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ORIGINAL PAPER

A host-based approach for the prioritisation of surveillance of plant pests and pathogens in wild flora and natural habitats in the UK

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Abstract Non-native plant pests/pathogens are a mostly overlooked threat to biodiversity. Surveillance for plant pests and pathogens is key to early detection yet is rarely undertaken in natural habitats. Current methodologies to prioritise surveillance are pest-based, there is no methodology available to help managers identify 'at risk' hosts and habitats for targeted surveillance. This study compares four host-based methods. Prioritisation of: (1) plant genera known to host the pests/pathogens most likely to establish (Host-pest); (2) habitats known to host the greatest number of pests/pathogens most likely to establish (Habitat-pest); (3) plants classed as foundation species (those that drive ecosystem functioning and support populations of dependent biodiversity) (Foundation-species); (4) habitats with low plant species diversity and hence low resilience (Habitat-resilience). Twelve habitats and 22 heathland vegetation communities in the UK were used as a case-study. The Host-pest method gave 121 plant genera to monitor across all habitats and 14 within heathlands. The Habitat-pest and Habitat-resilience methods prioritised different habitats because the Habitat-pest method uses existing lists of pests which are biased towards those of commercial importance. The Foundation-species method gave 272 species for surveillance across all habitats and 14 within heathlands. Surveillance of habitats and plants prioritised on potential ecological impact (the Foundation-species and Habitat-resilience methods) is recommended rather than known pests/pathogens (the Host-pest and Habitat-pest methods) as this avoids biases within existing lists of pests/pathogens, removes the need for the prioritisation to be regularly updated as new pests/pathogens are identified and takes account of impacts on associated biodiversity and ecosystem functions.

Keywords Invasive · Monitoring · Pathogen · Pest · Plant health risk register · Wildlife disease monitoring

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Introduction

Non-native plant pests and pathogens, referred to here as pests throughout, can have a devastating impact on plant populations (e.g. Herms and McCullough 2014; Jacobs 2007; Potter et al. 2011; Wingfield et al. 2008). For example, the chestnut blight pathogen *Cryphonectria parasitica* killed billions of American chestnut trees following its introduction into North America in the early twentieth century. Dutch elm disease, *Ophiostoma novo-ulmi,* has killed millions of trees in Europe, North America and Asia and is still impacting trees where the last natural populations of elm remain (Brasier and Buck 2001; Brasier 2008). In Australia, South Africa and Europe the invasive pathogen *Phytophthora cinnamomi* continues to cause enormous damage to native woody ecosystems (Brasier 2008). Most recently, the ash dieback epidemic, caused by the invasive fungal pathogen *Hymenoscyphus fraxineus,* is estimated to have cost the UK around £15 billion due to associated loss of numerous ecosystem services (Hill et al. 2019). Large-scale declines in native plant species caused by plant pests can lead to a range of cascading effects on associated biodiversity (species that use the host plant for feeding, breeding and shelter) and ecosystem functioning, (Ellis et al. 2012; Gandhi and Herms 2010a, 2010b; Hultberg et al. 2020; Lõhmus and Runnel 2014; Lubek et al. 2020; Mitchell et al. 2014, 2019). Declines in plant populations caused by non-native pests have been described as an insidious, mostly overlooked threat to biodiversity (Jonsson and Thor 2012) and the cause of extinction cascades (Hultberg et al. 2020). The invasion of alien species, which includes non-native pests, are one of the five direct drivers of global biodiversity loss (IPBES 2019). Plant pests are therefore a serious threat to the conservation of our biodiversity.

Surveillance is fundamental to the early detection of pests, allowing time for control measures to be implemented. National plant protection organisations have the responsibility for the surveillance of growing plants, both cultivated and uncultivated, including wild flora (European Food Safety Authority et al. 2020a). Surveillance for plant pests is usually targeted at specific pests in response to regularly requirements (European Food Safety Authority et al. 2020a) and prioritisation based on the risk of the pest establishing, their potential economic impact, traits and potential routes of establishment (e.g. Barwell et al. 2021; Raffa et al. 2023). The priorities for surveillance of pests of wild flora may differ from that for pests of cultivated plants. For example, one may wish to prioritise pests of hosts that drive key ecosystem functions or support key biodiversity instead of prioritising pests that drive yield loss for cultivated plants. Thus, in natural habitats a host-based approach to identifying risk and surveillance may be more appropriate. Managers of natural habitats need to know which habitats and plants are at greatest risk from plant pests in order to (i) prioritise surveillance, (ii) know where to prioritise biosecurity e.g. during habitat restoration or creation or other land management operations likely to introduce pests and (iii) know where to prioritise resources should a pest establish.

