New Phytologist

Review

Tansley insight

Cross-kingdom communication between plants and parasitic nematodes

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Received: *19 March 2026*
Accepted: *25 April 2026*

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New Phytologist (2026)
doi: 10.1111/nph.71283

Key words: biotrophic interaction, cross-kingdom communication, hatching, host approach, host arrival, plant-parasitic nematodes.

Summary

Plant-parasitic nematodes and their hosts engage in a continuous exchange of signals cross-kingdom. On the one hand, parasites exploit host-derived metabolites, proteins, and RNAs to sense host identity, proximity, and condition – and as a basis for manipulating host processes to their benefit. On the other hand, hosts respond to nematode-derived pheromones, proteins, and metabolites to either subvert or accommodate parasitism. Our recent understanding is that microbes play a role mediating, at least in part, a communication, which ultimately shapes the developmental trajectories of both host and parasite, in concert. In this Tansley insight, we review the current understanding of communication between plants and parasitic nematodes, framed by the developmental timeline. We focus on notable, reciprocal signals between plant and parasite that gate key life cycle transitions in the parasite, while acknowledging that these processes are embedded within, and inseparable from, a plethora of other signals – and indeed communication with other organisms. The frequency, reciprocity, and gravity of the exchange leads us to argue that it is best described as a nuanced communication, in which parasitism succeeds or fails based on interpretation and response.

I. Hatching

The first, and one of the most striking, examples of cross-kingdom communication governs the hatching of infective juveniles from the egg (Fig. 1). The hatching of certain cyst nematodes is among the clearest examples of signal-dependent development in any plant pathogen. Rather than emerge spontaneously, several cyst nematode species (i.e. certain *Globodera* and *Heterodera* spp.) are developmentally arrested within their eggs, potentially for several decades. Hatching is triggered by exposure to root exudates (Ochola *et al.*, 2021) that indicate the presence, proximity, and even physiological status of an appropriate host (e.g. resistant/susceptible status (Lu *et al.*, 2023) or concurrent abiotic stress (Williams & de Vries, 2020)). While hatch-inducing compounds for various plant-parasitic nematode species have been well-studied (Perry *et al.*, 2024), recent works reveal that communication extends beyond a simple two-partner signalling exchange between plant and parasite – it forms part of a broader,

