Review

Pathogenesis, parasitism and mutualism in the trophic space of microbe–plant interactions

Adrian C. Newton[1], Bruce D.L. Fitt[2], Simon D. Atkins[2], Dale R. Walters[3] and Tim J. Daniell[1]

[1] Scottish Crop Research Institute, Invergowrie, Dundee DD2 5DA, UK
[2] Rothamsted Research, Harpenden, Herts AL5 2JQ, UK
[3] Scottish Agricultural College, West Mains Road, Edinburgh EH9 3JG, UK

Microbe–host interactions can be categorised as pathogenic, parasitic or mutualistic, but in practice few examples exactly fit these descriptions. New molecular methods are providing insights into the dynamics of microbe–host interactions, with most microbes changing their relationship with their host at different life-cycle stages or in response to changing environmental conditions. Microbes can transition between the trophic states of pathogenesis and symbiosis and/or between mutualism and parasitism. In plant-based systems, an understanding of the true ecological niche of organisms and the dynamic state of their trophic interactions with their hosts has important implications for agriculture, including crop rotation, disease control and risk management.

Categorising microbe–plant interactions

Microbial organisms associated with plants have been categorised as 'pathogens', 'parasites', or 'mutualists', and these can be considered as the three extreme types (Figure 1). Thus, relationships ranging from mutualistic, where both plant and microbe benefit, to parasitic, where the microbe receives some benefit from the interaction at the expense of the host, can all be considered as symbiotic (Glossary). Parasites colonise their host but cause only what might be described as collateral damage by their physical presence and by taking resources from their hosts. By contrast, pathogens can actively damage the host plant for their own trophic benefit, frequently causing necrosis. However, new evidence from, for example, molecular detection methods is revealing that many microorganisms enter several different relationships with plants during their life cycles [1,2]. If microbes are placed in discrete categories it does not take into account the dynamic nature of these interactions that are crucial to the reproduction of both the plant and microbe and can be altered in favour of the microorganism or plant host. In an agricultural context, it is normally the grower's aim to favour the plant host and to eliminate the microorganism(s) if they are known only as pathogens. However, this might not always be the best strategy; some microorganisms currently regarded as crop pathogens can complete their life cycle on the same crops or other plant species without causing disease because they remain asymptomatic parasites or even mutualists (i.e. providing benefit to the host).

If pathogenesis, parasitism and mutualism describe important attributes of the relationship between microbes and plants, to influence the dynamics of these interactions it is necessary to understand how a specific relationship fits within these three categories at any given time during the microbial life cycle. For example, in an agricultural context, it could mean that application of a fungicide might increase yield when it is timed to prevent the interaction entering a pathogenic phase, but this might reduce yield if timed so that it damages a mutualistic trophic interaction.

The key to sustainability of semi-natural and agricultural communities is to manage the status of the interactions between all component organisms. This review aims to demonstrate the need to determine the dynamic nature and balance of ecological relationships between microbes and their plant hosts in order to moderate these interactions effectively. This review will not consider the phenomenon of latency, whereby a necrotrophic pathogen

Glossary

Biotroph: 'an organism that can live and multiply only on another living organism' [66]. This definition should apply only to obligate biotrophs and might, such as with parasitism, involve some detriment to the host organism.
Commensalism: 'a relationship between two species in which one species benefits and the other is not affected either negatively or positively' [66].
Endophyte: 'an organism which completes its life cycle in a plant which shows no external sign of the infection' [67].
Hemi-biotroph: Literally, half biotroph.
Mutualism: 'a mutually beneficial relationship between two species, especially an obligate mutually beneficial relationship without which neither can survive' [66].
Necrotroph: 'an organism that feeds on dead tissues or cells' [66].
Parasitism: 'a relationship between two species in which one, the parasite, benefits from the other, the host; it usually also involves some detriment to the host organism' [66].
Pathogenesis: 'the source or development of a disease or disease process. *Cell Biology*. in particular, the cellular events and reactions occurring during the disease development. *Medicine*. (Pathogenic) giving rise to morbid tissue changes or to a pathological condition by which a diagnosis can be made' [66].
Symbiont: 'an organism that forms a close association with another organism' [66]. A symbiont can be categorised as mutualistic, commensal, or parasitic in nature.
Trophic: 'of or having to do with nutrition or the nutritive process' [66].

Corresponding author: Newton, A.C. (adrian.newton@scri.ac.uk).