Here we explore how a host-based approach for identification of wild flora and habitats at greatest risk from plant pests might work. For both hosts and habitats we compare two approaches (a) assessment based on known risks—lists of known pests and (b) assessment based on potential ecological impact (Table 1). Internationally there are existing lists of quarantine pests and many countries have their own risk registers of plant pests (e.g. Defra 2021b). Such lists may be used to identify hosts that support the greatest number of pests on such risk registers and habitats composed of hosts that support high numbers of such pests. An alternative is to identify plant species or habitats where pests would have the greatest ecological impact using ecological theories about a) foundation species and b) resilience and diversity. Foundation species are “a single species that defines

Table 1 The four methods for prioritisation of surveillance for plant pests in wild flora and natural habitats

What to monitor	Approach	
	Known risks	Potential ecological impact
Plant species/genera	*Host-pest*: plants known to host the greatest number of known pests that are most likely to establish prioritised	*Foundation-species*: species whose loss or decline would drive changes in populations of associated species and ecosystem services prioritised
Habitat	*Habitat-pest*: habitats that host the greatest number of known pests that are most likely to establish prioritised	*Habitat-resilience*: habitats with low species diversity which therefore might be less resilient due to lack of functional redundancy prioritised

The method names, used throughout the study, are shown in italics much of the structure of a community by creating locally stable conditions for other species, and by modulating and stabilizing fundamental ecosystem processes" (Dayton 1972). For example, *Quercus* trees in an oak woodland or *Calluna vulgaris* on a heather moorland. If a foundation species is lost or declines in abundance due to a pest than it will have a greater effect on the ecosystem than if non-foundation species are impacted (Ellison et al. 2005). One can therefore argue that if resources are limited, surveillance should be prioritised for foundation species. There is no list of foundation species on which to draw but, given the above definition, a simplistic assumption is that those species that occur at high abundance are most likely to be foundation species. Diverse communities are generally considered more stable and more resilient than less diverse communities (Dovciak and Halpern 2010; Naeem and Li 1997; Tilman et al. 2006). In part, this is because they are likely to have high functional redundancy with species able to substitute for each other if species are lost due to pests, because other species are present within the system that fulfil similar functions (Laliberte et al. 2010; Pillar et al. 2013; Rosenfeld 2002). Plant pests are likely to have a greater ecological impact on habitats with low resilience meaning that those habitats with low diversity should be prioritised. In addition, more diverse communities may reduce disease risk/damage by reducing disease transmission/pest persistence (Keesing and Ostfeld 2021). This study therefore compared two approaches for prioritising surveillance: known risk and potential ecological impact for each of plant species/genera and habitats giving four methods for prioritisation (Table 1): (1) 'Host-pest': those plant species or genera known to host the greatest number of pests that are most likely to establish; (2) 'Habitat-pest': those habitats known to host the greatest number of pests that are most likely to establish; (3) 'Foundation-species': those host species classed as foundation species and whose decline in abundance would drive changes in ecosystem functioning and cascading changes in the populations of dependent biodiversity; (4) 'Habitat-resilience': those habitats with low species diversity and hence likely to have low resilience due to a lack of other species occupying similar ecological niches.

To assess the potential advantages and disadvantages of the different methods this work used the UK as a case study. Using the UK Plant Health Risk Register (PHRR) (Defra 2021b) and the UK's National Vegetation Classification (NVC) system (Rodwell 1991a, b, 1992, 1995, 2000) the study aim to provide a prioritised list for 12 habitats across the UK and for 22 heathland vegetation communities to show how the methods might work at different scales.

Method

The analysis used two datasets: The UK Plant Health Risk Register (PHRR) (Defra 2021b) and the UK National Vegetation Classification (Rodwell 1991a, b, 1992, 1995, 2000).

The UK Plant Health Risk Register (PHRR)

The UK PHRR (Defra 2021b) provides information (e.g., host range, distribution and regulatory status) for more than 1000 plant pests. The pests include bacteria, fungi, insects, mites, nematodes, oomycetes, phytoplasma, viruses and viroids. The PHRR includes a likelihood (of occurrence) score, ranging from 1-low to 5-high. The calculation of the likelihood score differs depending on whether the pest is already present in parts of the UK (Defra 2021a). If the pest is absent from all parts of the UK then the likelihood score is composed of two sub-scores, those of entry into and establishment within the UK. The PHRR uses the lower of the two scores of entry and establishment: "This is because both entry and establishment are necessary for a pest to be introduced. The limiting step for introduction of a pest is therefore whichever component is least likely" (Defra 2021a). The UK PHRR usually only includes pests which are present in limited areas of the UK, not those that are present nationwide. For those pests already present in the UK the likelihood score is based on how likely the pest is to spread to maximum extent in the next five years. The PHRR provides likelihood scores both with and without mitigation. This study used the likelihood scores with mitigation assuming that all mitigations, such as import prohibition on the key hosts, had been implemented. The impact assessment from the PHRR were not used as this is largely based on the impact on commercial operations not the natural environment (Defra 2021a).

The PHRR is only searchable by pest (Baker et al. 2014). For each pest it provides a list of hosts contained as one data entry point (cell) in the spreadsheet. Thus, it is not possible to search the PHRR for a list of pests found on any one host. The PRHH was downloaded and the data manipulated to provide a separate record for each pest/host combination, allowing one to search by host and obtain a list of all pests listed on that host. The host name was further subdivided into host genera and host species to allow searches to be made at either genera or species level. This downloaded and manipulated dataset from the PHRR is termed PHRR-edited throughout.