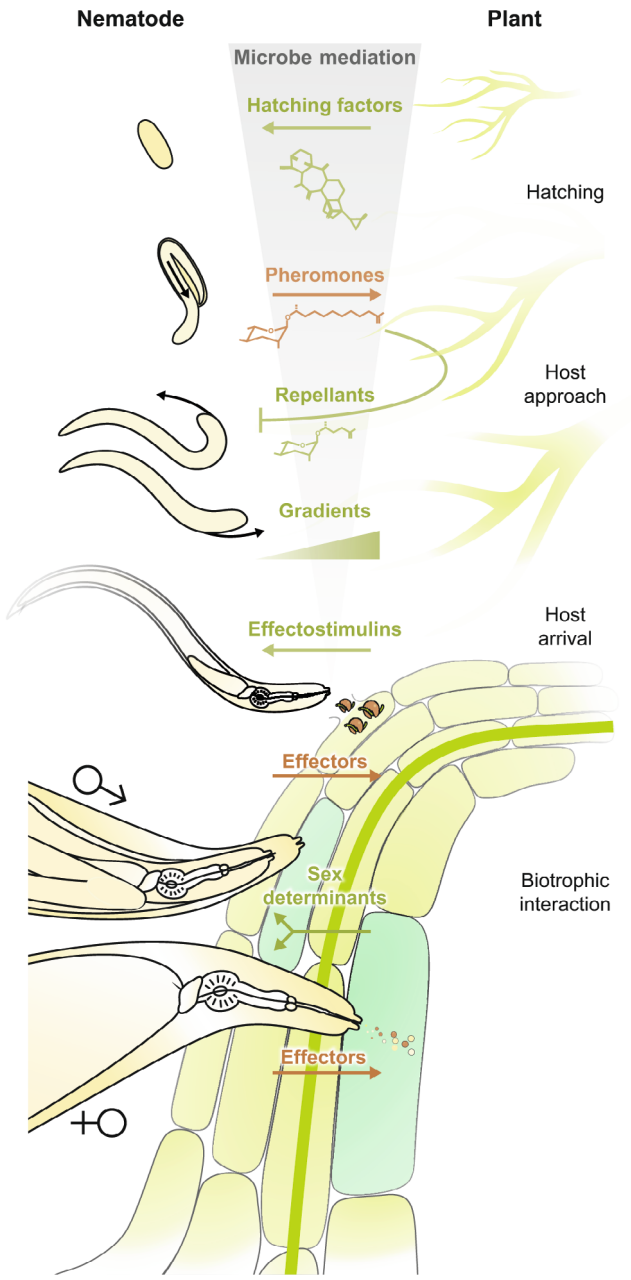

Fig. 1 Cross-kingdom communication between plants and parasitic nematodes. Examples which collectively illustrate reciprocal exchange of signals between nematodes (left) and their host plants (right). The grey triangle represents the potential for microbe-mediation in the communication. Four major categories, which structure the review, are hatching, host approach, host arrival, and biotrophic interaction.

multi-partner, ecological communication. First, root exudate composition and abundance may vary through feedback systems involving the host plants concurrent interactions with other organisms (Sharma *et al.*, 2023; Fan *et al.*, 2025), which can then impact plant-parasitic nematode behaviour (Hoysted *et al.*, 2018; Topalović *et al.*, 2020). Second, exuded signalling molecules can be transformed, metabolised, and/or degraded by the surrounding soil microbiome. For example, the *Globodera* hatching factor solanoeclepin B is microbially converted within the rhizosphere of *Solanum* roots into solanoeclepin A, which acts as a more potent hatch inducer (Shimizu *et al.*, 2023; Akiyama *et al.*, 2025). A model is emerging in which plants ordinarily exude compounds to build a beneficial microbiome (Zou *et al.*, 2024; Tian *et al.*, 2025); however in susceptible scenarios, plant-parasitic nematodes hijack these signals to detect the presence and condition of nearby hosts – akin to striga intercepting plant-mutualist strigolactone communication (Clark & Bennett, 2024). In this framework, hatching does not simply mark the beginning of infection but, in certain nematodes, reflects an outsourcing of critical aspects of developmental timing. This strategy reduces the likelihood of hatching in the absence of a suitable host, or in the presence of a host on which the nematode would perform sub optimally, thereby improving infection success and coordination of subsequent host–parasite communication. By contrast, reliance on individual host-derived compounds to coordinate communication is generally absent in the polyphagous root-knot nematode species (*Meloidogyne* spp.) (Wesemael *et al.*, 2006).

II. Host approach

As the parasitic nematode may eavesdrop on plant–microbe communication to initiate hatching, the plant may eavesdrop on nematode–nematode communication. The newly hatched juvenile secretes/exudes a variety of molecules into the rhizosphere, including proteinaceous materials and small molecule pheromones ordinarily involved in nematode–nematode signalling (notably Ascaroside 18, Mendy *et al.*, 2017, Manosalva *et al.*, 2015). Interestingly, Ascr#18 appears to be internalised by the plant, and metabolised into shorter chain nematode-repellent derivatives by host peroxisomal acyl-CoA oxidases (Manohar *et al.*, 2020). These data point towards a model where plants do not just respond to parasite signals, but actively intercept, edit and re-emit nematode-derived messages, presumably to repel the approaching individual from which the signal originated, as well as their conspecifics (Manohar *et al.*, 2020).

The juvenile motile nematode must next navigate through the soil by following chemical gradients of root-derived volatiles, sugars, organic acids, and phytohormones, each carrying different information (Siddique *et al.*, 2022). While many of these cues are attractants (e.g. primary metabolites and polyamines, such as cadaverine, Oota *et al.*, 2019), certain phenolics or defence-related volatiles serve as repellents in resistant hosts (Zou *et al.*, 2024). Furthermore, the concentration of such compounds can dictate their effects, with several attractants repelling nematodes at greater concentrations (Siddique *et al.*, 2022). Recent work provides a compelling demonstration that, like hatching induction of cyst nematodes, rather than detecting plant-derived products directly, a root-knot nematode (*Meloidogyne incognita*) perceives microbially transformed chemical cues as host attractants (Wu *et al.*, 2025). In maize, benzoxazinoids released from the roots reshape the rhizosphere community and the resultant bacterial volatiles, particularly methyl ketones and 2-phenylethanol, are tracked by nematode-conserved chemosensory receptors *odr* and *gpa* (Shivakumara *et al.*, 2019; Li *et al.*, 2022; Wu *et al.*, 2025). It is suggested