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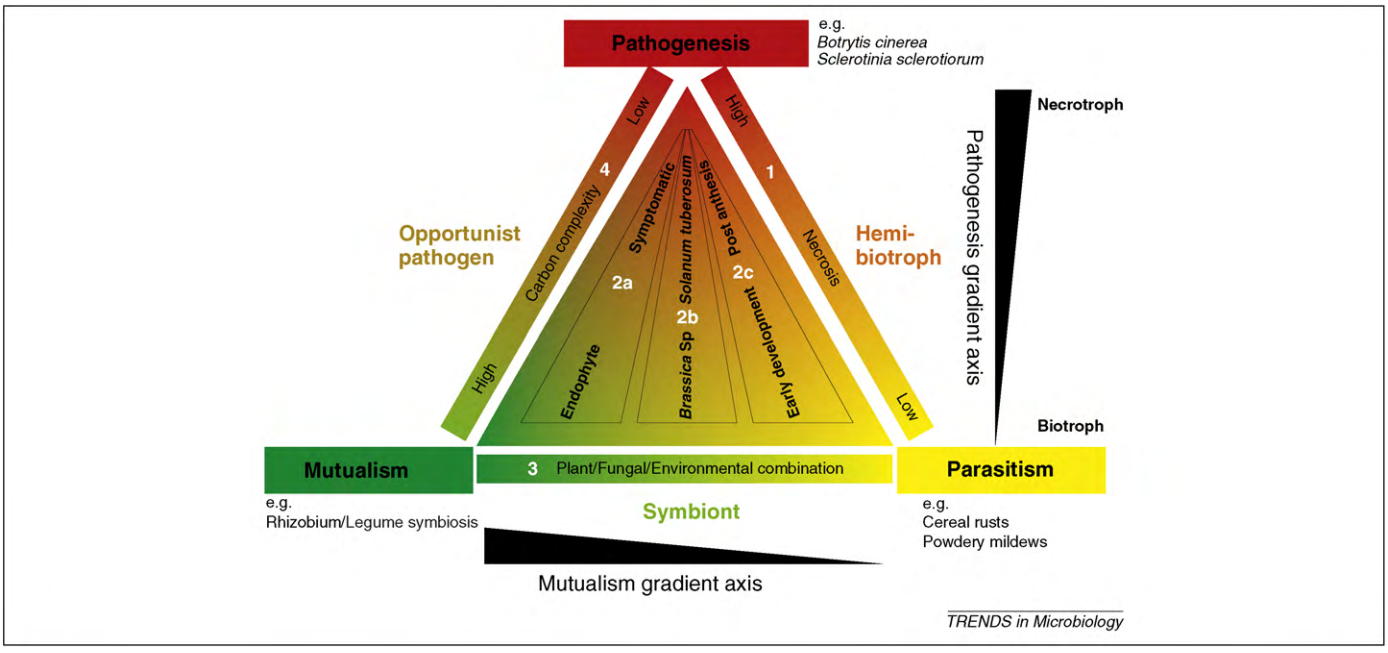

Figure 1. Trophic space occupied by microorganisms in association with plants. The range of trophic relationships of example microbe–plant associations is represented as space occupied between the three key trophic states of pathogenicity, mutualism and parasitism at the corners of the triangle. The vertical axis represents a gradient of pathogenesis from necrotroph to biotroph. The horizontal axis represents a gradient from mutualism to parasitism for symbiotic relationships. Individual organisms can predominantly occupy specific trophic spaces in these ranges, but frequently change between different trophic states during different stages of their life cycles in response to environmental, host developmental or microbe-specific triggers (Table 1, Figure 2). Examples of trophic interactions: 1, *Rhynchosporium secalis* on *Hordeum vulgare*; 2a, *Ramularia collo-cygni* on *Hordeum vulgare*; 2b, *Pectobacterium atrosecticum* on *Brassicae* and *Solanum tuberosum*; 2c, *Leptosphaeria maculans* on *Brassica napus*; 3, arbuscular mycorrhizal symbioses; 4, *Ceratobasidium cornigerum* on *Goodyera repens*.

remains in a quiescent state until stimulated by a host physiological change to reinitiate growth.

Microbes that cause plant diseases with both pathogenic and parasitic or mutualistic phases in their life cycles

Plant life cycles in both agricultural and semi-natural plant communities include seed dispersal, plant establishment, and a growth phase leading to reproduction and new seed (Figure 2). The extent of damage caused by pathogens can vary greatly, depending on the length of time they spend in pathogenic phases (e.g. causing necrotic lesions) or in asymptomatic parasitic or mutualistic phases. Microbes might behave as pathogens only at certain stages of their life cycle or under specific circumstances.

At one extreme, necrotrophic pathogens such as *Botrytis cinerea* (grey mould) and *Sclerotinia sclerotiorum* (stem rot) generally kill host cells when they are actively growing to provide themselves with food resources [3] (Figure 1, Table 1). At the other extreme, it is less clear whether obligately biotrophic microbes feeding on living host tissues, referred to as pathogens (e.g. rusts and powdery mildews on cereals), should be classed as symbiotic parasites because they frequently do not actively cause damage to their hosts even though they use host resources as a source of food. There can be long periods of symptomless growth before appearance of symptoms (often sporulation) associated with loss of photosynthetic tissue by the host, and necrotic lesions are generally absent. Between these extremes are hemi-biotrophic pathogens, such as *Phytophthora infestans* (potato late-blight), that can also have symptomless biotrophic growth phases in their life cycles before necrotic lesions are formed [4]. Here we use the broad definition of hemibiotrophy that includes pathogens with biotrophic, symptomless phases in their life cycles where they feed on living host tissues and not just those that form haustoria [5]. Another example of a 'pathogen' that causes disease but initially has an asymptomatic biotrophic (endophytic) phase is *Ramularia collo-cygni* (barley ramularia leaf spot). Developmental events associated with crop anthesis (flowering) appear to induce a change from a benign or beneficial biotrophic endophytic association between pathogen and host to a damaging relationship resulting in necrotic lesions. Necrosis results from the effects of light-dependent rubellin toxins that allow the pathogen to access resources for sporulation by destroying host cells [6,7]. Occurring after anthesis, this exploitation of host resources could be of little cost to a wild plant but of much greater cost to crop plants where the source–sink switch at anthesis is followed by a period of extended fruit or grain-filling; therefore the necrotrophic activities of the erstwhile biotroph can be very economically damaging.

