Commentary

Information potential of an ubiquitous phytochemical cue

Plants, like all organisms, use the language of chemistry as a means of communication. Plants have evolved this complex and sophisticated chemical language to sense their environment and interact advantageously with other living organisms and their nonliving surroundings. By eavesdropping on their chemical environment, plants can pick up cues that can indicate, or possibly predict, changing environmental conditions. In response, and to manipulate their ecological surroundings, plants can control the targeted release of chemical cues. Volatile compounds are well-suited and established as ecologically important plant signaling and defensive cues (Frost *et al.*, 2007, 2008; Maurya *et al.*, 2022), offering potential opportunities to influence plant productivity in agricultural settings (Freundlich *et al.*, 2021). That said, nonvolatile metabolites also play key roles as chemical signaling agents. These may be particularly prevalent in belowground environments where roots of different plants and plant species form direct contact networks with their rhizosphere fungal and microbial partners (Bais *et al.*, 2006). In this issue of *New Phytologist*, Li *et al.* (2023, pp. 2099–2112) provide a unique insight into the involvement of a nonvolatile metabolite, (−)-loliolide, as both an exogenous chemical cue and an endogenous regulator of several allelochemicals.

> *'How plants balance the competing information potential of chemical agents that can serve both exogenous and endogenous roles, as Li* et al. *(2023) suggest (−)-loliolide does, is a key question for the future.'*

Li *et al.*'s (2023) results are fascinating in part because (−)-loliolide is a well-known and ubiquitous nonvolatile monoterpenoid lactone. It was first isolated in 1964 from *Lolium perenne* (Hodges & Porte, 1964) and subsequently isolated from animals and marine algae (Percot *et al.*, 2009 and references therein). (−)-Loliolide is a potent repellent for some ant species (Okunade & Wiemer, 1985), and there is evidence that a dihydroxy derivative of loliolide is a component of a 'queen-recognition' pheromone for others (Rocca *et al.*, 1983). In terrestrial plants, among other activities, (−)-loliolide can be secreted from roots to inhibit the growth of competing plants and seeds (Li *et al.*, 2019). Apart from its fundamental biological and ecological significance, (−)-loliolide (primarily considered as an isolate from marine algae) has received attention for its pharmacological potential, showing neuroprotective, anti-inflammatory, anti-oxidant, anti-fungal, anti-bacterial, and anti-cancer properties (Silva *et al.*, 2021 and references therein). In short, (−)-loliolide is a cross-kingdom metabolite that has a wide range of biological and ecological effects with both exogenous and endogenous activity.

Li *et al.*'s (2023) focus on (−)-loliolide indirectly addresses a question that could be posed for any putative semiochemical cue: how is it possible for a chemical compound that is so widespread to convey reliable information about stressful ecological conditions? The argument is that it may be difficult for organisms to distinguish whether an ubiquitous chemical is an honest cue, innocuous background noise, or a potentially harmful dishonest cue, making its effective use prone to ecological error (Orrock *et al.*, 2015). This raises the question of how something that is present in such a widespread manner can still serve as an effective means of communication. Yet, Li *et al.*'s (2023) evidence that multiple plant species activate species-specific defenses in response to (−)-loliolide is compelling. Li *et al.* (2023) appear to answer, or at least address, this question by ascribing an endogenous role to (−)-loliolide's activity in addition to showing that endogenous (−)-loliolide is induced by a wide range of biotic and abiotic stresses.

By specifically contrasting the effects of (−)-loliolide with those of the phytohormone jasmonic acid (JA), Li *et al.* (2023) add to the intriguing possibility that (−)-loliolide acts endogenously like a phytohormone (Murata *et al.*, 2019). Growth and defense are highly coordinated and regulated by signaling networks of major hormones such as JA, salicylic acid, abscisic acid (ABA), auxin, cytokinins, brassinosteroids, gibberellins (GA), and ethylene. Li *et al.* (2023) show that (−)-loliolide is present in leaves and that its leaf concentrations are responsive to the belowground cues of plant competitors and all the forms of abiotic stress they tested. Moreover, they show that (−)-loliolide itself is sufficient to regulate concentrations of other important allelopathic agents such as momilactone B and tricin, meeting a basic criterion of an endogenous phytohormone (Murata *et al.*, 2019). So, Li *et al.* (2023) provide evidence that (−)-loliolide, like JA, has both endogenous and exogenous activity.