that rhizosphere bacteria amplify and stabilise plant-derived signals across diverse soil environments and plant species (Wu *et al.*, 2025). For a highly polyphagous pathogen such as *M. incognita*, responding to benzoxazinoid-shaped microbiomes provides a broad, cross-host indicator of suitable, actively growing roots, enabling effective host location across diverse plant species without relying on the highly variable chemical fingerprints of individual hosts. It is likely that the soil microbiome impacts a plethora of nematode attractants/repellents, which we are now starting to reveal (Lu *et al.*, 2026). Additionally, nematode infection itself restructures the root and rhizosphere microbiomes. For example, a *Pseudomonas* strain isolated from *M. incognita* galls attracts infective juveniles, potentially guiding them towards metabolically active or permissive regions of the root (Yergaliyev *et al.*, 2020), while broader microbiome shifts during root-knot nematode parasitism have also been reported (Masson *et al.*, 2020; Kudjordjie *et al.*, 2024). These findings support a view in which nematode host-finding reflects an emergent property of plant–microbe–nematode interactions, rather than a response to plant signals alone.

As well as eliciting hatching, attraction, and repulsion, components of host root exudates also stimulate the reciprocal release of molecules by the nematode, collectively referred to as effectors. For example, root-knot nematode species induce the expression of a plethora of effector proteins upon perception of host root exudates (Teillet *et al.*, 2013; Dou *et al.*, 2025), and the cyst nematode *Globodera pallida* additionally responds with the production of the phytohormone auxin (Oosterbeek *et al.*, 2026). Further still, the migratory root-lesion nematode *Pratylenchus coffeae* tailors the expression of cell wall degrading effectors based on the 'taste' of root exudates, namely the expression of a β-1,4-endoglucanase and a β-1,4-endoxylanase based on the perception of local cellulase and xylan abundances, respectively (Bell *et al.*, 2019).

III. Host arrival

Next, plant-parasitic nematodes must recognise that they have arrived at the host root. It seems plausible that this involves either distinct host-derived signals, or higher concentrations of so-called 'effectostimulins' that drive attraction and preinvasive effector production, thereby allowing the parasite to balance energetic restraint with readiness to invade (Hammond *et al.*, 2026). Recent work further suggests that signalling does not stop at the root surface, but changes again once the nematode enters host tissue. *H. schachtii*, for example, perceives effectostimulins released from lysed root tissue, leading to the upregulation of the transcriptional master regulator, called the Subventral gland Regulator-1 (SUGR-1; Pellegrin *et al.*, 2025). This, in turn, promotes the production of effectors involved in breaking open additional plant cells (e.g. cell wall degrading and protease effectors). These data led to the proposition of a feed-forward model in which nematode-induced host cell damage triggers the release of further effectostimulins, thereby stimulating the secretion of additional effectors that drives the parasite through root tissue. Whether this self-reinforcing cycle is more broadly applicable remains unclear. Indeed, while SUGR-1 appears to have a homologue in *H. glycines*, it is absent from other cyst nematodes that migrate in similar manner to *H. schachtii* (e.g. *Globodera*), as well as from nematodes that cause minimal cell lysis by migrating between cells (e.g. root-knot nematodes).

Importantly, this phase of infection also coincides with the onset of host immune recognition. Exudates released by infective juveniles ('NemaWater') elicit hallmark outputs of pattern-triggered immunity (PTI), including ROS bursts and defence-associated transcriptional reprogramming, which require the co-receptor BAK1 and the leucine-rich repeat receptor-like kinase, NILR1 (Mendy *et al.*, 2017). In compatible interactions, nematodes counter this recognition by deploying effectors that suppress PTI-associated outputs (Chronis *et al.*, 2013; Niu *et al.*, 2016). In incompatible interactions, however, some of these effectors, or the host processes they perturb, may be recognised by host extracellular (e.g. Cf-2 and RCR3-dependent recognition of *G. rostochiensis* effector VAP1) (Lozano-Torres *et al*, 2012) or intracellular (e.g. Gpa2-mediated recognition of the *G. pallida* effector, RBP-1 (Sacco *et al.*, 2009)) receptors, leading to immune responses. Thus, successful parasitism requires the nematode to balance these processes – it must remain responsive to plant signals that stimulate invasion, while deploying effectors to suppress the immune outputs those same activities provoke. Crucially, suppression is not confined to a single layer of immunity. For example, the cyst nematode effector, SPRYSEC15, binds to and inhibits NRC helper activity, thereby dampening effector triggered immunity (ETI) responses across the NRC dependent NLR network (Derevnina *et al.*, 2021; Contreras *et al.*, 2023), while the E3 ubiquitin ligase RHA1B suppresses immune responses mediated by multiple NLR receptors and attenuates PTI marker induction (Kud *et al.*, 2019). Together, these observations show that plant-parasitic nematode interactions are shaped by continual reciprocal sensing, immune activation and suppression.

