Integration of Plant Health planning into the new Scottish Biodiversity Strategy

Project Final Report

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Content

1 Executive summary

The impacts of introduced plant pests and diseases (henceforth "pests") have been substantial in recent times. With a changing climate and many known pests on the horizon, plant health impacts on biodiversity are expected to grow further in the years ahead. Thus, systematically considering the nature of plant health threats to the natural environment and embedding mitigating actions into biodiversity strategies is of increasing importance. In this report we provide an overview of the nature of plant health threats to Scottish plant biodiversity (where we define biodiversity as "The variability among living organisms from all sources including terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are a part" (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), 2023)). In addition, the factors that expert stakeholders consider of greatest importance are explored, and an examination of the relevant headline areas of the recently published Scottish Biodiversity Strategy (SBS) takes place.

1.1 Findings

Quantification of known pest threats:

- 241 plant genera important to Scottish biodiversity are likely hosts for known potential pest threats. Insects comprise the greatest proportion of these known threats.

- The greatest known threats are to plant genera that are also used commercially. This is probably due to increased scrutiny, as well as greater opportunity for pest evolution and introduction associated with production systems and/or shipping.

- 42 priority species in 29 genera that are outlined in the Biodiversity Action Plans (BAP) are potential hosts to pests from the UK Plant Health Risk Register (UKPHRR). These species are across Scotland, with small regions identified where there is a coincidence of a high density of priority species and a high density of high-risk potential pests.

Stakeholder and expert consultation:

- When a pool of stakeholders were consulted on the factors of greatest importance in plant health vulnerability in the natural environment, they were equally concerned about a) plant health impacts on species which support multiple specialised interactions, because the loss of these species would have cascading impacts through an ecosystem, and b) low intraspecific host genetic diversity (genetic diversity within a host species) or habitat species diversity (diversity of species within a habitat). Conversely, nearby vehicle traffic and exposure to weather patterns that may facilitate pest movement were of least concern. In additional narrative commentary:
    - Concern was raised regarding the biosecurity threats associated with pest movement from plant trade into the wider environment.
    - Constraints on governmental and scientific resource allocation to the natural environment were also raised as concerns. This included a lack of pre-existing research on pest and host interactions, which makes plant health risk assessment for conservation challenging.

- A subsequent more focused plant health expert ranking exercise was undertaken and rated:
    - Pre-existing disease pressure to be the highest plant health risk factor to individual plants species and populations, followed closely by other stresses including climate stress and low intraspecific genetic diversity.
    - Proximity to plant traders was ranked most highly as a plant health risk factor at the environmental level, followed by proximity to large scale plantings.

- The information provided by experts and the data on current plant health threats in the UKPHRR, were brought together to create a new, simple framework for articulating the vulnerability of species and habitats to plant health threats.

<u>Plant health integration with national biodiversity strategies</u>

- In recognition of the profound impacts caused by introduced pests, biosecurity has successfully been incorporated into national biodiversity strategies in some countries, with New Zealand and Australia giving the clearest examples.

- The SBS recognises the importance of National Parks and protected areas, making them exemplars for restoration. It is therefore critical that National Parks and protected areas also become exemplars for biosecurity, creating and demonstrating safe processes for plant production, movement and planting during species and habitat restoration and recovery programmes.

- As large-scale tree plantings are increasingly used to promote biodiversity recovery and habitat connectivity, as well as sustaining timber production and carbon sequestration, it is crucial that plant health and biosecurity are embedded across the multiple actors and participants in tree-planting schemes.

- A key component of establishing resilience to plant health threats is to allow continued evolution of hosts to respond to emerging pressures; management practices which promote natural regeneration and adaptation are important components of building resilience to current and future pest pressures.

- SBS and its delivery partners need to maintain active collaboration with plant health structures and staff in England for mutual learning, early warning and collaborative action.

- Overall, the results of this study reinforce the importance of more active consideration of plant health threats in biodiversity strategies and related conservation activities.

2 Introduction

Globally, invasive species, which include introduced plant pests and pathogens, are one of the main drivers of biodiversity loss (Duenas, et al., 2021). Once introduced into new regions, invasive species rapidly alter biodiversity and affect ecosystem functioning (Sala, et al., 2000).

Introduced plant pests and pathogens (henceforth "pests") have become a significant issue in the last 30 years due to the increased global movements of plants and plant-based products (e.g., timber, wooden products, soil). They can be inadvertently introduced in several ways, including on plants intended for planting, timber, wood packaging material and through hitchhiking (e.g., travelling in/on clothing or cars and trucks) (Spence, et al., 2020). Provided the conditions in a new area are conducive to the establishment and spread of an introduced species, they can go on to have permanent, profound, direct and indirect impacts.

A recent UK example of such an introduction is ash dieback disease, caused by the fungus *Hymenoscyphus fraxineus* (previously known as *Chalara fraxinea*). This fungus originates from East Asia and was unwittingly introduced into Europe in the 1990s. Since then, it has spread rapidly across the continent and killed millions of European ash trees (*Fraxinus excelsior*) (Bakys, et al., 2009). It was first officially discovered in the UK in February 2012 on infected trees sent from the Netherlands to a nursery in Buckinghamshire (Tomlinson, 2016). However, within two years it was realised that the disease was already widespread (i.e., there were 666 confirmed findings in July 2014; 26 in nursery sites, 355 in newly planted sites and 285 in established woodlands in the wider environment). It has since become established across the country (FERA, 2022).

Ash is an important species in Scotland. A recent study identified 955 ash-associated species (birds, mammals, fungi, lichens, bryophytes and invertebrates), 45 of which are obligate and therefore only live on ash (4 lichen species, 11 fungi and 30 invertebrates) (Mitchell, et al., 2017).

The introduction of the novel ash dieback pathogen into the UK has caused extensive ecological, economic and cultural damage, estimated to be around £15 billion (Hill, et al., 2019). Ash dieback is just one example of an introduced pest species which has had a significant impact. Other examples include Dutch elm disease, (fungus *Ophiostoma novo-ulmi*), chestnut blight (fungus *Cryphonectria parasitica*), oak processionary moth (*Thaumetopoea processionea*), Dothistroma needle blight (fungus *Dothistroma septosporum*) and horse chestnut bleeding canker (bacteria *Pseudomonas syringae* pathovar *aesculi*).

Some countries have acknowledged the importance of pest impacts in their biodiversity strategies; New Zealand for example have biosecurity at the heart of their 2020 Biodiversity Strategy (New Zealand Government, 2020).

However, generally speaking, managing the causes of plant pest impacts are not explicitly mentioned in biodiversity strategies. For example, the Aichi Targets of the Convention on Biological Diversity mentions invasive species in Target 9, but not introduced plant pests (such as disease-causing pathogens). Specifically, Target 9 states that "By 2020, invasive alien species and pathways are identified and prioritized, priority species are controlled or eradicated, and measures are in place to manage pathways to prevent their introduction and establishment" (CBD, 2020).

Target 10 of the Global Strategy for Plant Conservation (CBD, 2011) did address biological invasions with "Effective management plans in place to prevent new biological invasions and to manage important areas for plant diversity that are invaded", but the implementation of this target has largely been focussed on invasive plant species (e.g., Smyth, et al., 2013).

Significant work is therefore required to promote the recognition of plant pest impacts in biodiversity strategies, leading to improved management and the reduction of new introductions. The c.170 species of the plant pathogen *Phytophthora*, for example, are causing significant biodiversity impacts across the globe as they are inadvertently introduced via the global trade in plants (Callaghan & Guest, 2015).

Scotland's Plant Health Centre has commissioned this study to review how plant health issues could be better integrated into the Scottish Biodiversity Strategy (SBS).

2.1 Aims

2.1.1. Known plant health threats to biodiversity assets. To use the UK Plant Health Risk Register (Baker et al. 2014) to identify known pest threats to plant species and habitats important to Scottish biodiversity.

2.1.2. Risk landscapes. To solicit expert opinion to identify key characteristics signifying future plant health risks beyond known threats and produce a framework for assessing plant health vulnerabilities.

2.1.3. Strategic actions and interventions. Produce guidance for the inclusion of plant threats and vulnerabilities into the new SBS. This will include best-practice examples of plant health integration into national biodiversity planning, and those identified from international examples.

3 Methods

3.1 Known plant health threats

The UK Plant Health Risk Register (UKPHRR) is a publicly available and regularly updated database of the principal plant health threats to the UK, and expert risk assessments of their potential impacts (Baker et al., 2014; Defra, 2022). Organisms, collectively referred to as pests, from viroids and phytoplasmas to insects and pathogenic or parasitic plants, are listed along with their known major hosts; their likely economic, environmental, and social impact should the pest enter and establish in the UK or spread to its maximum range; the mitigated and unmitigated likelihood for this impact to be realised; the value at risk; and an overall risk score encompassing impact, likelihood and value at risk.

The UKPHRR's overall risk score is not an appropriate measure for a pest's risk to the natural environment, because the biodiversity value at risk is not well captured in economic figures. We therefore considered the modified risk rating of each pest's Impact x Likelihood, as suggested by Baker et al (2014). This metric used the mitigated 'Likelihood', the estimated likelihood of establishment or spread given mitigations already in place. The UKPHRR's Impact and Likelihood entries are scaled from 0-5 to reflect the economic impact, while the modified risk rating is scaled from 0-25 to reflect a pest's risk to the natural environment.

New pests are regularly added to the Risk Register. We report here on figures updated from the risk register version 'Risk Register 12_09_2022 10 58 18'.

Pest associations were inferred at the genus level, as the potential for many risk register pests to form a host association with plant species important to the Scottish environment is unknown. Thus, a potential association was assumed where a plant's genus appeared in a pest's UKPHRR Major Hosts.

Plants important to Scottish biodiversity (except bryophytes, which don't appear as hosts in the PHRR) were extracted from the BRC Biological Records Centre PLANTATT dataset (Hill et al., 2008), and then further filtered to include those listed within the Scottish National Vegetation Classification Scheme (NVC) (Joint Nature Conservation Committee (JNCC) n.d.). Those included in the Biodiversity Action Plan (BAP) Priority List for Vascular Plants (JNCC, 2007) were tagged as of special conservation concern.