Li *et al.*'s (2023) results will inevitably add to the discussion of phytohormone crosstalk in regulating and fine-tuning plant responses to environmental stress and variation. The concept of crosstalk derives from now considerable evidence that plant hormones operate via concerted rather than stand-alone actions to respond to environmental stress and that crosstalk functionally operates by a complex interaction web of activation and repressor molecular pathways (Kohli *et al.*, 2013). Li *et al.* (2023) show that (−)-loliolide applied exogenously to roots stimulates endogenous JA production, while inhibitors of JA signaling block the induction

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of Momilactone B by (−)-loliolide. That is, JA and (−)-loliolide apparently have regulatory effects on each other.

The question remains whether Li *et al.*'s (2023) findings indicate that we are ready to modify the phytohormone crosstalk interaction map to include (−)-loliolide. While it is a bit early to conclude this, Li *et al.* (2023) have certainly made a step in such a direction. There is clearly much work to do if Li *et al.* (2023) have correctly identified that (−)-loliolide operates with an endogenous capacity to initiate signal transduction pathways and modulate phytohormone cross-talk networks. For one, endogenous activity implies receptor-mediated signal transduction. Many of the established plant hormone receptors operate through the ubiquitin–protein conjugation pathway and downstream signaling proteins for auxin, GA, JA, and ABA are subject to ubiquitin-dependent degradation (Santner *et al.*, 2009). Whether (−)-loliolide or similarly structured monoterpene lactones also have receptors in the ubiquitin–protein conjugation pathway is a key question for the future but resolving receptor–ligand interactions takes time. As one example, even though the phytohormone role of jasmonates has been firmly accepted, the mechanism for JA activity (as jasmonoyl–isoleucine) was not established until 2007 (Chini *et al.*, 2007; Thines *et al.*, 2007; Yan *et al.*, 2007) and the receptor definitively elucidated a few years later (Sheard *et al.*, 2010), almost 30 yr after the first physiological processes regulated by jasmonates were described, and > 40 yr after the methyl ester of JA was first detected in *Jasminium grandiflorum* flowers.

Setting aside the question of endogenous phytohormone activity, Li *et al.*'s (2023) findings should inspire many other questions. For example, how do plants regulate exogenous (−)-loliolide concentrations to achieve ecological outcomes? A central question in defining the role of semiochemical efficacy is one of concentration and ecological relevance. Li *et al.* (2023) elegantly show broad generalized effects of (−)-loliolide at 50 mM concentrations. As a putative semiochemical, what type of response does (−)-loliolide at concentrations in the rhizosphere soil elicit? (−)-Loliolide at a physiological concentration of 5 nmol g^{-1} soil induces the release of the benzoxazinoid compound 2,4-dihydroxy-7-methoxy-1,4-benzoxazin-3-one (DIMBOA) from wheat roots (Kong *et al.*, 2018). Li *et al.*'s (2023) supplemental data also provide tantalizing insights into this question, but more work in this area is required to provide ecological detail. What are the mechanisms that regulate (−)-loliolide release from the root? Since (−)-loliolide has an ubiquitous effect on numerous plant species, will it also affect the dynamics, composition, or chemical signaling of the rhizosphere microbiome? If so, is it possible that the rhizosphere microbiome could itself produce (−)-loliolide and thereby co-opt plant stress resistance for their own benefit (Liu *et al.*, 2020)? There is no doubt that Li *et al.*'s (2023) results are therefore fodder for understanding plant–plant and plant–microbe interactions, as well as chemical mechanisms that structure competitive rhizosphere interactions.

How plants balance the competing information potential of chemical agents that can serve both exogenous and endogenous roles, as Li *et al.* (2023) suggest (−)-loliolide does, is a key question for the future. When faced with potential chemical cues from their environment, plants – like any organism – face the challenge of responding to those cues in ways that enhance their ecological success. But, they may also respond erroneously by ignoring *bona fide* threats or responding to false threats or dishonest cues. Since the effect of these errors is often asynchronous, it is a reasonable assumption that plants are under strong selection pressure to 'get it right' (Orrock *et al.*, 2015). This is particularly true if the chemical agent has both exogenous and endogenous activity, as such cases may be more likely the subject of exploitation since endogenous phytohormone activity implies the regulation of fundamental physiological processes. Now that Li *et al.* (2023) have identified (−)-loliolide as a general signal of plant stress, the questions of whether and how (−)-loliolide contributes to an ability to coordinate an ecologically beneficial response, while avoiding exploitation and conveying ecologically relevant information, is ripe for the asking.

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