The application of new methods [e.g. green fluorescent protein (GFP)-labelled pathogens to visualise and quantitative PCR to quantify pathogen biomass in symptomless tissues] has generated new insights into the distinction between symptomless biotrophic and necrotrophic pathogenic phases in the life cycles of the hemi-biotrophic pathogens *Rhynchosporium secalis* (barley leaf blotch [8]) and *Leptosphaeria maculans* (phoma canker on stems of oilseed and vegetable brassicas [9]). In barley crops, typical necrotic rhynchosporium leaf lesions (Figure 3a) might not form until months of symptomless growth have elapsed [8,10] in both resistant and susceptible cultivars (Figure 3b,c).

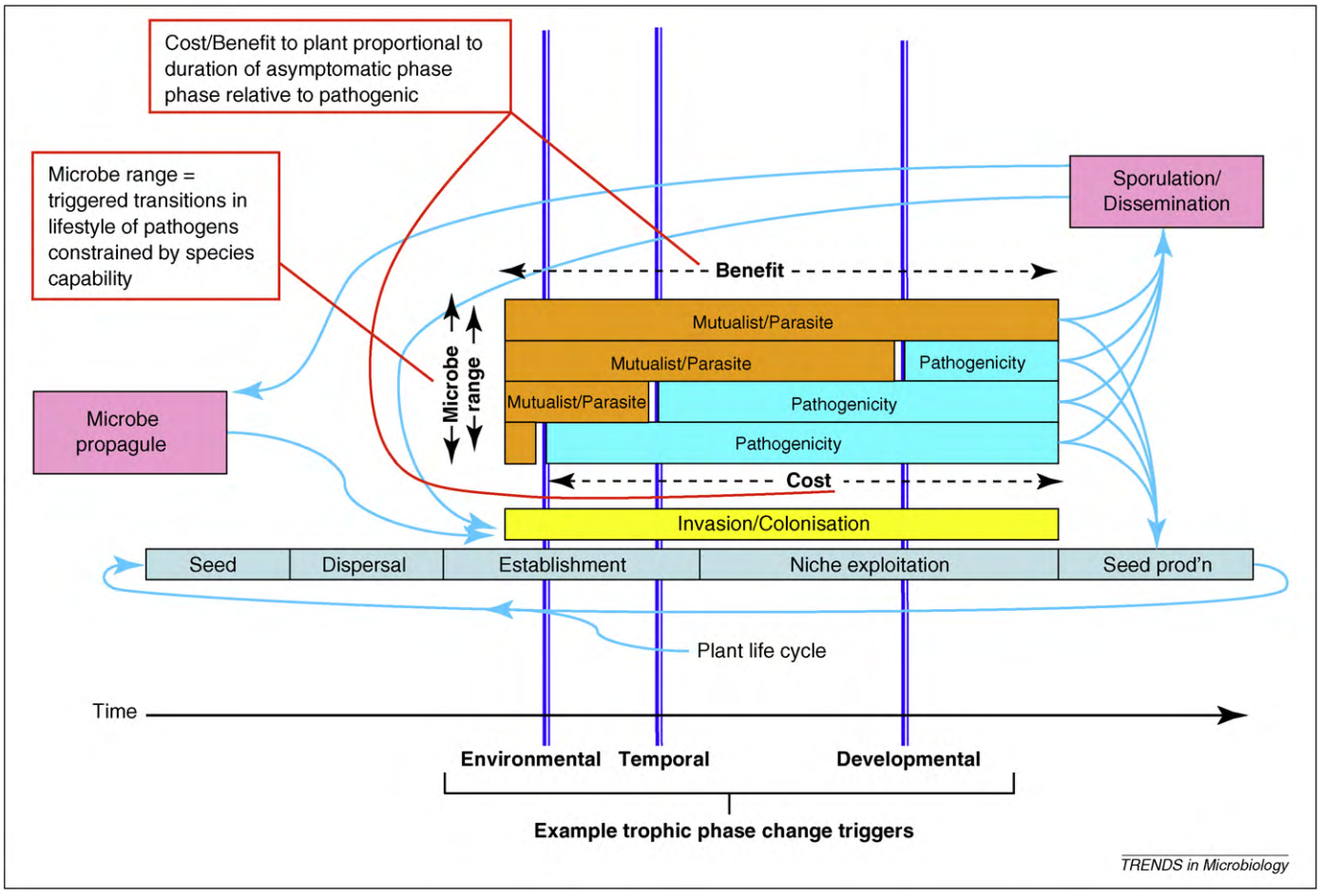

Figure 2. Triggers that differentiate symptomatic and asymptomatic interactions between host plants and microbes. Typical plant life-cycles progress from seed, through dispersal and establishment, to exploit their ecological niche and then produce new seed for dispersal. Microorganisms associated with plants use the same environmental triggers, plant developmental triggers and plant dispersal mechanisms in different ways to promote their life cycles, depending on their trophic and dissemination requirements.