All plant genera in the NVC floristic table were matched with risk register pests, tabulated and visualised using custom scripts in the R language (R Development Core Team, 2022; Wickham, 2016; Wickham et al., 2019). Counts of pests were summed by genera and community. While pests may be represented on more than one genus per community, we assumed the impact to be cumulative for each potential host genus.

The potential pest load on Scottish habitats was visualised using the open-source geographic information system QGIS (QGIS, 2019). First, we mapped NVC community codes to EUNIS habitat type using NVC floristic and correspondence tables. Then, the community pest data were mapped by EUNIS code on the Habitat Map of Scotland (Scottish Environment Protection Agency, 2018).

3.2 Risk landscape

While visualising the known current plant health risk to Scottish plant biodiversity is a useful exercise, it encompasses only part of future risk. Left remaining is the uncertainty around the effects of these known, potential future threats, as well as the threats we do not yet know exist.

The unknown threats are numerous. Plant pests often do not emerge as problematic until moved out of their home range, just as the ash dieback pathogen (*Hymenoscyphus fraxineus*) is mostly a harmless endophyte in its home range (Cleary et al., 2016). Furthermore, most plant health research concerns agronomic systems, so not only may the effects of known pests on plants in the wider environment be unknown, but the pests themselves in these systems may be overlooked.

Similarly, there may be little or no information about rare plants' genetic diversity, breeding systems, and much less their susceptibility to any new plant health threat, or the compounded effects of multiple threats. Thus, a more general understanding of plant health vulnerability and future resilience is required.

3.3 Stakeholder survey

While the most important known pest threats to UK plant health have been comprehensively assessed with regards to production systems and forest trees, their potential impacts on biodiversity are poorly characterised, and future unknown threats, by definition, remain unassessed. We therefore used expert knowledge to create a framework for assessing the vulnerability of plant species and communities to catastrophic pest outbreaks or epidemics.

Firstly, we surveyed stakeholders at Scotland's Plant Health Conference on 28 May 2019. This audience of approximately 120 researchers, policy makers, and professionals with interest in plant health were presented with a list of either "species or population" or "community or environmental" traits that may contribute to vulnerability (Table 1). In response to the question "What…traits contribute to risk of significant loss of biodiversity, productivity, or ecosystem services due to plant disease epidemics?" they were asked to rate the importance of these factors from 1-10, with 10 being very important, and to suggest any that were missing.

3.4 Expert opinion

Following this stakeholder feedback, factors were refined and narrowed to a short list of six factors at the scale of species or population, and nine at the scale of site or plant community (Table 2). Forty-two independent experts, working internationally at PhD level-academic or national-level policy positions related to plant health in the natural environment, were invited to complete an anonymous survey in which they ranked the factors in head-to-head comparisons of each factor pairwise against the others, at each of the two scales.

Experts were also asked to report their own level of knowledge, and their responses were only included in the pool if they reported expertise or proficiency in any of the fields of plant pathology, entomology, epidemiology, plant ecology and, more widely, plant disease dynamics in the natural environment. This created a final pool of 8 expert evaluators.

The evaluators' pairwise rankings were combined to form a structure for assessing the vulnerability of Scottish plant species and habitats to future plant health threats.

Table 1 - Risk factors rated for importance by stakeholders

Species or population
The plant health impacts on species which support multiple specialised interactions (because the loss of these species would have cascading impacts through an ecosystem) or plant considered as a key stone or foundation species supporting many other species
Low genetic diversity, small effective populations size, low migration, and/or small populations (or lack of information)
Long generation times
Range limitation (eg altitude, soil type, weather). Includes limitation due to future climate impacts, e.g. alpine species
Otherwise stressed or expected to be in future (50 yr) climate conditions (edge of range, climate, grazing, pollution etc), or already has some form of conservation protection e.g. red data book species
Pre-existing pathogen load
Relatives in cultivation (including forestry) within 10 km

Plant community or environment
Low species diversity
Isolation/low connectivity to similar habitat
High foot traffic
High vehicle traffic within 1 km
Timber mills, ports and airports within 10 km
Large development: landscaping, roadworks, dual carriageways, golf courses, planting of new woodlands within 10 km
Landscaping, woodland planting, or restoration works including transplants or soil movement on site.
Plant nurseries within 10km
Exposure to pest pressure from mainland Europe through weather events

Table 2 - Risk factors at the scale of Species/Population and Site/Community ranked in pairwise comparisons by an expert panel

Abbreviation	**Risk Factor**
	Species or Population
disease	Pre-existing pathogen load, e.g., where a species/population is currently under heavy disease pressure, such as ash under ash dieback
stress	Pressure from other stress factors, e.g. due to grazing, climate change, or pollution, NOT including other pathogen pressures
cultivation	Closely related to species in cultivation, including forestry
range	Range limitation, e.g. due to altitude, soil type, or weather
diversity	Low genetic diversity, including small effective populations size, low migration, and/or small populations
generation	Long generation time, i.e. the time from seed germination to reproductive maturity
	Site or Plant Community
recreation	High recreational use, e.g. number of visitors on walking, mountain biking, horse riding, or ATV trails
plantings	Proximity to recent (5 years) large-scale new plantings, e.g. timber plantations or habitat restoration
connectivity	Proximity/high connectivity to similar habitat, i.e., the area of same habitat type within a specified radius
exposure	Distance from mainland Europe, i.e. degree of exposure to airborne pests in weather from continental Europe
diversity	Low species diversity
roads	Proximity to the road network, i.e.., M, A, or B roads
traders	Proximity to plant traders, e.g. plant nurseries, garden centres, large plant retailers
development	Proximity to recent (5 years) large infrastructure development, e.g. new roads or major roadworks, new housing estates
ports	Proximity to international points of entry, e.g. military bases or installations, timber mills, maritime ports or international airports

4 Results

4.1 Known threats

Of the 1409 pests listed in the UKPHRR on 12/09/2022, 1061 were associated with genera represented in Scottish vegetation. Two hundred and twenty-five of this subset are listed as already 'present' in the UK. Risk register pests were associated with 241 of the 650 total plant genera in NVC Scottish habitats (Supplementary Table 1), and with 42 species designated as biodiversity priorities in the Scottish Biodiversity List, in 29 genera (JNCC, 2007) (Table 3).

The greatest number of known pest threats were insects (Figure 1). Insects made up 57 of the 66 pests associated with Salix (Table 3), and 137 of 299 associated with *Solanum,* which had the greatest cumulative "risk" (UKPHRR Impact x Likelihood) of all Scottish genera (Supplementary Table 1). For clarity, *Solanum* scores highly on the UKPHRR because of the threat to potato (*S. tuberosum*) but there is only one native *Solanum* species in Scotland, *S. dulcamara*.

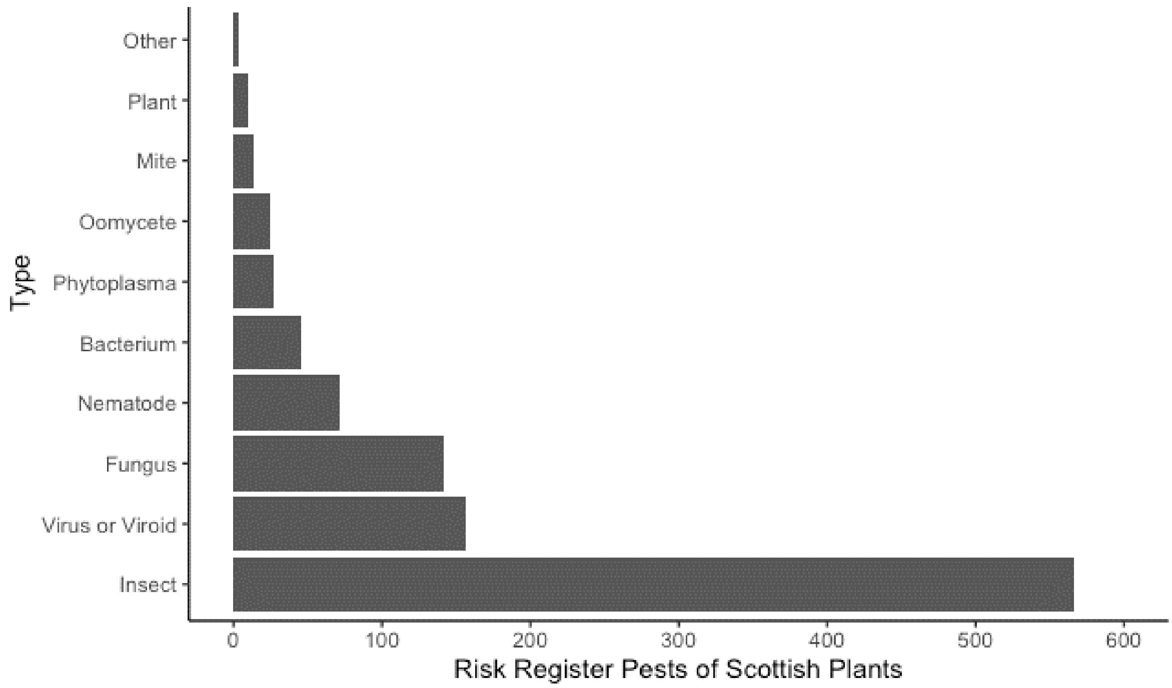

Figure 1 - Broad taxonomic classification of UKPHRR potential pests for Scottish plant biodiversity

Among UKBAP priority species, the genera *Salix, Chenopodium, Juniperus* and *Malus* were associated with especially high cumulative pest risk ratings. Cumulative rating of *Salix* was more than twice as high as those of *Chenopodium, Juniperus*, and *Malus*, which were in turn more than twice as high as the next nearest neighbour. This reflects an overall over-representation in host associations of genera containing species with major economic uses. Likewise, the five most represented of all Scottish genera were *Solanum, Prunus, Malus, Pinus* and *Quercus*.