The UK National Vegetation Classification (NVC)

The vegetation of the UK is classified by the National Vegetation Classification system (NVC). This lists 12 habitat types: Aquatic communities; Calcicolous grasslands; Heathlands; Mires; Maritime cliff communities; Mesotrophic grasslands; Open habitats; Swamps and tall-herb fens; Shingle, strandline and sand-dune communities; Salt Marsh; Calcifugous grasslands and montane communities; Woodlands. Open habitats includes, disturbed or colonising habitats, arable weed communities, weedy pastures, gates, paths, verges, wasteland and urban habitats (Rodwell 2000). Within each habitat are vegetation communities. In total, across the 12 habitat types there are 286 communities. In some instances, there are further sub-communities, but this study only used the habitats and the community level data. For each community, the NVC lists the frequency and abundance (percentage cover presented as Domin scores) of the plant species present. In this study the abundance data was used and, where a range was given the higher value was used.

Linking the datasets

The NVC and PHRR-edited were imported as two separate tables into an MS Access database (called combined database). The tables were linked at the plant genera level, i.e. both tables had a field for 'plant genera'. This allowed information for plant genera to be extracted from both tables. The tables were linked at the genera level rather than the species level as a) many native UK plant species are not included as hosts in the PHRR, rather their commercial varieties are included (Defra 2021a; Mitchell 2023b) and b) this takes account of pests establishing on new hosts within the same genera. For all the methods below bryophytes, lichens and algae were removed from the analyses as the PHRR does not include hosts from these taxonomic groups.

For each of the methods below the analysis was conducted at two levels; (a) at the habitat scale; (b) at the community scale. The study focused on the 22 communities within the heathland habitat as an example of how the methods may provide information at this scale. Unless otherwise stated, the study focused on plant species described within the NVC communities (Rodwell 1991a, b, 1992, 1995, 2000) as occurring with a Domin score of 6 or more (i.e. an abundance of more than 25% cover). Such species were thought to form a significant part of the community and would cause ecosystem change if loss or a decline in abundance resulted from a pest.

Methods: Host-pest and Habitat-pest

For the Host-pest method all the plant genera hosting at least one pest with a mitigated likelihood of 4 or 5, the highest two categories, were extracted from the combined database. Those genera that host the greatest number of pests are suggested as being most at risk and hence prioritised for surveillance. Lists of genera are provided for each habitat and then for each heathland vegetation community. The list of hosts from Host-pest method was then used to calculate which habitats or heathland communities could host the greatest number of pests with a mitigated likelihood of 4 or 5. Those habitats or heathland vegetation communities that hosted the greatest number of pests are suggested as being most at risk and prioritised for surveillance by this Habitat-pest method.

Method: Foundation-species

Plant species occurring at more than 75% cover in any plant community in the NVC were extracted. The assumption was made that those species occurring at high abundance are likely to be foundation species. It is acknowledged this is an oversimplification. However, (a) loss or decline of species occurring at more than 75% cover will have a major impact on community composition, even if they may not strictly be defined as foundation species; and (b) this provided a pragmatic approach to help managers identify what might be considered foundation species. A list of plant species categorised as foundation species, and thus suggested for surveillance, was produced for each habitat and for each heathland vegetation community. This methodology therefore prioritises foundation species irrespective of whether they are at risk from a known pest. The prioritisation is based on potential impact and allows account to be taken of the 'known unknown' pests.

Method: Habitat-resilience

The number of species in each vegetation community that occur at more than 25% cover were extracted. We fitted a generalized linear effect model with a Poisson distribution using the glm function within *lme4* (Bates et al. 2015) in R version 3.6.2 (R Core Team 2018) with habitat as the predictor and species richness as the response variable. We tested the significance of this glm using Chi squared. Secondly we ran Tukey's pair-wise comparisons to determine differences between pairs of habitats, and *P* values were adjusted using the Tukey correction method for multiple tests (Lenth 2019). For each habitat the average number of species per a community was calculated, and those habitats with the lowest average species diversity are suggested as being prioritised for surveillance. For the vegetation communities within the heathland habitat, those communities with the lowest species richness were suggested as being prioritised for surveillance.

Results

The PHRR lists 916 pests which could be hosted by genera that occur in natural habitats at more than 25% cover in the UK. When refined by the mitigated likelihood of the pests establishing with a likelihood of 4 or 5 (the highest two likelihood categories), the list reduces to 91 (Supplementary material Table S1). Fourteen of these have a likelihood of 5 and 77 have a likelihood of 4.

Surveillance based on host-pest methodology

There are 121 plant genera occurring at more than 25% cover that host pests with a mitigated likelihood of establishment of 4 or 5 (the highest two categories) (Table S3). In declining order of the number of pests hosted, the genera *Prunus, Solanum, Rosa, Fragaria, Acer, Salix, Ulmus, Lactuca. Rubus, Fraxinus, Pinus, Quercus, Betula, Viburnum, Allium, Brassica, Corylus, Iris, Juniperus* could all host 6 or more pests with a mitigated likelihood of 4 or 5. *Prunus* and *Solanum* host more than 20 pests. Thus, those genera with the potential to host the greatest number of pests would be prioritised for surveillance.

Across the 22 heathlands communities there are 14 plant genera that can host pests with a likelihood of 4 or 5 (Table 2) and should therefore be surveyed. The number of genera to survey per a heathland community was between one and seven (Table S4). There are consistent patterns across the different heathland communities with *Calluna, Erica, Festuca* and *Vaccinium* all highlighted for surveillance in ten or more of the 22 communities and the other ten genera only suggested for surveillance in five or less of the communities.