During this period of symptomless growth, *R. secalis* sporulates profusely (Figure 3d) and spore dispersal by rain-splash can spread epidemics throughout crops. It is likely that environmental factors trigger the sudden appearance of necrotic symptoms in late winter over large areas of previously symptomless infected barley crops. By contrast, the two symptomless phases of *L. maculans* influence epidemics in winter oilseed rape very differently. In Europe, at first, there is a short symptomless phase after infection of leaves by ascospores in autumn, followed by the formation of necrotic phoma leaf spots after a few weeks (Figure 3e) [11,12]. These spots then provide a food base to

Table 1. Examples of microbe–plant interactions in different categories

Microbe example	Current classification	Triggers for pathogenesis[a]	Trophic space classification
Botrytis cinerea	Necrotrophic pathogen	Host detection	Pathogen
Sclerotinia sclerotiorum	Necrotrophic pathogen	Host detection	Pathogen
Rhynchosporium secalis	Hemi-biotrophic pathogen	Environmental and epidemiological[b]	Hemi-biotroph[c]
Phytophthora infestans	Hemi-biotrophic pathogen	Temporal	Hemi-biotroph
Moniliophthora perniciosa	Hemi-biotrophic pathogen	Fungal trigger	Hemi-biotroph
Pseudomonas syringae	Hemi-biotrophic pathogen	Quorum sensing	Hemi-biotroph
Ramularia collo-cygni	Endophyte/pathogen	Developmental and environmental	Hemi-biotroph
Pectobacterium atrosepticum	Symbiont/pathogen	Host-induced	Hemi-biotroph
Leptosphaeria maculans	Hemi-biotrophic pathogen	Temporal and developmental	Hemi-biotroph
Puccinia striiformis f.sp. *tritici*	Biotrophic pathogen	None	Parasite
Blumeria graminis f.sp. *hordei*	Biotrophic pathogen	None	Parasite
Pirosporoforma indica	Non-pathogenic endophyte	None	Symbiont
Arbuscular mycorrhizal species	Mutualistic fungi	None	Symbiont
Ceratobasidium cornigerum	Mutualistic fungus	Carbon status	Hemi-biotroph
Rhizobium species	Mutualistic bacteria	None	Mutualist

[a]i.e. symptoms – excludes disease expression, which is influenced by environmental (e.g. temperature) and genetic (e.g. partial resistance) factors.
[b]e.g. inoculum concentration.
[c]Hemi-biotroph: occupying the trophic space between biotroph and necrotroph, requiring signal(s) or triggers to change state but able to complete life cycle in either state. Non-pathogenic state, quiescent hemi-biotroph; pathogenic state, induced hemi-biotroph.