We used a risk metric modified from the UKPHRR, in that it considered only the projected pest impact—including social and ecological impact—and likelihood of arrival or spread and omitted the 'value at risk' portion of the UKPHRR's standard risk rating. Yet, the over-representation of agronomic genera is not unexpected: the global trade and high host densities of commercial species are strongly associated with the emergence of new pests (Parker and Gilbert, 2004; Stukenbrock and McDonald, 2008). Conversely, rare plants are by definition at low density relative to the landscape and often in isolated patches; a pattern that may be somewhat protective of pest emergence from an evolutionary ecology point of view.

Human biases also play a role, as the risk register is not an exhaustive list of all pests and all their hosts. Pests listed are those that have attracted concern, which is most likely where hosts are economically important. Furthermore, host relationships are less likely to be known, and therefore listed, for host-pest combinations that have not had the opportunity to occur (e.g. because of geographic separation) or that do occur but have not been observed (e.g. because of host rarity or lack of study).

The cumulative risk from known risk pest threats to NVC plant communities was estimated from the summed modified risk ratings (likelihood x impact) for the pests associated with the resident genera. The potential burden was greatest in hardwood dominated, species rich woodland and underscrub communities (Supplementary Table 2). Communities with high cumulative risk were distributed across Scotland, with a particular concentration of medium-to-high scores in the Inner Hebrides (Figure 2).

This simplification does not take into account pest interactions or compounding effects, but does to some extent capture ecological roles, in that impact scores are high where the loss of a species is expected to confer more ecological damage. The cumulative metric may be inflated, however, where species diversity is high, and may underestimate true risk in species-poor communities, further pointing to the need for a more comprehensive framework to describe plant health risk.

Table 3 - UK Pest Risk Register high-impact pests associated with the genera of Scottish Biodiversity Priority Species. Genus is the list from which the pests have been recorded from, and species are the list of the Scottish UKBAP priority species within the genus. N is the count of potential pest associations, Risk is the sum of the pests' risk rating as Impact x Mitigated Likelihood, rather than the UKPHRR 'Risk' rating which includes a measure of value at risk. "Present" indicates the number of pests known already to be present in the UK; the rest have unknown distributions or have not yet been detected.*

Genus	Species	N	Risk*	Present	Bacteria	Fungi	Insects	Mites	Nema-todes	Oomy-cetes	Phyto-plasmas	Pest Plants	Viruses
Salix	*S. lanata, S. lapponum, S. myrsinites*	66	387	9	3	3	57	0	1	1	0	0	0
Chenopodium	*C. urbicum, C. vulvaria*	28	162	7	2	0	9	0	7	0	0	0	10
Juniperus	*J. communis*	27	156	5	0	10	13	1	2	1	0	0	0
Sorbus	*S. arranensis, S. pseudofennica*	29	153	9	2	7	16	0	1	0	0	0	3
Artemisia	*A. norvegica*	22	70	2	1	0	19	0	0	1	0	0	1
Taraxacum	*T. clovense, T. geirhildae*	8	57	2	0	0	1	0	1	0	0	0	6
Poa	*P. flexuosa, P. glauca*	10	48	5	0	1	4	0	3	0	0	0	2
Stellaria	*S. palustris*	12	48	7	0	1	1	0	4	0	0	0	6
Rumex	*R. aquaticus*	12	44	4	0	1	7	0	1	0	0	0	3
Ranunculus	*R. arvensis*	7	35	5	0	0	2	0	2	0	1	0	2
Ajuga	*A. pyramidalis*	3	24	0	0	0	2	0	1	0	0	0	0
Erigeron	*E. borealis*	7	24	1	0	1	4	0	1	0	0	0	1
Cerastium	*C. articum, C. fotanum* subsp.*scoticum, C. nigrescens*	3	22	1	0	0	0	0	1	0	0	0	2
Polystichum	*P. lonchitis*	3	17	1	0	0	1	0	2	0	0	0	0
Dryopteris	*D. cristata*	1	16	1	0	0	0	0	0	1	0	0	0

Genus	Species	N	Risk*	Present	Bacteria	Fungi	Insects	Mites	Nema-todes	Oomy-cetes	Phyto-plasmas	Pest Plants	Viruses
Carex	*C. maritima*	3	12	0	0	0	3	0	0	0	0	0	0
Salsola	*S. kali* subsp. *kali*	1	12	0	0	0	1	0	0	0	0	0	0
Polygonatum	*P. vreticillatum*	1	8	0	0	0	1	0	0	0	0	0	0
Saxifraga	*S. cernua, S. cespitosa, S. hirculus*	2	8	1	0	0	0	0	1	0	0	0	0
Centaurea	*C. cyanus*	2	6	0	0	0	2	0	0	0	0	0	0
Fumaria	*F. purpurea*	1	6	1	0	0	0	0	0	0	0	0	1
Melampyrum	*M. sylvaticum*	2	6	0	0	2	0	0	0	0	0	0	0
Pulicaria	*P. vulgaris*	1	6	0	0	0	1	0	0	0	0	0	0
Calamagrostis	*C. scotica, C. stricta*	1	4	0	0	0	1	0	0	0	0	0	0
Potamogeton	*P. compressus, P. rutilus*	1	4	1	0	0	1	0	0	0	0	0	0
Astragalus	*A. alpinus, A. danicus*	1	0	1	0	0	1	0	0	0	0	0	0
Campanula	*C. rapunculus*	2	0	2	0	0	0	0	1	0	0	0	1
Galeopsis	*G. angustifolia*	1	0	1	0	0	0	0	0	0	0	0	1
Lythrum	*L. hyssopifolia*	1	0	1	1	0	0	0	0	0	0	0	0

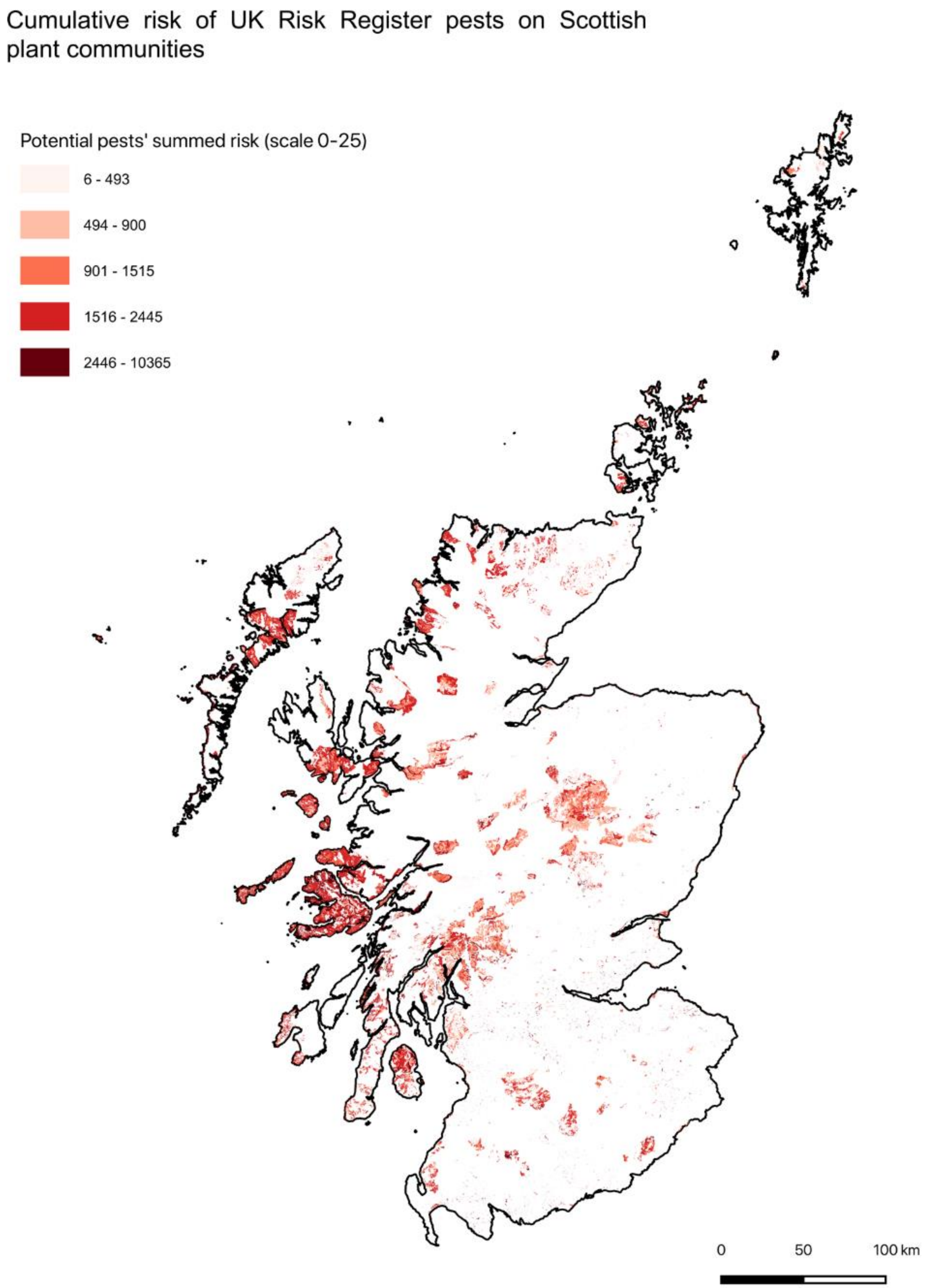

Figure 2 - Risk scores (Impact x Likelihood) of UKPHRR pests across Scottish natural habitats, summed across each community's plant genera. This is the cumulative potential plant health risk inferred from UKPHRR host relationships, mapped across potential hosts.

4.2 Risk landscape

4.2.1 Stakeholder survey

Of the 120 surveys distributed, 38 were returned. Stakeholders on average placed importance most highly on genetic diversity and a keystone community role of individual plant species or populations, and lowest on range limitation and having related plant species growing in cultivation nearby (Figure 3). However, ratings were broadly scattered and there was not a clear difference in central tendency among factors: the highest median rating was 9, and the lowest 7.