Surveillance based on habitat-pest methodology

When compared across all the habitat types, woodlands (87 pests) and open habitats (54 pests) have the potential to host the greatest number of pests listed in the PHRR with a likelihood (mitigated) of 4 or 5. Aquatic habitats and salt marshes, on the other hand, have the least at 9 and 14, respectively. This approach would therefore suggest prioritising surveillance towards woodlands and open habitats [i.e. those more disturbed communities, see Rodwell (2000)] (Fig. 1a).

If the analysis is refined to the 22 heathland vegetation communities, then it is possible to target communities at risk. If those communities able to host the greatest number of pests with a likelihood of establishment (mitigated) of 4 or 5 are prioritised, then the four communities *Calluna vulgaris-Scilla verna* heath (H7), *Vaccinium myrtillus-Cladonia arbuscula* heath (H19), *Calluna vulgaris-Ulex gallii* heath (H8) and *Vaccinium myrtillus-Racomitrium lanuginosum* heath (H20) (Fig. 2a) should be prioritised.

Surveillance based on foundation-species methodology

Two hundred and seventy-two plant species were identified that occur at more than 75% cover in plant communities across the UK (Table S5). However,

Table 2 Comparison of the genera/species suggested for surveillance for heathland communities in the UK under two different methods: Host-pest (genera known to host the greatest number of pests most likely to establish) and Foundation-species (species occurring at > 75% cover)

Genera	Species	Method	
		Host-pest	Foundation-species
Agrostis	*Agrostis capillaris, Agrostis curtisii*		*Yes*
Arctostaphylos		Yes	
Calluna	*Calluna vulgaris,*	Yes	Yes
Carex	*Carex arenaria, Carex bigelowii*		
Dactylis		Yes	
Empetrum	*Empetrum nigrum*		Yes
Erica	*Erica ciliaris, Erica cinerea*	Yes	Yes
Festuca	*Festuca ovina*	Yes	Yes
Genista		Yes	
Juncus		Yes	
Juniperus		Yes	
Molinia	*Molinia caerulea*		Yes
Nardus	*Nardus stricta*		Yes
Plantago		Yes	
Pteridium		Yes	
Rubus		Yes	
Salix		Yes	
Teucrium		Yes	
Ulex	*Ulex europaeus, Ulex gallii*		Yes
Vaccinium	*Vaccinium myrtillus*	Yes	Yes

See Table 1 for further details of methods

the number of species suggested for surveillance for any one habitat was considerably lower, ranging from 71 in woodlands to 11 in Calcicolous grasslands (Table S5).

The 14 species (Table 2) suggested as foundation species for surveillance in the heathland habitat may be further sub-divided within the 22 heathland vegetation communities (Table S6). Two communities, *Ulex minor-Agrostis curtisii* heath (H3) and *Calluna vulgaris-Ulex gallii* heath (H8), have five species for surveillance. One community, *Vaccinium myrtillus-Cladonia arbuscula* heath H19, has four species for surveillance and two communities (*Vaccinium myrtillus-Deschampsia flexuosa* heath (H18) and *Ulex gallii-Agrostis curtisii heath* (H4) have three species. This approach gives two communities with no foundation species for surveillance. *Calluna vulgaris-Racomitrium lanuginosum heath* (H14) only has bryophyte species occurring at more than 75% cover and this approach is focussed on surveillance of vascular plants. *Vaccinium myrtillus-Rubus chamaemorus* heath (H22) has no species that occur at more than 75% cover.

Surveillance based on habitat-resilience methodology

Habitat significantly influenced species richness ($\chi^2(11, N = 265) = 1705$, $p < 0.0001$) and there were significant differences between pairs of habitats in their species richness (Fig. 1b). Under this methodology those habitats with lower species richness would be prioritised for surveillance in declining order of priority: Salt Marsh, Swamps and tall-herb fens, Heathlands, Mires, Aquatic communities, Calcifugous grasslands and montane communities, Open habitats, Maritime cliff communities, Calcicolous grasslands, Shingle, strandline and sand-dune communities, Mesotrophic grasslands and Woodlands. However, there can be large variation in the species richness between communities within a habitat and therefore how resilient that community might be. Within the heathlands habitat (Fig. 2b) H21: *Calluna*