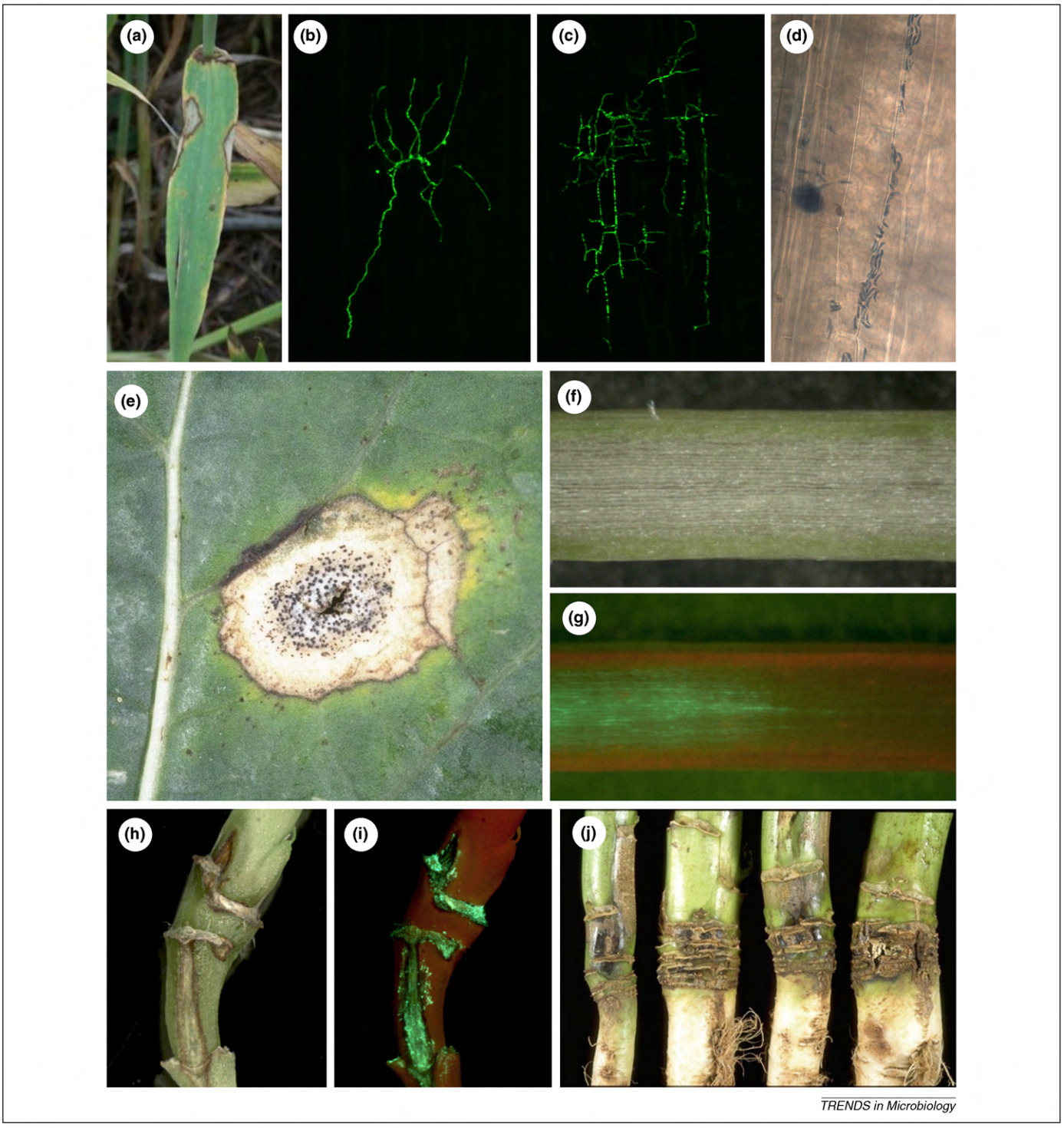

Figure 3. Cereal and brassica plants showing extensive asymptomatic infections. **(a)** On a cereal plant (barley), *Rhynchosporium secalis* can produce typical pale necrotic lesions with dark brown borders but it frequently grows without symptoms in the subcuticular layer of leaves of both **(b)** resistant (cv. Osiris) or **(c)** susceptible (cv. Digger) cultivars, as shown 10 days after inoculation with a GFP-expressing isolate. **(d)** During such symptomless growth it might sporulate profusely (cv. Sumo); these spores can spread the pathogen to new plants in the absence of visual symptoms. **(e)** On a brassica plant (oilseed rape), *Leptosphaeria maculans* produces typical pale necrotic lesions with brown borders containing distinctive pycnidia on leaves in autumn. **(f)** It then spreads without symptoms along the petiole of these leaves, as shown with a GFP-expressing isolate viewed 20 days post inoculation of leaves (cv. Eurol) viewed with brightfield illumination or **(g)** a GFP2 filter to reach stem tissues at the site of **(h)** leaf scars (47 days post inoculation) as viewed with brightfield illumination or **(i)** a GFP2 filter. **(j)** At these sites, brown necrotic lesions develop to form typical phoma stem cankers (cv. Lipton).

support a second symptomless phase, lasting up to eight months, when *L. maculans* spreads from the leaf spots along veins and traverses the petiole to reach the stem at the site of leaf scars (Figure 3f,g) [13]. The fungus continues to colonise stem tissue symptomlessly (Figure 3h,i) until damaging cankers form in the spring, possibly in response to changes in host development during flowering (Figure 3j). Quantitative resistance against *L. maculans* operates to slow its growth during this second symptomless phase [1].

Pseudomonas syringae is a classical hemi-biotrophic bacterial pathogen that expresses no symptoms while

multiplying first on the leaf surface and then in the apoplast. However, when the population size exceeds a quorum sensing threshold, this triggers the formation of lesions associated with symptoms such as bacterial speckle of tomato (*P. syringae* pv. *tomato* [14]). Quorum sensing regulated properties might also be the basis of the inoculum threshold effects in fungal pathogens, because *Candida albicans* and *Saccharomyces cerevisiae* have similar mechanisms for evoking species-specific behaviour change [15–17].

The bacterial pathogen *Pectobacterium atrosepticum* (formerly *Erwinia atroseptica*), the cause of potato blackleg, is commonly found associated with the roots of other host plants, particularly brassicas [18]. This association is probably attributable to brassica root-adhesion and nitrogen-fixation-associated genes found in *P. atrosepticum*. These were identified by sequence comparison with other bacterial genomes and subsequent identification of genes unconnected with its known pathogenic lifestyle, often clearly acquired by horizontal gene transfer [19]. Such organisms might therefore normally have benign lifestyles, or confer benefits on their hosts, but simply be opportunistic pathogens in certain agricultural situations. Thus they need to be managed appropriately to maintain their benefits, but to reduce the risk of disease, crop rotation sequences that potentially increase amounts of inoculum must be avoided.

Expression of visual disease symptoms can be controlled by a range of different mechanisms. *In planta* growth of cereal rust and powdery mildew biotrophic parasites is characteristically limited by either specific major gene resistance (which is frequently rendered ineffective by changes in pathogen populations) or non-host resistance, both of which prevent or strongly limit growth [20,21]. However, some forms of non-host resistance allow extensive colonisation of the host (including sporulation), allowing the microbe to complete its life cycle without development of macroscopic symptoms [22]. Whereas traditional classification of organisms as pathogens inevitably focuses attention on their ability to cause disease symptoms, this classification could underestimate the importance of other phases of their life cycles that might be important in terms of ecosystem function.