There was a similar scatter but a greater difference in ratings at the scale of community, in which low species diversity was ranked most important, and exposure to potential pest migration via European weather events and nearby vehicle traffic the lowest.

The stakeholders were invited to write in additional factors that might be important. Many of the write-ins (Supplementary Table 3) were concerned with biosecurity and pest movement from plant trade into the wider environment. These included statements such as “Bulk selling cheap plant material by Euro supermarkets,” “biosecurity and international movement of plants and soil,” and “border pressure and checks.”

Governmental and scientific resource allocation to the natural environment were additional concerns. “Lack of pre-existing research information about hosts and diseases” highlights the difficulties in plant health risk assessment to the natural environment. Factors were suggested that highlighted difficulty in obtaining funding and political support for non-commercial species, such as “Being part of a wider community i.e. no immediate business impact” and “Popularity with the public relative to increased/decreased funding or participation for conservation.” These highlight the importance of political buy-in to conservation, and knock-on effects of economic concerns to plant health in the wider environment.

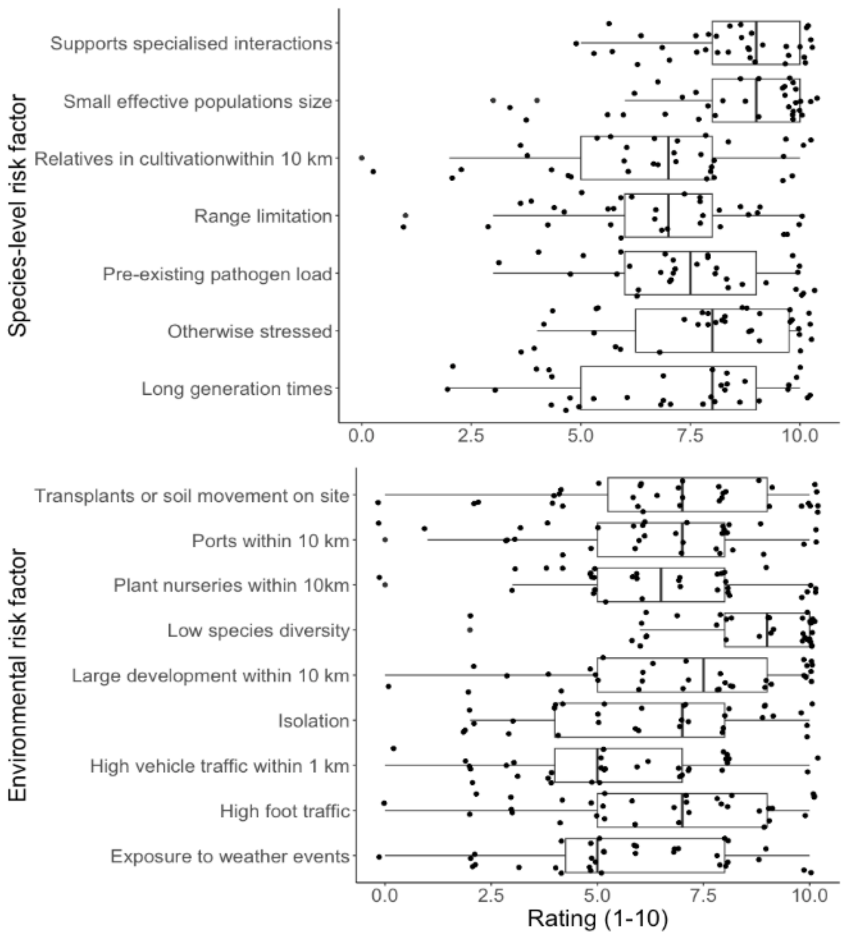

Figure 3. Stakeholders' ratings of importance of plant health risk factors at (upper) the scale of a population or species and (lower) a plant site, community or environment.

4.2.2 Expert opinion

Plant health experts made pairwise comparisons of each of 6 risk factors contributing to plant health vulnerability of plant species, and 7 risk factors contributing to vulnerability of a site, environment, or community (Table 4).

Of 42 invitations issued, 9 were returned, of which 8 met the criteria for inclusion. The pool included experts in each of the fields of plant pathology, epidemiology, plant ecology and plant disease dynamics in the natural environment. No respondents reported expertise in entomology.

Each cell in Table 4 contains the number of times the risk factor in the row name was picked as more important to plant health vulnerability than the factor in the column name. For example, at the species scale 'disease' was ranked as more important than 'stress' 6 times and conversely stress was ranked more important than disease twice in pairwise comparisons by 8 different experts. Where values are 4, the two factors were picked equally.

At the scale of plant species or population, experts most consistently ranked pre-existing disease pressure as the highest plant health risk, followed closely by other stresses including climate stress and intraspecific genetic diversity. Range restriction and long generation times were less often ranked highly against the first four.

At the site or plant community scale, proximity to plant traders was ranked most highly, with proximity to large-scale plantings, including conservation, forestry, or landscaping next. Of the ten, developments other than planting projects and exposure to airborne pests via continental weather events were least often placed highest.

Table 4 - Experts' pairwise ranking of risk factors for catastrophic disease loss at two different scales. For each pair of factors, experts were asked to choose the more important one. Each cell contains the number of times the reference (row names) was ranked as more important than the factor in the column name. Each row sum is the total number of times its corresponding factor was picked, thus cells on either side of the diagonal sum to 8. For full risk factor descriptions see Table 2.

Population or Species Comparison

	disease	*stress*	*diversity*	*cultivation*	*range*	*longlived*	Sum
disease		6	3	7	6	6	28
stress	2		5	6	8	6	27
diversity	5	3		5	7	6	26
cultivation	1	2	3		7	7	20
range	2	0	1	1		6	10
Generation	2	2	2	1	2		9

Site or Community Comparison

Reference	*trade*	*plants*	*ports*	*recrea*	*divrs*	*roads*	*connct*	*devel*	*expose*	Sum
traders		4	6	7	6	8	7	8	8	54
plantings	4		5	6	5	7	7	6	8	48
ports	2	3		2	5	8	7	7	7	41
recreation	1	2	6		5	8	6	4	7	39
diversity	2	3	3	3		4	5	4	5	29
roads	0	1	0	0	4		5	8	6	24
connectivity	1	1	1	2	3	3		8	5	24
development	0	2	1	4	4	0	0		0	11
exposure	0	0	1	1	3	2	3	0		10

These pairwise comparisons are necessarily a vast oversimplification of the complexities of disease dynamics, and a counter example could no doubt be found to any 'rule' described here. Nonetheless, they provide an initial summary of the surveyed expert opinion of the factors that most confer plant health vulnerability. Together, these coalesce to form a picture of interlinked threats. Existing disease threats compound pressures of climate stress, habitat loss, range contraction and fragmentation, all of which can reduce intraspecific genetic diversity or, in the case of extirpation, habitat species diversity. Live plant movements, whether in trading centres or via planting projects, can introduce new pests. Recreation, industry or development, and roads facilitate the movement of these pests into habitats.

4.3 A framework for evaluating plant health vulnerability

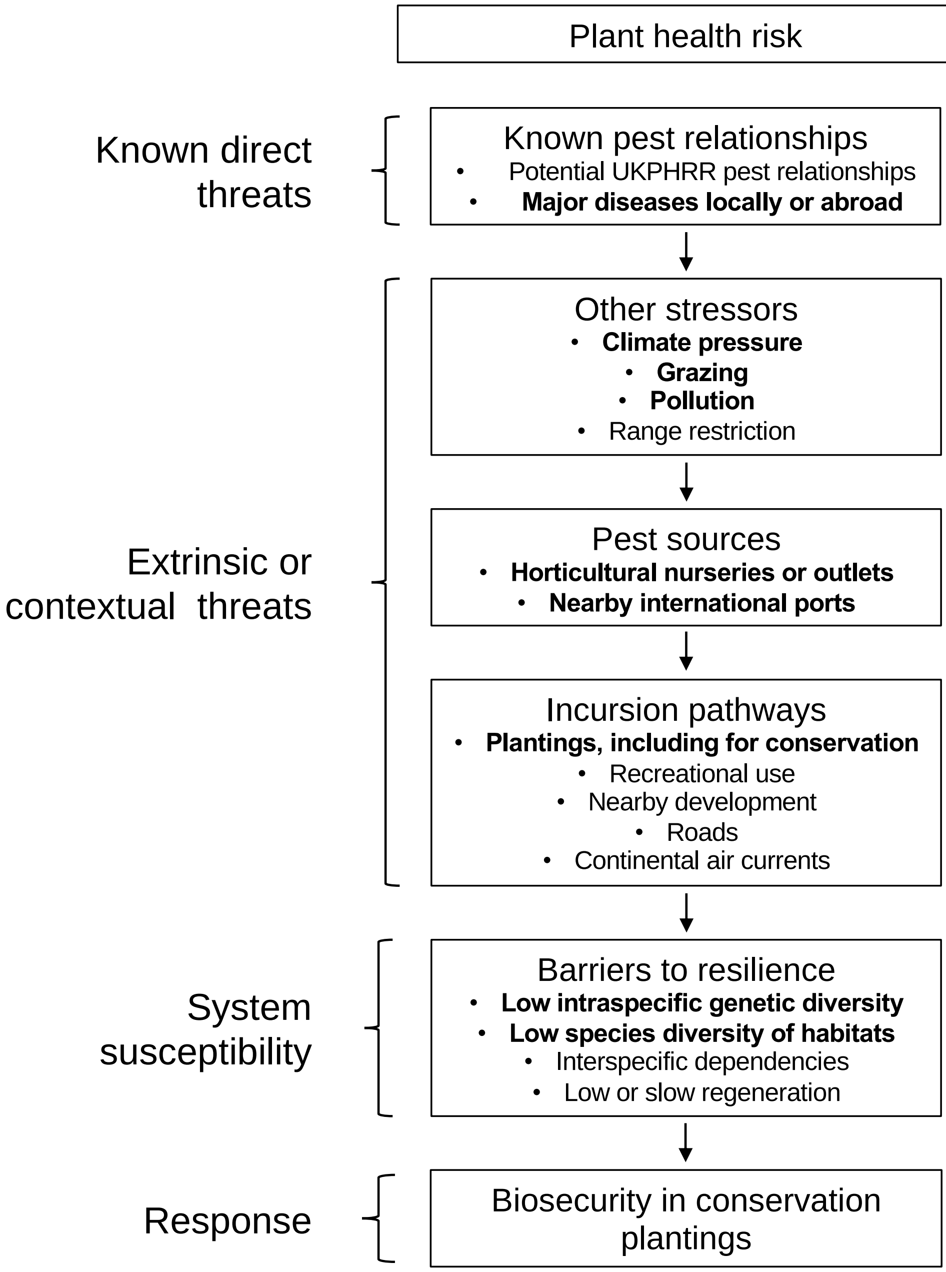

Figure 4. Conceptual framework of plant health vulnerability. Bold text indicates factors given especially high weight.