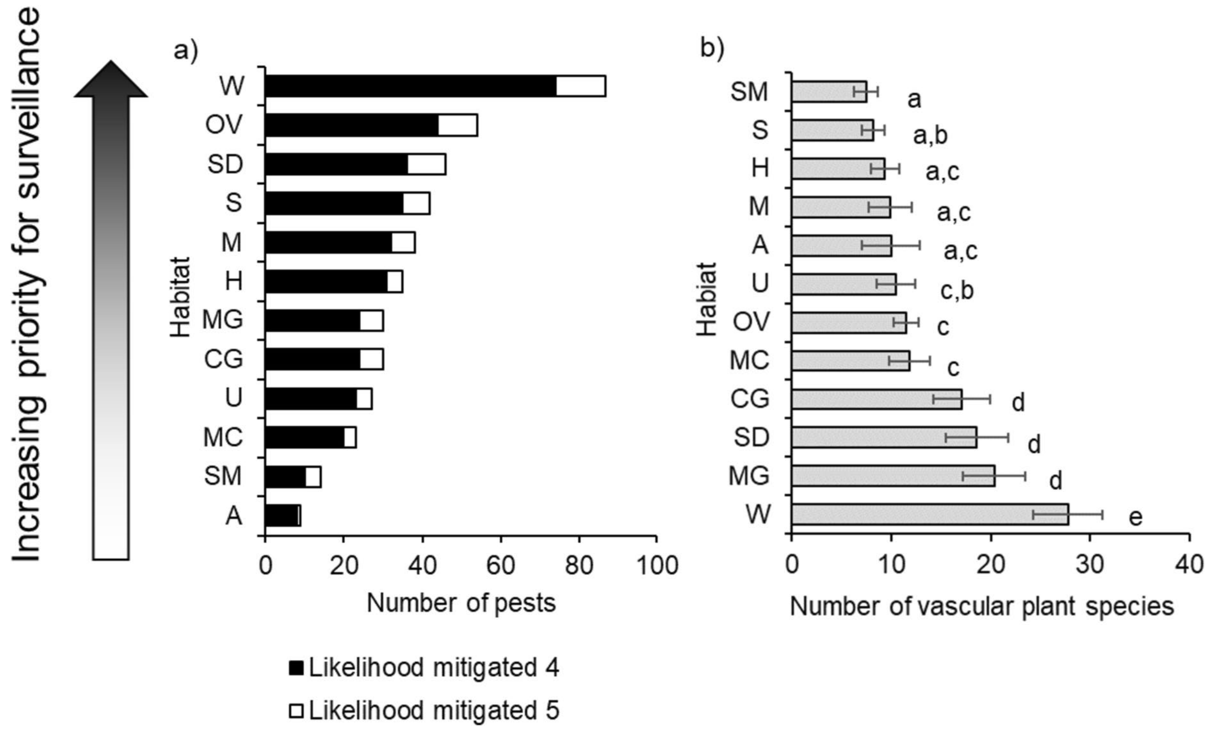

Fig. 1 Prioritisation of habitats in the UK for surveillance for plant pests when prioritised by: a) Habitat-pest: habitats known to host the greatest number of pests most likely to established (likelihood mitigated 4 or 5) as listed in the PHRR. b) Habitat-resilience: habitats with the lowest resilience, here defined as those with the lowest number of vascular plants occurring at > 25% cover. Mean number of vascular plant species at > 25% cover per community within each habitat shown ± 1SE. Bars with different letters are significantly different from each other ($p < 0.05$) as tested by Tukey pair-wise comparisons. A, Aquatic communities; CG, Calcicolous grasslands; H, Heathlands; M, Mires; MC, Maritime cliff communities; MG, Mesotrophic grasslands; OV, Open habitats; S, Swamps and tall-herb fens; SD, Shingle, strandline and sand-dune communities; SM, Salt Marsh; U, Calcifugous grasslands and montane communities; W, Woodlands

vulgaris-Vaccinium myrtillus-Sphagnum capillifolium heath is suggested as the least resilient, with only two species occurring at more than 25% cover and H8: *Calluna vulgaris-Ulex gallii* heath as the most resilient with 21 species occurring at over 25% cover.

Discussion

The work presents a unique 'host-based' surveillance approach for plant pests in natural habitats. The need for a host-based surveillance approach is similar to that for wildlife disease surveillance where there are many examples of the ranking of wildlife diseases for surveillance (e.g. Boadella et al. 2011; Ciliberti et al. 2015) but there have been few attempts to rank their hosts (Cardoso et al. 2022). The results from this work suggest that prioritisation of plant species or habitats for surveillance based on potential ecological impact (as assessed using ecological theory), rather than risk (known pests), provides a less biased (towards plants of commercial importance) list and allows for the detection of new pests, the known unknowns.

Traditionally surveillance for plant pests is pest specific and is usually directed at detecting quarantine pests (e.g. European Food Safety Authority et al. 2020a). Methods for forecasting which pests are most likely to be invasive and hence which ones to prioritise surveillance for include: using prior pest status in native and previously invaded regions (e.g. Eschen et al. 2014, 2015; Kumschick and Richardson 2013); use of pest traits and gene sequences (e.g. Barwell et al. 2021; Uden et al. 2023); evolutionary divergence time between native and novel hosts (e.g. Mech et al. 2019; Schulz et al. 2021); sentinel and

