and Comparative Biology (SICB) conference was intended to help address this challenge. The collection of symposium papers in this issue represent the broad set of approaches and scales we feel are necessary to tackle this complex and important problem (Fig. 2).

Organismal perspectives on plant–pollinator interactions

Understanding how plants and their pollinators interact, from an experimental, organismal, and species level is one key piece of this puzzle. The articles included here utilized organismal perspectives on these interactions in both plants and pollinators. From the plant perspective, Bode et al. (2025, this issue) illustrate how plants can move beyond nectar rewards and visual cues to manipulate environmental cues, such as humidity, to modify microhabitats and attract pollinators; disrupting canonical understanding of highly specialized brood–pollinator relationships. Ekemezie et al. (2025, this issue) take a pollinator driven approach to illustrate that nectar content, in terms of pollen and microbe "contaminants" may influence bumble bee foraging behavior. These two studies, while presenting different organismal perspectives, both indicate the complexity of plant–pollinator interactions, and how these interactions may incorporate multi-modal sensory (and reward) cues. Expanding upon the complexity of these plant–pollinator interactions, Potdar et al. (2025, this issue) synthesize and compare plant and pollinator epigenetic inheritance, providing insights as to how within generation plant–pollinator interactions may facilitate trans-generational change, both within the respective plant or pollinator, and between the interacting parties.

Utilizing the rich data on european honeybees, *Apis melifera*, Pike and Ritschof (2025, this issue) conducted a meta analysis to elucidate the impacts of naturalized european honeybees, on wild bee communities. While resource competition appears problematic in some habitats, the lack of consistent trends across existing studies indicates a need for future clarifying research. Jain et al. (2025, this issue) showcase how computer vision and automation can address a key challenge in pollinator health research: understanding the organismal impacts of stressors such as neuroactive insecticides. Tracking individual bumble bees exposed to a neonicotinoid and a "bee-safe" butenolide across social behavior within the nest and foraging contexts, they reveal the complex, multi-faceted effects of these pesticides. The study underscores the potential of "ethomics"

Fig. 2 Sketch notes from two days of pollination talks.

to provide a holistic, integrative view of global change stressors on pollinator biology, behavior, and plant interactions.

Community responses to environmental change

Interactions between individual plants and pollinators will scale up to population and/or community level impacts. Several papers in this issue focus on experiments at this level of organization. Fisogni et al. (2025, this issue) explore how climate change-driven shifts in the timing of flowering and pollinator activity can cause phenological mismatches, potentially weakening or disrupting mutualistic interactions. The authors emphasize major complexities that limit our ability to predict outcomes, including critical aspects of organismal complexity such as individual-level variation in phenology rather than just community-level averages, and the need to study entire life cycles (rather than single phenophases) to understand evolutionary and ecological outcomes. This highlights the critical role of life-history traits and plasticity in mediating species responses to shifting environments, threatening not only individual species but also the broader network of pollination services that support biodiversity and food security. Fetters et al. (2025, this issue) delve into the role that pollinator proclivities play in transmission of pollen-viruses. They found that pollinator generalists not only facilitated greater viral transmission, but were also associated with a more diverse pollen virome. Likewise, attractive floral characteristics, such as bilateral symmetry, were associated with viral diversity "hotspots." This work emphasizes the importance of considering species interactions beyond the boundary of the canonical "plant–pollinator" lens. Kutcherov & Westerman (2025, this issue) utilize community science data from iNaturalist to assess flower preferences in Lepidoptera, illustrating the power of crowd-sourced data for capturing pollinator–plant interactions through time, and demonstrating that even so called "generalist" pollinators like butterflies have important—and lineage-specific—floral preferences. Phylogenetic preference patterns have the potential to impact which flowers are likely to be pollinated (or cross pollinated with heterospecific pollen), especially as pollinator species assemblages shift in response to climate change (Edwards et al. 2025).

Modeling insights into plant–pollinator complexity

Some of the challenges inherent in understanding systems based in complex interspecies interaction can be addressed *via* modeling, as this approach allows us to observe impacts at greater temporal and spatial scales (or under a wider range of conditions) than we can easily tackle experimentally. Models that incorporate ecologically and ethologically relevant variables will provide more germaine insights. Several papers in this issue take important steps toward building complex models grounded in the organismal biology of plants and pollinators. Mailly et al. (2025, this issue) incorporate agent-based components into modeling pollen distribution, allowing an exploration of the interactions between pollinator learning and nectar renewal rates, and how those interactions in-turn influence pollen distribution. This approach provides not only a lens into the ecological impacts of pollinator cognition, but insights into coevolutionary forces on plant and pollinator physiology. Continuing this theme, Valdovinos (2025, this issue) uses a mechanistic consumer-resource model to examine how a critical behavior—fixed vs. adaptive pollinator foraging strategy—interacts with the architectural features of plant–pollinator networks (i.e., connectance and nestedness) to influence pollen deposition and pollination services. Moderate connectance combined with strong nestedness and adaptive foraging maximizes pollen transfer—largely because pollinators dynamically adjust their foraging to higher-reward plants, thereby reducing conspecific pollen dilution. This work highlights how pollinator behavioral plasticity (a critical organismal process) scales up to shape community-level outcomes.

Framing paths forward

Finally, two papers in this issue help frame the broader challenge of developing an interdisciplinary perspective on plants and pollinators, and how this understanding can facilitate training of the next-generation of organismally curious scientists. A review article (Sprayberry et al. 2025) bring together perspectives from a series of conversations among symposium-participants, as well as perspectives from a structured, community discussion at the SICB 2025 meeting, to distill the challenges and potential that an integrative, organismal perspective might bring to plant–pollinator interaction research. Baker et al. (2025, this issue) address the critical role that human systems have in the dynamics of plant–pollinator science, and offer insights into research approaches that integrate outreach, undergraduate education, and timely research needs with a review on pollination focused Course-based Undergraduate Research Experiences.

In addition to the papers presented in this issue of *Integrative and Comparative Biology*, our symposium on plant–pollinator interactions included insights from presenters. Matthew Smith ("The effects of competition on individual foraging patterns and within nest behavior across bumble bees") demonstrated the role of behavioral flexibility in individual bees in responding to competition and the consequences of plant–pollinator networks, and Amanda Katzer ("Transcriptional differences in nectar volume between bee and hummingbird pollinated Penstemon") highlighted how closely related plants with different pollinators provide different rewards, which may be associated with pollinator specialization. The symposium was complemented by an insightful set of additional talks given by a number of researchers who contributed to the lunch discussion incorporated into our review article (Sprayberry et al. 2025), as well as a workshop on using machine learning and AI to enhance the study of plant–pollinator interactions led by James Crall and Matthew Smith (workshop materials available at https://github.com/Crall-Lab/SICB2025_CV). The papers included in this issue are representative of the breadth and forward looking approaches of the cross-disciplinary discussions in our symposium and associated talks and workshops, and we hope they inspire future cross-disciplinary cutting edge research in the ecologically and economically important field of plant–pollinator interactions.

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Conflict of interest

The authors have no conflict of interest in this work.

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