The information on current plant health threats in the UKPHRR, brought together with stakeholder and expert consensus, create a framework for understanding the vulnerability of species and habitats to plant health threats (Table 4; Figures 3 and 4).

Diseases currently impacting our plant biodiversity clearly play a large role in allowing us to assess both current and future threats, as does horizon scanning for potential high-impact pests have a role. However, these are only part of the equation, as the total of all future threats cannot be known, nor can impacts be fully predicted, especially where information is poor.

Contextual threats such as habitat loss due to climate change or grazing, while not directly plant health related, form their own contribution to species' vulnerability. The interactions are numerous and important. For example, climate stress can make plants susceptible to pests they would otherwise tolerate, and habitat loss can further reduce population sizes and genetic diversity, contributing to greater system susceptibility.

The likelihood of introduction and establishment of new pests are key players in habitat vulnerability. The international plant trade plays a major role in pest introduction and establishment (Smith, et al., 2007), and both new and 'established but damaging' pests can be efficiently propagated and spread in the nursery trade (Brasier 2008). Plant traders and major plantings are thus important contributors to habitat vulnerability, and the role of plantings is evidenced by the probable spread of *Phytophthora austrocedri* through conservation plantings in British juniper woodlands (Donald et al., 2021; Riddell, et al., 2020), and the repeated spread of *Phytophthora* species from restoration nurseries to high-conservation value habitats in California (Frankel, et al., 2020).

Pests may be introduced through climatic events, highlighting an intersection with climate pressures, or through other human-mediated activities. Recreational uses, roads, and industry can all ease the introduction and establishment of new pests (Jules, et al., 2002; Numinen and Laine 2020).

Thirdly, characteristics of the systems themselves can add to their vulnerability. Small or genetically uniform populations may be intrinsically more susceptible and may not recover from large losses due to a new epidemic. Likewise, habitats dominated by or dependent on one or a few species are vulnerable to catastrophic loss of the keystone[1], while those with more diversity of species and dependencies may better tolerate a single species loss.

Finally, conservation responses may themselves contribute to species and habitat vulnerability. Conservation nurseries share the qualities that can foster pest introductions and disseminations and can themselves be a threat to plant health (Frankel, et al., 2020). As discussed in Mitchell (2023), effective biosecurity processes in nurseries and in the field can minimise the risks of spreading existing pests and the inadvertent introduction of new species.

[1] Keystone - a species that plays a disproportionately large role in their ecosystem relative to its abundance. A keystone species therefore helps define an entire ecosystem.

5 Plant health implications of the Scottish Biodiversity Strategy

The SBS recognises that biodiversity is declining faster than at any other time in human history (Scottish Government, 2022). It also supports the IPBES Global Assessment of Biodiversity Report (2019) which identified five direct drivers of global biodiversity loss:

1) Changing use of the land and sea especially for agriculture, forestry, fish farming and coastal infrastructure
2) Direct exploitation of organisms via harvesting, logging, hunting and fishing
3) Climate change
4) Pollution
5) Invasive non-native species (which includes the growing prevalence of novel pests and pathogens).

These drivers are strongly interconnected; climate change for example will potentially increase the prevalence of novel plant pests (Pathak, et al., 2018; Garrett, et al., 2021). This situation has already reached a crisis point in the UK due to the inadvertent introduction of new plant pests over the last 30 years (Brasier, 2008; Spence, et al., 2020). Trees have been particularly hard hit with epidemics such as ash dieback and Dutch elm disease causing permanent damage to treed landscapes (Figure 5).

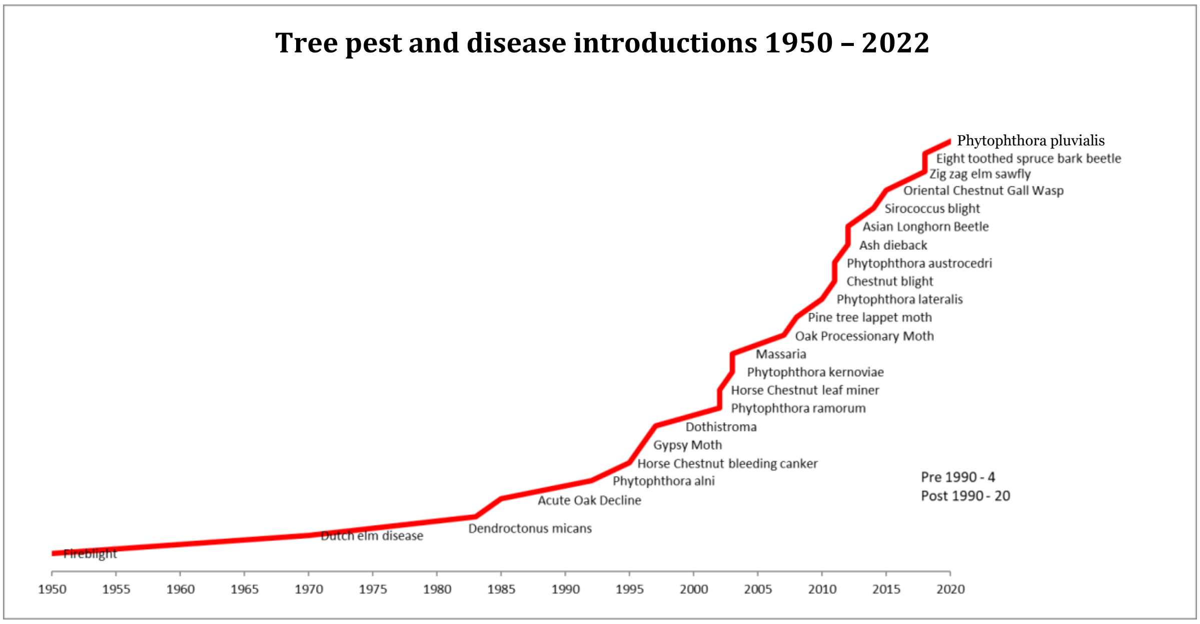

Figure 5. The incidence of significant tree pest and disease introductions 1950 – 2022.

5.1 International approaches

Some countries have made biosecurity central to their biodiversity strategies. The latest New Zealand Biodiversity Strategy for example puts introduced species (which includes plant pests and pathogens) at the top of the list of pressures that impact biodiversity (NZ Government, 2020). As a result, biosecurity is central to their strategy to improve the biodiversity of their natural habitats whilst reducing the impacts of introduced species.

For clarity, it is important to realise that in some countries, plant pests and pathogens are not legislatively separated from animal health, or invasive species, as they are in UK legislation. In New Zealand for example, the Biosecurity Act (1993) is aimed at managing "all unwanted organisms" (NZ Government, 2022). Therefore, in the following approaches, plant pests and pathogens are captured within wider "biosecurity threats". The explicit nature of this approach ensures that there is clarity on management of all introduced species, rather than an implicit approach in other countries where there is often ambiguity regarding the management of plant pests and other invasive species. The "*all unwanted organisms"* approach is perhaps the most critical factor in biosecurity success when compared to countries with more complicated approaches.

Objective 11 in the New Zealand Biodiversity Strategy is "Biological threats and pressures are reduced through management". This includes specific actions regarding invasive organisms:

"By 2025 – new and emerging biosecurity threats, including weeds, animal pests and diseases (e.g. introduced invasive plants, algae, mammals, fish, invertebrates and micro-organisms), in all domains are actively identified and managed early through improvements in decision making, Treaty partnership approaches, skills and technology.

"By 2030 – the highest priority biosecurity threats, including weeds, animal pests and diseases (e.g. introduced invasive plants, algae, mammals, fish, invertebrates and microorganisms), in all domains have been identified and are being managed based on current and potential future impacts on indigenous biodiversity.

"By 2050 – introduced biosecurity threats, including weeds, animal pests and diseases (e.g. introduced invasive plants, algae, mammals, fish, invertebrates and micro-organisms), in all domains have been eradicated or are being managed to reduce negative impacts in areas of high biodiversity value."

A similar approach is taken in Australia (Australian Government, 2019). As far as introduced species are concerned, objective 7 "Reduce threats and risks to nature and build resilience" addresses policy related to both the management of established species as well as managing the risk of the introduction of new species. Specifically:

7C Extent and success of management programs for established invasive species that pose a significant threat to species and/or ecosystems that are vulnerable to this threat.

7D Extent and success of management programs to minimise incursion and spread of new and emerging invasive species.

By 2030, Australia has a much stronger environmental biosecurity system enabling more effective:

- Prevention: The number of new invasive species entering Australia has been reduced and no new very-high-risk invasive species have become established.
- Eradications: Priority invasive species are being systematically eliminated from both the mainland and islands.

- Containment and control: Invasive species have not caused any more extinctions, high priority invasive species are being effectively contained or controlled, and priority biodiversity sites are being protected.

5.2 The Scottish Biodiversity Strategy

The SBS sets out Scotland's ambitions for urgently tackling the crises identified by IPBES. The aim for Scotland is to be "Nature Positive" by 2030, and by 2045 "Scotland will have restored and regenerated biodiversity across our land, freshwater and seas".

The first version of the SBS had specific metrics indicated. Although these were made more generic in subsequent versions, it is helpful to map plant health and biosecurity to these earlier metrics as they provide a useful framework for specific actions.