Microbes not recognised as pathogens that colonise plants

The root surface (or rhizoplane) and surrounding rhizosphere support complex microbial communities that can influence nutrient availability and the ability of opportunistic pathogens to colonise roots [23]. Such microbial diversity is likely to be important in impeding infection by pathogens [24,25]. Wheat rhizosphere microbial communities have been shown to differ between wheat cultivated in a continuous monoculture and wheat grown after a break crop [26]. Furthermore, there is growing evidence that genotypes of wheat might differ in their microbial communities, including their ability to support the growth of beneficial *Pseudomonas* species [27–29]. Such variation can influence the growth of subsequent crops [30]. Some wheat genotypes can suffer greater yield losses than others when they are grown after another wheat crop (see Recommended Lists at: www.hgca.com), possibly because they support different microbial rhizosphere communities with either direct or indirect effects on interactions with pathogens, including *Gaeumannomyces graminis* var. *tritici* ('take-all'). Indeed this relationship has been studied more intensively in natural systems, where such plant–soil feedback phenomena have been linked to succession [31].

Interactions within the rhizosphere provide excellent examples of interactions traditionally considered to be mutualistic, including the symbiosis of legumes and rhizobium bacteria, and woody hosts and mycorrhizal fungi (Figure 1). The microbes are symbiotic biotrophs, feeding on living host tissues in such as way as to benefit their plant hosts (e.g. through provision of nitrogen or other nutrients to the host). In the legume–rhizobium symbiosis, microbially-fixed nitrogen in root nodules is exchanged for plant-produced carbon. Arbuscular mycorrhizal fungi form symbiotic relationships with the majority of land plants, providing plants with benefits such as enhanced uptake of nutrients (particularly phosphorus) and water and increased resistance to pathogens, whereas the plant provides the mycorrhizal fungi with their only source of carbon [32]. However, the effects of these symbioses are variable, depending on both plant host and fungal species [33]. A relationship can become parasitic when the fungus removes more carbon than the relative benefit it provides to the host plant, resulting in stunted plant growth. It is difficult to demonstrate this because the natural state of most plants is mycorrhizal (making suitable controls difficult), and microbes can provide important protection against pathogens [34]. By contrast, there are also examples where (parasitic) plants provide little or no carbon to fungal partners, or even take resources from them [35,36].

Examples of transition from a mutualistic to a pathogenic relationship are few. The relationships between orchids and their mycorrhizal partners are poorly understood. The relationship might favour the plant, certainly early in its development, with many plants maintaining such a relationship throughout their life cycle [36]. However, there are examples where a mutualistic symbiosis is established, for example between *Goodyera repens* and *Ceratobasidium cornigerum* where carbon exchange with the fungus in adult plants has been demonstrated [37]. However, the first stages of colonisation of the seedling by the fungus are crucial for the outcome of the symbiosis. It has been demonstrated *in vitro* that the balance of the symbiosis is precise, with the nature of the fungal interaction determined, at least in part, by the carbon status of the medium – high carbon complexity (e.g. cellulose) results in a symbiotic relationship whilst replacement with an equal concentration of relatively simple carbon compounds results in a pathogenic interaction with soft rot symptoms and subsequent destruction of the seed [38]. All plants maintain relationships with a plethora of microorganisms with many being beneficial to some or all partners at some or all stages of their life cycles. Despite a relative paucity of data, it is clear that relationships are dynamic and responsive to their environment.

Trophic space and signals that cause changes between microbial life-cycle phases

These relationships between microorganisms and their host are essentially determined by specific environmental, temporal or developmental triggers (Figure 2). The dynamics of the relationships can be described by the changes in trophic interactions that take place as each partner goes through different stages that depend on the phases of the life cycles of both organisms. Such interactions can be represented as trophic spaces occupied in the continuum between pathogenic, parasitic and mutualistic states (Figure 1). In this representation, the vertical axis ranges from symbiotic biotrophy to pathogenesis, whereas the horizontal axis ranges from mutualism to parasitism (Figure 1). The organisms occupying the centre of this trophic space can be described as hemi-biotrophs; they can be quiescent or induced hemi-biotrophs depending on their state (position on the vertical axis), with changes between trophic states often initiated by triggers (Figure 1).

The triggering of the change to a symptomatic or pathogenic phase is important for dissemination and propagation of both the pathogen and its host. Ideally, this change should not induce excessive defence responses by the host plant nor compromise its reproduction. However, constraining host population size and vigour might be an integral component of successful long-term community dynamics to ensure niche occupation by the pathogen without resource exhaustion [39]. The key triggers for trophic changes in microorganisms are not well understood. Environmental stress factors can include light, nutrient, water and/or temperature stress, but some triggers are linked to pathogen inoculum or host developmental signals [40]. Whatever the actual signals, they are likely to indicate a decline in the availability of the nutrients or water that are necessary for continued survival. Both the stress- or developmentally-related triggers and the pathogen responses need to be quantified in molecular terms in stressed plants. To achieve this, a broad range of host and pathogen genes will need to be assayed for changes in their regulation across specific stress interactions for a range of key time-points. Study of these interactions might provide an ideal system to gain an understanding of differences in gene expression associated with different symbiotic or pathogenic states.