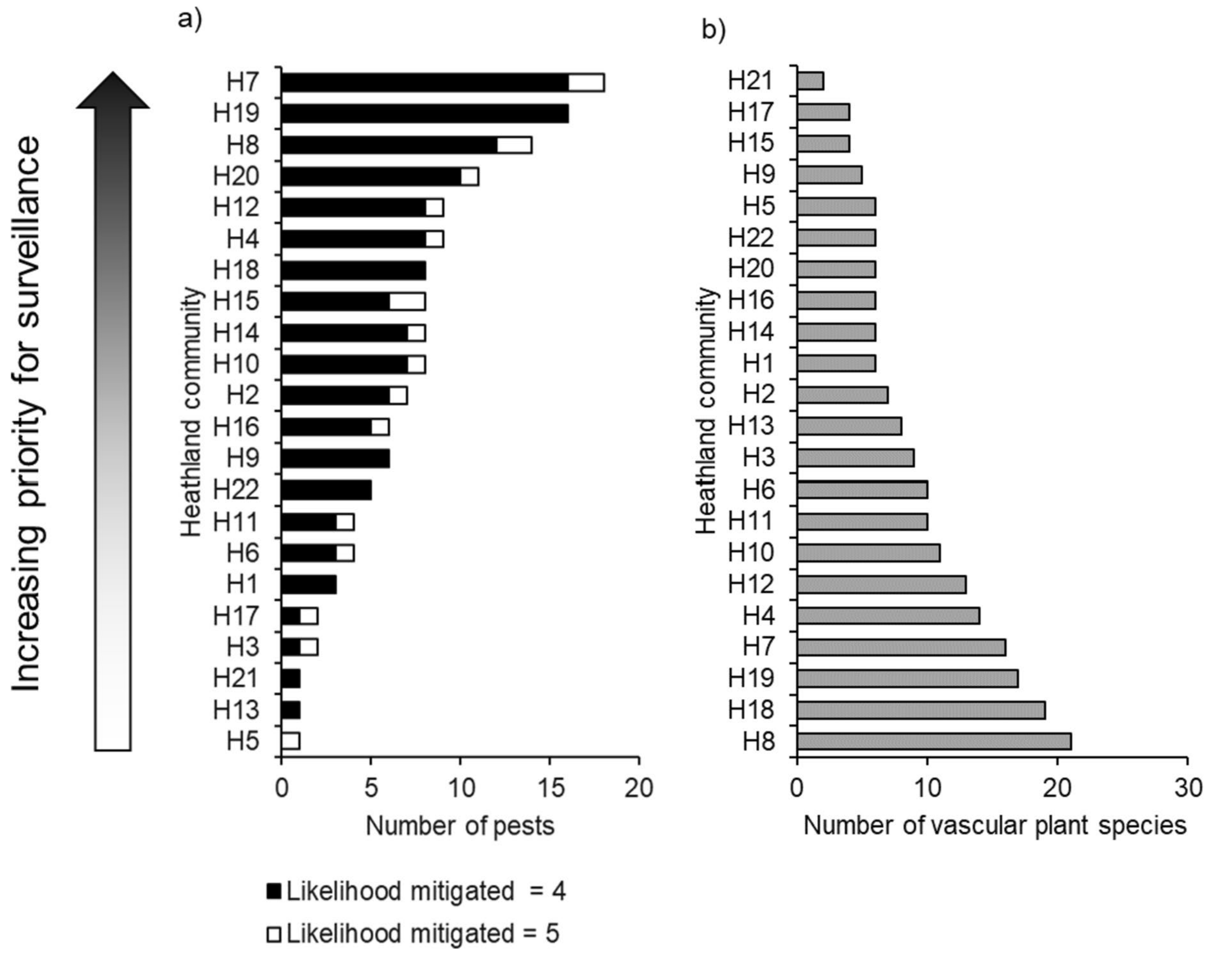

Fig. 2 Prioritisation of heathland communities in the UK for surveillance for plant pests when prioritised by: **a)** Habitat-pest: communities known to host the greatest number of pests most likely to established (likelihood mitigated 4 or 5) as listed in the PHRR. **b)** Habitat-resilience: communities with the lowest resilience, here defined as those with the lowest number of vascular plants occurring at > 25% cover. H1, *Calluna vulgaris-Festuca ovina* heath; H2, *Calluna vulgaris-Ulex minor* heath; H3, *Ulex minor-Agrostis curtisii* heath; H4, *Ulex gallii-Agrostis curtisii* heath; H5, *Erica vagans-Schoenus nigricans* heath; H6, *Erica vagans-Ulex europaeus* heath; H7, *Calluna vulgaris-Scilla verna* heath; H8, *Calluna vulgaris-Ulex gallii* heath; H9, *Calluna vulgaris-Deschampsia flexuosa* heath; H10, *Calluna vulgaris-Erica cinerea heath*; H11, *Calluna vulgaris-Carex arenaria* heath; H12, *Calluna vulgaris-Vaccinium myrtillus* heath; H13, *Calluna vulgaris-Cladonia arbuscula* heath; H14, *Calluna vulgaris-Racomitrium lanuginosum* heath; H15, *Calluna vulgaris-Juniperus communis ssp. nana* heath; H16, *Calluna vulgaris-Arctostaphylos uva-ursi* heath; H17, *Calluna vulgaris-Arctostaphylos alpinus* heath; H18, *Vaccinium myrtillus-Deschampsia flexuosa* heath; H19, *Vaccinium myrtillus-Cladonia arbuscula* heath; H20, *Vaccinium myrtillus-Racomitrium lanuginosum* heath; H21, *Calluna vulgaris-Vaccinium myrtillus-Sphagnum capillifolium* heath; H22, *Vaccinium myrtillus-Rubus chamaemorus* heath