IV. Biotrophic interaction

Once the nematode reaches the vascular cylinder, a permanent feeding site is established. This requires a clean transition from destructive migration to biotrophic interaction – that is the lytic feed-forward loop of SUGR-1 signalling must be overridden such that biotrophic effectors (e.g. but certainly not limited to, those which mimic plant–peptide hormones (Replogle *et al.*, 2011)) can function unimpeded. Indeed, a switch is evidenced in transcriptomic analyses of *H. schachtii* effector deployment concurrent with feeding site establishment (Molloy *et al.*, 2024). Failure to override SUGR-1 signalling at this stage would likely be detrimental, as inappropriate expression of lytic effectors during feeding site establishment would be catastrophic. Therefore, a robust mechanism must drive this change. What host-derived signals initiate the override is unclear, but, given the cost, the most simplistic solution (the absence of lytic effectostimulins in the vasculature) seems unlikely.

Cross-species single-cell analyses support the transition from migration to developmental control, revealing conserved cell-type-resolved transcriptional reprogramming in infected root cells of both Arabidopsis and rice, including stemness acquisition and *de novo* organogenesis-like programmes, consistent with feeding site establishment (Saura-Sanchez *et al.*, 2025). This is consistent with

earlier work demonstrating that nematodes manipulate host developmental circuitry and hormone balance during feeding site formation, including the deployment of nematode-derived cytokinin to promote host cell division and organogenic reprogramming (Siddique *et al.*, 2015). Successful feeding site establishment, therefore, depends on maintaining host cells in a developmentally permissive but immunologically restrained state.

Recent advances have revealed that in addition to proteins, microRNAs are also involved in reciprocal cross-kingdom communication between nematode and host (Leonetti *et al.*, 2024). Root-knot nematodes express a range of microRNAs (Wang *et al.*, 2015), some of which are secreted in lipid-bound exosomes (Maxwell *et al.*, 2026). This cargo systemically aids susceptibility, likely through influencing plant developmental pathways. Identifying secretion mechanisms/pathways rather than single effectors will fundamentally reframe how we view plant–nematode interactions and open up new targets for broader and more robust control options.

A major bifurcation in the communication occurs after establishing a feeding site. Juvenile nematodes, broadly irrespective of which cell type they infect (Golinowski *et al.*, 1997), can develop into either males or females. Females will continue to engage in communication with the plant for several weeks until they lay eggs and ultimately die. Males, however, disengage from the feeding site, moult, regain motility, and leave the root in search of a female. It is widely accepted that some metabolic signal, directly or indirectly, from the host is responsible for this developmental decision. Recent work on the topic proposes an interesting model where male development represents the default pathway – that is, the default is to stop engaging in communication with the feeding site – and this can be overridden by a female sex determinant(s) (Schaveling *et al.*, 2026). Supporting the plausibility of such a mechanism, unrelated work suggests that plant-parasitic nematodes can perceive and respond to ingested plant-derived metabolites (Maxwell *et al.*, 2025).

In summary, plant–nematode interactions are not a simple sequence of attack and defence, but a continuous exchange of information in which each partner shapes the developmental trajectory of the other. At each transition of the parasite's life cycle (Fig. 1) both partners emit, perceive, and respond to chemical cues originating from the other, with wider participation of the rhizosphere residents. Parasitism is driven by dynamic cross-kingdom communication in which known signals account for only part of the conservation – the consistency and precision of nematode development imply further layers of communication that are yet to be identified. Understanding these hidden signals may prove more beneficial than fully understanding the ones we are already aware of.

Acknowledgements

CAB is supported by a BBSRC Discovery Fellowship (BB/X009823/1). Work on plant-parasitic nematodes at the University of Cambridge is supported by DEFRA licence 125034/359149/3, and funded by BBSRC grants BB/R011311/1, BB/S006397/1, BB/X006352/1, and BB/Y513246/1, a Leverhulme grant RPG-2023-001, and a UKRI Frontier Research Grant EP/X024008/1, Royal Society research grant RGS\R1\231239, the Gatsby Charitable foundation, and through the Cambridge-Africa ALBORADA Research Fund.

Competing interests

None declared.

Author contributions

CAB, LD and SE-vdA reviewed the literature and wrote the manuscript.

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