These metrics include 26 Priority Actions which, if met, will address biodiversity loss in Scotland. This will be achieved through (a) Statutory Targets for nature restoration in a Natural Environment Bill, and (b) Delivery Plans containing detailed actions which will be reviewed every five years.

Priority action 1 - Accelerate restoration and regeneration

An important aspect of this priority action is the introduction of a programme of ecosystem restoration, using National Parks and protected areas as exemplars of ecosystem restoration and regeneration. In plant health terms, restoration projects need to be carefully planned to ensure that any plants used for reintroductions or translocations are disease free (Gaywood, et al., 2022) (Figure 6). The inadvertent introduction of a disease into a sensitive habitat will seriously undermine conservation efforts.

With this in mind, it is important that as National Parks and protected areas become exemplars for restoration, they also become exemplars for biosecurity, creating safe processes that reduce the risk of the inadvertent introduction of new pests into important habitats in Scotland.

Figure 6. A Royal Botanic Garden Edinburgh (RBGE) reintroduction project for Cicerbita alpina in the Scottish Highlands.

Natural regeneration is an important mechanism for adaptation to pests over time (Fischer, et al., 2016). Although trees are long lived and cannot physically move as the climate changes, they can adapt genetically through gene flow. As the climate changes, the offspring produced by trees will be better adapted to their local environment over time (Savolainen, et al., 2007). This process is significantly disrupted when an introduced species impacts a population, reducing its number and ability to adapt. This leads to a lower genetic diversity in the surviving population, which will reduce its resilience to future threats.

In Scotland, deer numbers are very high, which reduces the opportunity for natural regeneration and natural spread of some native plant species (Forestry & Land Scotland, 2021). The SBS Priority Actions to a) substantially reduce deer densities, and b) reduce herbivore impact from livestock grazing, will enable natural regeneration, and therefore adaptation, to take place which will increase landscape resilience.

Priority Action 2 - Expand protected areas to 30% and improve connectivity and condition

Protected areas provide an opportunity to increase landscape scale resilience whilst demonstrating conservation best practice. An important part of this best practice is the consideration of plant health and biosecurity when creating or expanding protected areas. This should include the safe sourcing of plants to prevent the introduction of a new insect pest or pathogen.

Plant health processes, such as surveillance and monitoring, should be part of planning frameworks so that any issues can be identified early and managed in a timely fashion (Kalaris, et al., 2014). This is particularly important in protected areas that contain sensitive habitats which can be irreversibly damaged by an introduced pest.

An additional complication is that enhancing connectivity can allow introduced species to expand their range along with the intended species (Moslonka-Lefebvre, et al., 2011). However, this needs to be balanced against the negative consequences of fragmentation; isolated populations can decline due to genetic isolation (Baack, et al., 2015), therefore connectivity and the associated gene flow can improve resilience to disturbance events, and increase pest resistance (Jousimo, 2013). One approach to addressing this trade-off is to introduce heterogeneity in habitat creation to reduce the risk of encouraging pest dispersal along corridors (Hamilton, et al., 2006), while still reducing the negative risks of population isolation and fragmentation.

Priority Action 3 - Support nature-friendly farming, fishing and forestry

Forestry is an important industry in Scotland, which has been particularly hard hit by a series of introduced pests over the last 30 years (Spence, et al., 2020). For example, *Phytophthora ramorum* has had a significant impact on plantations of Japanese larch since its discovery in 2009 (Figure 7). This has led to large areas of Scotland being clear-felled to control the disease, particularly in the west which is climatically more conducive to *Phytophthora* (King, et al., 2015). In addition, the pathogen persists in the soil (Shishkoff, 2007) making sites unsuitable for replanting larch or other potential hosts.

Figure 7. A dead Japanese larch plantation infected by P. ramorum in Dumfries and Galloway.

It is therefore critical that whilst increasing biodiversity and habitat connectivity, as well as sustaining timber production and carbon sequestration, consideration of plant health issues are central to forestry planning processes. This may include diversification of the species that are currently utilised in order to build resilience into the future of forestry in Scotland (Ennos, et al., 2020).

A critical element of future forestry planning should be to continue to protect important native woodlands from introduced pests, for example, the irreplaceable Caledonian Pine Forests of Scotland (see Case Study 1). International examples of how to protect important native species from introduced pathogens are available. For example, Kauri (*Agathis australis*) forests in New Zealand have been severely impacted by an introduced *Phytophthora* species and as a result the Department of Conservation has introduced physical measures to protect the kauri forests (Figure 8).

Figure 8. Biosecurity measures introduced to protect a New Zealand native forest from disease.

<u>Priority Action 4 - Recover and protect vulnerable and important species</u>

As mentioned in Priority Action 1, plant health considerations are central to species recovery, reintroduction and reinforcement programmes (Gaywood, et al., 2022). The accidental introduction of a pest into a natural population through a reintroduction programme is a very real risk. Therefore, biosecurity processes need to be built into recovery programmes from their initiation to ensure safe practices are in place.

This is particularly important when considering programmes for some of Scotland's more sensitive habitats such as the temperate rainforests (Figure 9) along the west coast since these delicate habitats are ideal for pathogens such as *Phytophthora* species (see Case Study 2). These pathogens require water in order to survive and spread, therefore a rainforest is ideal (Tracy, 2009). The impact of the introduction of such a pathogen would be catastrophic. Therefore, good biosecurity processes are critical in these areas.

Figure 9. Ballachuan Atlantic hazel wood on Seil Island, near Oban.

<u>Priority Action 5 - Generate the investment needed to support nature recovery</u>

It is widely recognised that in plant health terms, investing in prevention of new species introductions through improved biosecurity is far cheaper than managing their impacts in the long term (Rout, et al., 2011). For example, the economic, ecological and cultural cost of the ash dieback epidemic (Figure 10), caused by an introduced fungus, has been calculated at £15 billion in the long term (Hill, et al., 2019). Whilst this pathogen may have blown into GB from continental Europe, it was the trade in cheap ash saplings that exacerbated the epidemic. If measures were put in place when the disease was first discovered in Europe in the 1990s, the spread and impact could have been more effectively managed (Enderle, et al., 2019).

Therefore, early investment in biosecurity to protect Scotland's most important species is critical to avoid significant costs into the future.

Figure 10. The symptoms of ash dieback disease.

In summary, the Priority Actions outlined in the SBS provide good opportunities to incorporate plant health and biosecurity in conservation programmes and actions. **At present, the recently published SBS (Sept 2023) does not explicitly mention plant pests, but there is a clear opportunity to include plant health and biosecurity at the delivery stage to ensure biosecurity processes are in place to prevent the introduction of novel plant pest species** (Table 5). Likewise, an accompanying Plant Biodiversity Strategy for Scotland has been published, which explicitly includes addressing plant health threats to biodiversity.

Table 5. A summary of the plant health issues arising from the SBS

Conservation element	Plant health issues	Mitigation
Recovery	Adaptation through natural regeneration is an important part of recovery from epidemics. For this to happen in Scotland, herbivore pressure needs to be reduced in many areas, in particular red deer and sheep, to enable regeneration.	A national deer management strategy to keep numbers at a level which allows widespread regeneration and recovery of natural habitats. Surveillance and monitoring program to monitor levels of natural regeneration.
Restoration (reintroduction and reinforcement)	Restoration activities have the potential to inadvertently introduce plant pests into a new habitat. Disease symptoms often take time to become noticeable, therefore diseased plants can unwittingly be used in conservation activities. This may have profound implications for the habitat into which the disease is introduced.	Good biosecurity procedures are critical to any restoration activities. Plants must be sourced from nurseries that adhere to the strictest biosecurity processes. A quarantine period of 12 months will help to identify any latent pathogens.

Expansion of protected areas	If expansion requires an increase in planting, the plants used should be free from pests. If expanding an area where a pest is already present, then careful planning should take place.	Surveillance and monitoring program within the protected area to identify plant health issues early and allow for corrective actions to be taken.
Connectivity	There is a risk that increasing connectivity also provides corridors for introduced pests. Conversely, populations in isolation are vulnerable to disturbance. Connectivity is therefore linked to scale. In some instances, it is better to allow for gene flow, and therefore adaptation, to occur through connected landscapes rather than promote isolation. However, for small, isolated populations, it is potentially more important to maintain their isolation to protect them from new pests and/or diseases.	Heterogeneity in habitat creation can reduce this risk, especially if pests are host/habitat specific. Effective national plant health surveillance and monitoring program to catch newly introduced species early and halt their spread through landscapes before they become a wider issue.

Case Study – The Caledonian Pine Woods

Scotland's pine woods appear on the Scottish Biodiversity List (2020) and are of particular importance for biodiversity conservation in Scotland. They are genetically distinct from the boreal pinewoods which extend across northern Europe and are thought to be approximately 25,000 ha in size (JNCC, 2022).

The Caledonian pinewoods comprise relict, indigenous pine forests of Scots pine (*Pinus sylvestris* var. *scotica*) along with birch (*Betula* spp.) and juniper (*Juniperus communis*) woodlands (figure 11). The ground flora typically includes the dwarf shrubs heather (*Calluna vulgaris*), bilberry (*Vaccinium myrtillus*) and cowberry (*V. vitis-idaea*), wavy hair-grass (*Deschampsia flexuosa*), and the bryophytes *Dicranum scoparium*, *Hylocomium splendens*, *Pleurozium schreberi* and *Rhytidiadelphus loreus* (JNCC, 2022). These woods also support rare plants including creeping lady's-tresses (*Goodyera repens*), twinflower (*Linnaea borealis*) and the moss *Ptilium crista-castrensis*.


Figure 11. Part of the Caledonian pinewoods on the Mar Lodge Estate.

There are a number of significant plant pests which present a significant threat to Scotland's pine woods. Currently, Dothistroma needle blight, caused by a fungal infection of pine needles, is having an impact on pine species across Scotland (Fraser, et al., 2015). The pathogen, *Dothistroma septosporum* is known to have two mating types and multiple genotypes, which means that there is a significant risk of genetic exchange, therefore making future virulence unpredictable (Groenewald, et al., 2007). There is also another species of *Dothistroma*, *D. pini*, which would have an additional impact if it were introduced (Barnes, et al., 2004).