Changes in trophic relationships can also be induced by the microorganism directly (e.g. quorum sensing) or indirectly through manipulation of host defences using hormones and hormone mimetics [41]. For example, the pathogen causing witches' broom disease of cocoa, *Moniliophthora perniciosa*, produces five times more salicylic acid (SA) in infected brooms (dense shoot deformity) than do healthy shoots [42]. The SA pathway can downregulate the jasmonic acid (JA) signalling pathway, which is involved in resistance to insect herbivores and necrotrophic pathogens [43,44] and therefore probably render host tissue susceptible to the necrotrophic phase of the fungus. Chaves and Gianfagna [39] speculated that *M. perniciosa* might have acquired the ability to produce SA, facilitating its evolution from a biotrophic endophyte to a hemi-biotrophic pathogen. The hemi-biotrophic bacterial pathogen *P. syringae* has also been shown to induce systemic susceptibility to subsequent *P. syringae* infection in *Arabidopsis* [45]. This systemic induced susceptibility was caused by the pathogen-produced toxin, coronatine, a JA mimetic that could block the SA pathway, rendering host tissues susceptible to the biotrophic phase of the pathogen.

Plant genotype functionality, such as responsiveness to stress and resource utilisation, can be enhanced by the presence of endophytes; for example *Piriformospora indica* in barley [46] does not change to a pathogenic state. *P. indica* is thought to achieve mutualism through interference with host cell death mechanisms [47]. In fact, there is probably a bacterium associated with the fungus [48] that confers on the host salt tolerance (through increased production of antioxidants) [49,46], and enhanced systemic resistance (through the jasmonate pathway) [50] against pathogens such as *Fusarium graminearum,* because the bacterium alone confers similar properties [51]. Other endophytes can be effective against pests such as weevils [52]. Furthermore, having a heterogeneous assemblage of bacterial or fungal endophytes could be correlated with plant functionality [29].

Asymptomatic fungal infections of semi-wild grasses are common (cryptic infections) and observed in all parts of plants, although some are confined to roots or foliage, and the primary route of transmission is often by infection of seed [53]. The fungi involved in these colonisations are often the same or closely related species of pathogens of cultivated or wild plants [54]. To understand the dynamics of host–microbe interactions in the pathogenic, mutualistic or parasitic continuum, we must understand the triggers that control the transitions between trophic states.

Impacts on plant reproduction and yield

Pathogens are often widespread in agriculture, whereas in natural ecosystems they are present but not normally dominant [55]. Crop genotypes have generally been bred to maximise the yield of an economically-desirable part (e.g. seed, fruit) and to minimise their diversity to improve agronomic 'efficiency' [56]; both these trends frequently conflict with ecological advantage [57]. For example, cultivated cereals have been bred to have an extended grain-filling phase which produces larger grain, whereas in natural ecosystems plants with more, smaller grain, which disperses more readily, might have a selective advantage.

Host genotypes that are infected by pathogens but sustain little loss in economic yield are considered tolerant. Although in an agricultural context host tolerance is normally associated with infection by pathogens [58], the tolerance might also involve interactions with symbiotic mutualistic or parasitic microorganisms because it is a measure of interactions or responses to microbial coexistence and not just to pathogens recognised by symptoms. Crop genotypes that are tolerant suffer less loss in economic yield than would be expected from the amount of (visible) disease. It is possible that crop tolerance involves interactions with a range of microbes and that apparent tolerance of a host to a pathogen could result from its preferential interaction with beneficial organisms. This could affect the pathogen's ability to induce damage or

decrease yield. The yield loss for a given severity of disease might be less in some crop genotypes than others because the genotypes differ in the extent to which they are colonised asymptomatically by a mutualist or a beneficial phase in the life cycle of a pathogen. Wheat genotypes are known to differ in their tolerance to foliar diseases such as septoria leaf blotch [59] and there is also evidence that genotypes of barley and other crops differ in disease tolerance [58]. Thus, as for pathogenicity, the concept of tolerance is best understood in an ecological context where the effects of both symptomatic and asymptomatic infection are considered.

The peculiar status of certain pathogens defined by their recognition as causal agents of crop plant disease is illustrated by *Ramularia collo-cygni* [6,7]. In its asymptomatic biotrophic phase, *R. collo-cygni* might be expected to be mutualistic and confer some benefit to the host during that stage of the plant life cycle in order to offset any damage conferred when the fungus changes to a pathogenic phase to provide resource for fungal reproduction and dissemination. Whereas in natural vegetation these effects might be in ecological balance, in agriculture they are not – at least during the extended grain-filling stage when the damage occurs. Therefore we would expect that, if the trigger(s) for the pathogenic phase change were not received, and the infection continued to be mutualistic, then the benefits would also continue, and be expressed more strongly in a crop. Preliminary data indicates that this is the case in barley where enhanced asymptomatic infection is correlated with enhanced yield in several cultivars.