other plantings to expose plants to pests (e.g. Barham 2016; Roques et al. 2015; Vettraino et al. 2015); and laboratory assays using plants under controlled conditions (e.g. Lynch et al. 2016; Newhouse et al. 2014). Raffa et al. (2023) proposed methods for integrating these multiple pest-based approaches and a multicriteria methodology for ranking plant pests in the EU has been developed (European Food Safety Authority et al. 2022). However, forecasting which pests will become problematic before they are introduced remains highly challenging (Kumschick and Richardson 2013; Mech et al. 2019; Schulz et al. 2021) and is a major limitation in pest-based surveillance approaches. Pest-based surveillance approaches don't provide land-managers with tools to identify which plant hosts or habitats might be most at risk from plant pests nor identify where the greatest impacts of pests on wider biodiversity and ecosystem function might occur. Such knowledge is required to enable land managers to (a) identify where to target resources to make habitats more resilient e.g. by removing, where possible, other pressures; (b) identify habitats of high risk for pest establishment during habitat restoration or creation; or (c) know where to target use of new technologies such as airborne surveillance for biosecurity (Carnegie et al. 2023).

Surveillance based on current known risks or potential impact

Surveillance based on known risks i.e. lists or risk registers of plant pests (in this study the Hosts-pest and Habitat-pest methods) assumes that a complete list of pests is available and that their risk of establishment has been correctly assessed. The current low sampling effort in most natural habitats and wild flora means that risk based on the greatest number of known pests associated with a host/habitat will tend to prioritise only the better-sampled hosts/habitats (probably ornamental/amenity plantings and woodlands (Green et al. 2021)). A literature review by Mitchell (2023b) identified a further 142 pests hosted by plant genera present on UK moorlands that are not listed on the PHRR. These additional pests may include species that are already present and widespread in the UK, and hence not included in the risk register, e.g. heather beetle *Lochmaea suturalis* Thomson, but whose severity or distribution could change with climate change (Scherber et al. 2013). A further example is that one of the most concerning current plant health threats, the bacterial plant pathogen *Xylella fastidiosa* which has a wide host range (Rapicavoli et al. 2018), is only listed in the PHRR as a threat for a limited range of host species. *Xylella fastidiosa* is known to be hosted by *Calluna vulgaris* (L.) (Chapman et al. 2022) but *C. vulgaris* is not included as a host in the PHRR. Thus, the problem of prioritising surveillance based on current known risks is that the prioritisation process must be repeated every time a new pest or host is identified. As shown for wildlife disease surveillance (Boadella et al. 2011), any surveillance method needs to be flexible enough to incorporate new pests.

The two approaches gave very different sets of species/genera or habitats to prioritise, depending on whether the prioritisation was based on known risks (Host-pest and Habitat-pest methods) or potential impact (Foundation-species and Habitat-resilience methods) (Table 2, Figs. 1, 2). The Host-pest and Foundation-species methodologies for heathland communities gave a combined list of 24 genera for surveillance. However, only three genera are common to both lists (*Calluna, Erica, Vaccinium*) (Table 2). The differences in the genera selected for surveillance from the Host-pest and Foundation-species methodologies are due to the PHRR being biased towards pests of commercial importance, with the hosts listed being predominantly relevant to agriculture, horticulture or forestry (Mitchell 2023b). This bias of existing risk registers may limit their suitability for use in natural habitats. For example, the Host-pest methodology for heathlands lists *Dactylis, Juncus, Plantago, Salix* and *Teucrium*, which are all genera of some commercial importance; none of these genera are listed under the Foundation-species methodology. At the habitat scale the list of genera for surveillance generated by Host-pest methodology is also dominated by genera that have commercial value, e.g., *Prunus, Solanum, Rosa*. It maybe that plant species in natural habitats that are closely related to species of commercial importance are more threatened than other species (Eschen et al. 2017) as trade of plants is the main pathway of introduction of non-native pests (Roques et al. 2009; Santini et al. 2013). However, such an approach takes no account of the potential for a pest to jump hosts. The basis towards plants of commercial importance then influences which habitats or communities are prioritised in the Habitat-pest method. Deciding which parameters to target for surveillance is key to improving surveillance of wildlife diseases (Boadella et al. 2011) and this study shows how the targets for surveillance change depending on how the prioritisation is carried out.

Prioritisation based on potential ecological impact rather than known risk has many advantages. The Foundation-species method allows surveillance to be targeted on those plants whose decline would have the greatest impact on wider biodiversity, ecosystem function and service delivery. The ranking therefore takes account of the wider risks to the whole ecosystem rather than just the risk to a specific plant species. Another advantage of this method is that it does not require surveyors [which may include citizen scientists, land manager or other passive surveyors (Brown et al. 2020)] to identify specific pests. Rather the surveyors could be encouraged to report signs of unusual ill health such as bleeds or dying foliage to the relevant authorities, who would then identify the cause. The Habitat-resilience method also takes account of the wider ecosystem level impacts, targeting those habitats or communities that may recover less quickly. Prioritisation across all habitats may not be appropriate as not all habitats will be found within a region/site. Rather the prioritisation could be done within a habitat, at the community level, as illustrated here for heathlands. Both the Foundation-species and the Habitat-resilience methodologies allow for the detection of new pests and pathogens, and do not require a reprioritisation of the list every time a new pest is found.