Another important tree species in this habitat is juniper (*Juniperus communis*). Unfortunately, this important native conifer has been severely impacted by the introduced pathogen *Phytophthora austrocedri* (Green, et al., 2015). This pathogen is now widespread in juniper populations across northern England and throughout Scotland (Forest Research, 2022).

In addition to the pests which are currently present in Scotland, there are several future potential threats for pine. The UKPHRR (Defra, 2022) lists 43 pests where *Pinus* is the principal host, of which 33 are Regulated Quarantine Pests. These threats include:

- Pine pitch canker; a disease caused by the fungus *Fusarium circinatum,* which leads to extensive tree deaths, reduced growth and timber quality degradation. It is present in Europe (France and Italy), North America and parts of Asia. Spores are spread by wind and enter trees through wounds (e.g., wind damage, branch removal, insect damage, etc.). The fungus can live for more than a year in wood and can infect seeds (Forestry Commission, 2017). The movement of pine seeds and plants is therefore a significant disease pathway.
- Pine wood nematode (PWN) (*Bursaphelenchus xylophilus*); a microscopic worm-like organism which causes pine trees to wilt and die because the nematodes feed on the epithelial cells lining the resin ducts and block the water transport system of the tree.

PWN are spread by sawyer beetles (species in the *Monochamus* genus) which are not native to the UK. PWN is present in Europe and there is a significant risk of it, and the sawyer beetles, being moved around through the international trade in plants, wood and wood products.

- Pine Processionary Moth (PPM) (*Thaumetopoea pityocampa*); a moth species with human and animal health hazard implications due to the hairs on the caterpillars, which cause severe allergic reactions in those who encounter them. There have been interceptions of this pest in the UK, so vigilance is required to keep this pest out of Scotland.

These threats have been compounded by the relationships between native pine and juniper to commercial forestry species, and particularly to large scale plantation forestry of *Pinus* species. The Dothistroma needle blight epidemic has been amplified by the introduction of new pathogen genotypes on plantation pine (Ennos, et al., 2020). Pine import controls have been tightened in recent years, yet pine plants for planting may still be imported from Europe, and pine seed worldwide (UK Animal & Plant Health Agency, n.d.). While phytosanitary inspection and certification are required for plant and seed imports, these are not guarantees and the introduction of pine pitch canker, PWN, and PPM remain possible.

Phytophthora austrocedri, a threat to native *Juniperus*, was also introduced on plants for planting, but in this case on *Juniperus* planted out for restoration of poorly regenerating juniper woodlands (Donald, et al., 2021). The pathogen has now been detected in streams and paths through much of Scotland.

In contrast to pine and juniper, twinflower has very few known pests, and none in the UKPHRR. Its primary threat has been identified as extreme habitat fragmentation, as in Scotland it grows almost exclusively in Caledonian pinewood. There are currently just a few known patches of twinflower, most of which are represented by a single clonal genotype (Wiberg, et al., 2016). Self-incompatibility and the lack of gene flow among sites due to fragmentation, perpetuate this clonal reproduction and make sites vulnerable to extirpation.

An action plan for twinflower will thus necessarily include nursery propagation and plant translocations (Wiberg, et al., 2016; Wilcox 2002). Twinflowers are propagated via stolon cuttings, which may carry with them any associated microbes, whether mutualists, commensals or pathogens. Propagating any mutualists with the twinflower will clearly have a positive effect on their health. However, nurseries are prolific sources of soil pests like *Phytophthora* species (Gaywood, et al., 2022), and there is a risk that soil carried with propagated twinflower may contain propagules of pests that, even if they cause no harm to twinflower, can easily spread to susceptible species around them.

Pine, juniper, and twinflower have differing known pest threats, but all are affected by the fragmentation of pinewoods, which can be exacerbated by the planting of exotic conifer plantations. In this case, fragmentation is a contextual pressure that prevents gene flow among patches, which is a barrier to resilience and adaptation. Where the intervening landscape is filled with plantations, these may act as corridors for the transmission of pests and pathogens, whilst not necessarily providing any connectivity benefits (in terms of beneficial gene flow to the host species).

In addition to nearby forestry, conservation plantings (as evidenced by juniper) and recreational uses such as walking and mountain biking, for which pinewoods are popular destinations, are likely conduits for new pests.

The fates and resilience of all plants in the pinewood community are tied to Scots pine; the loss of which has had knock-on effects on dependents such as twinflower. Conservation responses for such species with poor regeneration often must include augmentation of genetic diversity. However, these augmentations must follow good biosecurity practice to avoid becoming a threat in their own right.

These examples show that when considering the conservation of a population of important plants, biosecurity should be central to planning and delivery. In particular, the sourcing of plants is a critical aspect, ensuring that the risk of the inadvertent introduction of the known pests on the UKPHRR, and the unknown pine pests that are yet to be discovered, is kept to a minimum.

6 Summary and Conclusions

The impacts of introduced pests have been significant in recent times and with many known pests on the horizon, and in a changing climate, these impacts will only become greater if this aspect of loss is not addressed within biodiversity strategies. With nearly a third of the world's tree species threatened with extinction (BCGI, 2021), and the risks posed by emerging diseases to worldwide biodiversity only increasing (Fisher, et al., 2012), the stakes have never been higher.

Of the 1409 pests listed in the UKPHRR on 12/09/2022, 1061 were associated with genera represented in Scottish vegetation. 225 of these pests are already present in the UK and the remainder will have an impact if they get here. Forty two of the host species in question are designated as biodiversity priorities in the Scottish Biodiversity List, therefore the need to act is now.

The priority species' genera *Salix*, *Chenopodium*, *Juniperus* and *Malus* were associated with especially high cumulative pest ratings. *Salix* cumulative rating was more than twice that of *Chenopodium*, *Juniperus*, and *Malus*, which were in turn more than twice as high as the next nearest neighbour. With impacts already present on these species (e.g., *Phytophthora austrocedri* infecting *Juniperus communis* across Scotland), it is critical that no more new introduced species are brought into these habitats to further increase biodiversity loss.

The stakeholders consulted in this study placed importance most highly on the plant health impacts on species which support multiple specialised interactions (because the loss of these species would have cascading impacts through an ecosystem) and also low intraspecific genetic diversity or habitat species diversity (which increase susceptibility to plant health threats). Conversely, nearby vehicle traffic and exposure to weather patterns that may facilitate pest movement were judged as least important. This is surprising given the numerous examples of pests that have arrived in GB through these pathways. For example, *Ips typographus* (the larger eight-toothed European spruce bark beetle) which has been intercepted in the south of England (potentially via wind dispersal from the continent) and Scotland (assumed to have arrived on timber). This pest will have a significant impact on forestry should it become established in GB.

Stakeholders were concerned with the biosecurity regarding pest movement from plant trade into the wider environment, illustrated by comments such as "Bulk selling cheap plant material by Euro supermarkets," "biosecurity and international movement of plants and soil," and "border pressure and checks." Addressing these aspects of biosecurity are being explored in the Plant biosecurity strategy for Great Britain (2023 to 2028) (Defra, 2023).

The lack of governmental and scientific resource allocation to the natural environment was also a concern. This included a lack of pre-existing research on pest and host interactions, which makes plant health risk assessment for conservation activities very challenging. At the scale of plant species or population, experts most consistently ranked pre-existing disease pressure as the highest plant health risk, followed closely by other stresses, including climate stress and intraspecific genetic diversity. Range restriction (having a limited or marginal habitat) was rarely ranked highly against the other factors and, of the six factors evaluated, long generation times were considered least important.

At the site or plant community scale, proximity to plant traders and proximity to large-scale plantings, including conservation, forestry, or landscaping, were ranked highly. Landscape connectivity and exposure to continental weather patterns were least often placed highest. This clearly demonstrates that biosecurity should be central to conservation efforts at the landscape scale, so that all actors are able to consider and mitigate the risks.

Expert stakeholders also echoed the IPBES Global Assessment of Biodiversity Report (2019) in their recognition that the threats to plant biodiversity were interlinked. Existing disease threats compound pressures of climate stress, habitat loss, range contraction and fragmentation, all of which can reduce intraspecific genetic diversity, or in the case of extirpation, habitat species diversity. Live plant movements, whether in trading centres or via planting projects, can introduce new pests or spread existing ones. Recreation (e.g., hiking, mountain biking, etc.), industry or development, and roads, facilitates movement of these pests across the landscape.

The information provided by experts, and the data on current plant health threats in the UKPHRR, were brought together to create a novel framework for understanding the vulnerability of species and habitats to plant health threats (Figure 4). This framework can be used to assess and mitigate the plant health risks associated with conservation activities such as plant relocations, translocations, habitat creation and habitat restoration. For example, those carrying out woodland restoration in National Parks can use the framework to assess and address the plant health risks associated with that activity.

In recognition of these pressures on species and habitats, this study found that biosecurity has successfully been incorporated into national biodiversity strategies in some countries, including New Zealand and Australia.

The SBS recognises the importance of National Parks and protected areas, making them exemplars for restoration. It is therefore critical that National Parks also become exemplars for biosecurity, creating and demonstrating safe processes for plant production, movement and planting. Otherwise, conservation activities will be severely undermined with the inadvertent introduction of a novel pest into one of Scotland's iconic habitats, such as the Caledonian pinewoods (see Case Study).

Forestry is an important industry in Scotland which has recently been impacted by a number of severe introduced pests. As we utilise tree plantings to increase biodiversity and habitat connectivity, as well as sustaining timber production and carbon sequestration, it is crucial that plant health thinking is embedded in all activities. This includes species diversification to build resilience into forests and woodlands in Scotland (Ennos, et al., 2020) and increasing opportunities for promoting natural regeneration. This is particularly important as we strive to increase forest cover whilst protecting important native woodlands from introduced pests, for example, the irreplaceable Atlantic Rainforests.