In a food security context, tolerance should assume greater importance because it is an aspect of resilience, and both concepts are important components of a sustainable agro-ecosystem. Hitherto, tolerance has largely been considered in terms of its genetic and physiological basis. Ecological interactions, which will have genetic and physiological components, are likely to have similar or greater importance.

Consequences for crop management

Management of infection by microbes that can become pathogenic is clearly important for minimising both their direct impact on crop yield and their potential impact through generation of new, more pathogenic, races. However, this is still a pathogen-centred view of crop health, whereas a broader perspective of the balance between the organisms that comprise the crop ecological community, both above and below ground, is likely to result in more sustainable practices. This might be characterised as a change from management to eliminate pathogens to management to favour predominance of beneficial organisms and to confine potential pathogens to their asymptomatic, stable states. To achieve this, the control strategy might change from use of broad-range fungicides to use of narrowly targeted fungicides or resistance-inducing approaches. Alternatives to fungicides, such as resistance elicitors, might offer the potential for selective efficacy. This is because they can work through priming of broad-spectrum defence pathways, where resistance mechanisms are expressed only when potential pathogens change to pathogenic phases [60]. Although many resistance elicitors have been identified, and some are available as products on the market [61], there is a need to extend current knowledge of pathogenicity triggers in order to successfully exploit this crop management approach.

Minimising the impact of disease control on non-target organisms is important but is difficult to achieve, even with more biologically-based approaches. For example, because induced resistance generates defence against a broad spectrum of microbial pathogens, it seems reasonable to assume that it affects a wide range of microbes (e.g. phytobacterial communities). Although any effects of induced resistance are likely to be greatest for endophytic communities, epiphytic and rhizosphere communities might also be affected. Recently a comparison was made between endophytic and epiphytic bacterial communities on two mutants of *A. thaliana* deficient in SA and JA signalling pathways [62]. The results revealed that induction of SA-mediated defences reduced endophytic bacterial community diversity, whereas epiphytic bacterial diversity was greater in plants deficient in JA-mediated defences. Clearly, whatever crop protection approaches are adopted, a greater understanding of their effects on non-target microflora will be required.

Understanding the triggers for disease symptom expression, whether they are under pathogen, host, or environmental control, is likely to offer a robust strategy for achieving more durable resistance. Control of bacterial infection by quenching quorum sensing among plant pathogenic bacteria has been proposed as a transgenic approach, for example using expression of a bacterial auto-inducer inactivation (AiiA) protein [63]. Other mechanisms might be still more difficult to manipulate because they might represent basic developmental processes. Understanding environmental triggers will be helpful in disease forecasting as well as in developing new crop protection approaches.

Although approaches such as quenching quorum sensing are promising for control of target pathogens, avoidance of impacts on beneficial microbes will be challenging [64]. Asymptomatic infections by mildews on 'non-hosts', and by *R. secalis* of 'resistant' (showing no visual symptoms) barley, might also offer sources of durable resistance if the interactions are not associated with increased yield loss and can retain their expression in transfer. However, there could be fitness trade-offs associated with such resistance [65]. It is not clear whether such interactions should be classified as pathogenic or parasitic because there is no evidence that they actively cause damage to the host.

We advocate a more knowledge-based approach to crop management that will enable full use of molecular genetic understanding of microbe–plant interactions through all breeding and deployment approaches, including 'genetic manipulation'. The complex heterogeneity of multiple organism interactions builds resilience into host and microbial communities, leading to enhanced host function [56]. Tilting the balance in favour of beneficial organisms is crucial to the economic and ecological sustainability of the arable crop system. A more thorough understanding of all the organisms associated with crops and their trophic

relationships is required before effective crop management can be achieved.

Conclusions

It can be argued that associations which favour survival of all organisms in microbe–plant interactions are the ecological norm and that the pathogenic state is ecologically unsustainable in monocultures. Alternatively, it can be hypothesised that pathogenesis is just a functional phase of a life cycle where propagation of the microorganism is the appropriate priority at the expense of the host. This pathogenic phase is extended through the prolonged grain-filling phase in the context of a cereal crop, and this is unsustainable from an ecological perspective. Instead of attempting to eliminate potential pathogens, it might prove more effective, or sustainable, to develop breeding or crop-protection schemes that aim to manipulate trigger signals to favour more symbiotic, mutualistic states in their life cycles. Understanding the nature and control of trophic state-change triggers should therefore be a priority for research. This needs to be investigated in several microbe–plant associations because many mechanisms might be involved. Both the relative importance and dependence of different mechanisms must be understood. However, the past focus on understanding mechanisms of pathogenesis has also been to the detriment of understanding the mechanisms of symbiosis in the same organisms. To control disease in crops it could be as important to promote these mechanisms of symbiosis so as to avoid triggering pathogenicity mechanisms. Whether this objective is achieved by use of genetics, agronomy or applied crop-protectant fungicides to encourage beneficial microbial ecological interactions, or by a combination of these approaches, will be the outcome of such research. Understanding the basis of the relationships along the mutualism gradient axis can provide key insights into intimate microbe–plant interactions. In particular, it will define the trophic space occupied by active pathogenic, necrotic relationships. Clearly an understanding of the true ecological niche of organisms and the dynamic state of their trophic interactions with their hosts has important implications for agriculture, including crop rotation, disease control and risk management.

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