This work used the UK as a case-study, but the methods used are applicable outside of the UK and address a universal problem for plant health: that many pests are poorly known or even undescribed prior to their emergence in new regions and on new hosts. Databases such as EPPO global database and CABI ISC database both contain distribution tables for many pests and their hosts and could be used to develop a method like the Host-pest method for focal countries. The Habitat-pest method could be partially achieved in other countries by linking host genera to landcover or biome data. The Foundation-species and Habitat-resilience methods could be implemented in any country with their own National Vegetation Classification or similar e.g. (International Association for Vegetation Science undated) and there are several European-wide habitat classifications such as Corine, Palaearctic, and EUNIS which could contribute to similar methodologies.

Way forward

The methods explored here could be further developed to refine prioritisation. The pathways for introduction of pests into the UK are considered implicitly within the Host-pest and Habitat-pest methodologies. The mitigated likelihood score from PHRR assumes that action to inhibit pest spread via key pathways such as import prohibition on the key hosts have been implemented (Defra 2021a). However, pathways of induction or spread could be further considered within the prioritisation process. For example, sites where habitat restoration or creation is on-going and hence where there is greater risk of pests being introduced via dirty equipment and movement of soil and/or plants could be prioritised. However, recent work has shown that prioritisation of pathways for introduction of pests by those involved in habitat restoration or creation do not match the literature (Mitchell 2023a) and additional guidance may be required for site managers to correctly prioritize risk based on pathways of introduction. The Foundation-species method could be refined to include a trait-based approach to identifying foundation species. For example, databases such as TRY (Kattge et al. 2020) or PLANTATT (Hill et al. 2004) could be used to select traits for specific ecosystem functions. However, such a trait based approach wouldn't include information about the biodiversity supported by these plants, which is an important aspect of foundation species (Mitchell et al. 2019). The Habitat-resilience method could be enhanced by using metrics of plant phylogenetic and functional diversity/evenness as these metrics should be more closely aligned with the idea of functional redundancy compared to species diversity/evenness.

Plant pest surveillance is a key, but often missing tool, within the conservation toolkit to help alleviate the biodiversity crisis and 'bend the curve' (Leclere et al. 2020; Mace et al. 2018) of biodiversity losses. If plant pest surveillance was implemented in natural habitats it could reduce further biodiversity declines in not only host species but associated biodiversity dependent on the host. Many of the challenges and recommendations around implementing wildlife disease surveillance (e.g. Cardoso et al. 2022) are relevant to plant pest surveillance in natural habitats. One of the challenges for wildlife disease monitoring is the split in responsibilities for wildlife-related issues among administrations and departments (Cardoso et al. 2022). Plant pest surveillance in natural habitats crosses the conservation-pest management sector boundaries. The condition of habitats is usually viewed as the remit of conservation organisations, plant health is usually viewed as the remit of forestry, agriculture and horticulture. As in wildlife disease surveillance (Lawson et al. 2021), plant health surveillance needs to join up across these different sectors.

Resources are always a limiting factor, but experience in wildlife disease surveillance (Cardoso et al. 2022) shows that combined, cross-collaborative efforts allow establishing acceptable schemes with a low enough cost to be sustainable over time. Incorporation of both citizen science and "passive surveillance" by professional agents, land-users and owners (Brown et al. 2020), can facilitate large-scale surveillance, both in time and space, which would otherwise be financially infeasible, and raises awareness of incidents occurring on privately owned land (Hulbert et al. 2023; Lawson et al. 2015). Passive surveillance represent chance observations by individuals who may not necessarily be looking for signs of pests when they are discovered, but the incorporation of their records can be beneficial, particularly where resources are limited, and cost-effectiveness is paramount. The host-based approaches suggested here could be used to prioritise plants or habitats for which records of unhealthy-looking plants, recorded by volunteers, would be screen by professionals. Monitoring of known pests often requires specialist skills in their identification, which are often in short supply. Monitoring via the health of plants allows for wider participation and use of volunteers or citizen science. Once unhealthy plants are identified, then the specialists can be used to identify whether the pest is of concern. Volunteers, or amateur naturalists are already sending in plant records to national recording schemes and asking them to record plants potentially impacted by pests would increase the number of 'eyes' on the ground. In the UK, there are citizen science schemes for tree health (Tree alert) but no equivalent alert scheme for non-tree plants. The need to adopt a collaborative and multidisciplinary approach to plant health surveillance needs to be recognised and the public can make a significant contribution through citizen science.

This study has focused on identifying which hosts or habitats to prioritise for surveillance. To be a fully functional plant pest surveillance scheme, further work is required around establishing a reasonable sampling effort (European Food Safety Authority et al. 2020b) and a suitable sampling stratification to ensure detection of changes over time (Cardoso et al. 2022). Details of how the surveillance is conducted, whether through statutory agencies or with support of citizen science, need to be agreed and the appropriate resources put in place (Lawson et al. 2015). Any plant surveillance schemes should ideally have a joined-up approach across borders and should certainly communicate its findings to enable appropriate action in neighbouring countries (Lawson et al. 2021).

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Data availability No new data was collated in this study. Existing datasets were used: The Defra plant health risk register available at: https://planthealthportal.defra.gov.uk/pests-and-diseases/uk-plant-health-risk-register/. The UK National Vegetation Classification available at: https://jncc.gov.uk/our-work/nvc/#nvc-types-floristic-tables.

Declarations

Conflict of interest The author declares no conflicts of interest and has no relevant financial or non-financial interests to disclose.

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