In conclusion, the messages from this Plant Health Centre report could be incorporated into the Scottish Biodiversity Strategy as follows:

Additional point to Section 3.1 of the Scottish Biodiversity Strategy; What does success look like?

- Biosecurity will be at the heart of conservation work to prevent further pressure on habitats by the accidental introduction of new pests during tree planting, habitat restoration or translocations.

We would therefore recommend that the following points are incorporated into the implementation of the Scottish Biodiversity Strategy.

Additional points for Section 3.2 (Objectives for 2030)

<u>1. Accelerate restoration and regeneration</u>

Restoration needs to consider:

- Introducing biosecurity into restoration and regeneration plans to prevent further spread or introductions of pests.
- A framework for understanding the vulnerability of species and habitats to plant health threats is available from this report.
- Regeneration should be favoured over new plantings. This could include direct seeding and promoting the conditions required for natural regeneration.
- National Parks could act as exemplars of *effective biosecurity processes*, ecosystem restoration and regeneration.

<u>2. Protect nature on land and at sea, across and beyond protected areas</u>

- Biosecurity is central to the protection of habitats from the introduction and spread of new pests and diseases. Incorporating biosecurity into conservation plans before any work is carried out ensures that expansion of nature protection does not result in the expansion of pests and diseases.

<u>3. Embed nature-friendly farming, fishing and forestry</u>

- A biosecurity risk assessment is an essential element of delivering increased biodiversity and habitat connectivity whilst sustaining timber production and carbon sequestration.

<u>4. Recover and protect vulnerable and important species</u>

- Species recovery, reintroduction and reinforcement programmes should use the most effective biosecurity processes available to prevent the introduction of damaging species into sensitive habitats.

Additional points for Section 4 (Enabling Conditions for Success)

<u>4.1 Lessons</u>

- Learn from other countries that have successfully incorporated biosecurity into biodiversity strategies.

<u>4.2 Scotland's Biodiversity Delivery Framework</u>

- The five-year rolling Delivery Plans should contain a pest risk assessment to prevent further pest spread and introductions.

Additional points for Section 5 (Monitoring Framework)

<u>5.1 How we will know if and when we have halted biodiversity loss?</u>

- The suite of indicators used to reveal how biodiversity is responding to the various pressures should include an indicator for introduced pest pressure.

<u>5.3 Evidence-based good practice and monitoring is essential</u>

- A framework for understanding the vulnerability of species and habitats to plant health threats is available from this report.
- Evidence based good practice guidance for biosecurity for conservation work is now available and should be utilised in the Scottish Biodiversity Strategy going forward (Mitchell, 2023).

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8 Supplementary tables

Supplementary Table 1. The cumulative UK Plant Health Risk Register risk (as Impact x Mitigated Likelihood, scaled 0-25) of pests associated with genera of Scottish plant biodiversity. "Present" indicates the number of pests known already to be present within the UK; the remaining pests have unknown distributions or have not yet been detected nationally. Plant genera with no associated RR pests are not listed. Remaining columns represent the breakdown of 'n' into pest groups.

Genus	n	Summed Risk*	Present	Bacteria	Fungi	Insects	Mites	Nema-todes	Oomy-cetes	Phyto-plasmas	Pest Plants	Viruses
Solanum	299	1556	55	15	18	137	5	43	3	9	0	68
Prunus	245	1159	54	9	17	145	1	28	2	14	0	28
Malus	176	784	46	3	37	90	1	15	0	4	0	25
Pinus	143	753	19	0	33	88	0	11	2	1	8	0
Quercus	90	557	16	2	17	60	0	5	4	1	0	0
Rosa	90	511	20	2	2	54	5	14	2	3	0	8
Fragaria	107	465	47	4	12	31	3	25	4	11	0	17
Brassica	84	461	22	5	6	42	0	23	0	2	0	6
Ulmus	63	404	16	3	7	45	0	4	0	3	0	1
Picea	71	397	15	0	13	51	0	2	1	1	3	0
Populus	67	393	10	2	8	48	2	4	0	3	0	0
Salix	66	387	9	3	3	57	0	1	1	0	0	0
Acer	63	369	16	2	10	40	1	7	3	0	0	0
Lactuca	60	361	17	2	3	27	1	11	0	3	0	11
Larix	53	343	11	0	12	36	0	2	1	0	2	0
Vaccinium	61	336	17	2	9	24	0	7	4	5	0	10
Fraxinus	54	328	12	2	5	41	0	2	1	1	0	2
Rubus	81	315	36	4	5	29	1	12	3	3	0	24
Allium	58	307	22	3	4	24	1	17	0	3	0	6
Medicago	69	303	17	3	5	40	1	15	0	3	0	2
Beta	57	289	15	2	2	25	2	19	0	1	0	6
Betula	46	287	9	0	5	36	1	1	1	0	0	2
Chrysanthemum	47	271	15	1	2	29	1	4	1	2	0	7

Genus	n	Summed Risk*	Present	Bacteria	Fungi	Insects	Mites	Nema-todes	Oomy-cetes	Phyto-plasmas	Pest Plants	Viruses
Castanea	42	270	15	0	11	24	0	2	4	0	0	1
Daucus	49	269	16	3	2	20	1	15	0	3	0	5
Pseudotsuga	40	237	11	1	9	24	0	3	2	0	1	0
Trifolium	51	237	15	1	0	27	0	14	0	6	0	3
Apium	37	224	14	2	2	15	1	5	1	6	0	5
Triticum	42	196	6	1	5	25	0	10	0	0	0	1
Euphorbia	33	195	9	4	5	16	3	2	0	1	0	2
Corylus	29	176	12	3	8	14	1	0	1	1	0	1
Alnus	30	174	9	0	5	21	0	0	4	0	0	0
Amaranthus	29	174	5	1	0	18	2	0	0	3	0	5
Fagus	29	167	13	0	7	14	0	5	3	0	0	0
Aster	33	166	7	0	3	24	0	0	1	3	0	2
Hordeum	34	164	7	1	3	17	0	12	0	0	0	1
Crataegus	36	163	10	2	6	23	0	1	0	0	0	4
Chenopodium	28	162	7	2	0	9	0	7	0	0	0	10
Juniperus	27	156	5	0	10	13	1	2	1	0	0	0
Rhododendron	31	154	15	1	6	16	1	4	3	0	0	0
Sorbus	29	153	9	2	7	16	0	1	0	0	0	3
Avena	29	139	7	1	0	17	0	10	0	0	0	1
Cornus	26	138	6	0	1	21	0	2	1	0	0	1
Malva	20	133	3	1	0	11	1	1	0	0	0	6
Vicia	29	132	11	1	1	13	0	6	0	2	0	6
Aesculus	19	120	9	2	2	11	0	0	3	0	0	1
Viburnum	20	119	3	0	1	15	1	1	1	1	0	0
Taxus	15	110	6	1	2	5	1	4	2	0	0	0
Salvia	18	108	7	1	1	10	0	2	0	1	0	2
Ilex	21	105	6	0	3	12	0	4	2	0	0	0

Genus	n	Summed Risk*	Present	Bacteria	Fungi	Insects	Mites	Nema-todes	Oomy-cetes	Phyto-plasmas	Pest Plants	Viruses
Ligustrum	21	104	3	1	1	12	0	5	1	1	0	0
Mentha	16	103	7	0	1	9	0	4	0	0	0	2
Carpinus	17	99	3	0	2	13	0	1	1	0	0	0
Tilia	17	99	5	1	2	12	0	0	0	2	0	0
Convolvulus	14	95	6	0	1	5	1	2	0	2	0	3
Raphanus	20	95	3	3	0	13	0	4	0	0	0	0
Ribes	40	95	28	1	8	12	2	5	2	0	0	10
Sonchus	12	82	4	0	1	3	0	1	0	0	0	7
Impatiens	12	81	6	0	2	3	1	1	1	0	0	4
Plantago	9	81	3	1	0	3	0	0	0	0	0	5
Cichorium	14	80	4	0	0	5	0	2	1	2	0	4
Iris	11	78	6	0	0	3	0	6	0	0	0	2
Humulus	14	77	6	1	2	3	0	3	0	0	0	5
Euonymus	14	76	2	0	1	10	0	2	0	1	0	0
Lolium	16	71	6	1	2	7	0	5	0	0	0	1
Artemisia	22	70	2	1	0	19	0	0	1	0	0	1
Urtica	10	67	6	0	1	6	0	2	0	0	0	1
Buxus	10	59	2	0	0	8	0	1	1	0	0	0
Hedera	11	59	4	0	1	9	0	0	1	0	0	0
Taraxacum	8	57	2	0	0	1	0	1	0	0	0	6
Lonicera	11	56	3	2	0	7	0	0	1	0	0	1
Oxalis	10	56	3	0	0	4	1	2	0	0	0	3
Sambucus	13	53	7	0	1	4	0	2	0	1	0	5
Narcissus	9	51	6	0	0	1	0	6	0	0	0	2
Polygonum	8	51	3	0	0	4	0	2	0	0	0	2
Primula	9	51	7	1	0	3	0	1	0	2	0	2
Clematis	9	49	2	0	0	6	1	0	0	1	0	1

Genus	n	Summed Risk*	Present	Bacteria	Fungi	Insects	Mites	Nema-todes	Oomy-cetes	Phyto-plasmas	Pest Plants	Viruses
Poa	10	48	5	0	1	4	0	3	0	0	0	2
Stellaria	12	48	7	0	1	1	0	4	0	0	0	6
Anemone	9	46	8	0	1	0	0	2	0	3	0	3
Rumex	12	44	4	0	1	7	0	1	0	0	0	3
Lupinus	12	43	8	1	3	6	0	1	0	0	0	1
Festuca	6	39	2	0	1	3	0	2	0	0	0	0
Thymus	5	39	1	0	0	5	0	0	0	0	0	0
Atriplex	6	38	0	0	0	2	1	0	0	0	0	3
Agrostis	7	35	2	1	1	2	0	3	0	0	0	0
Hypericum	7	35	0	0	0	7	0	0	0	0	0	0
Ranunculus	7	35	5	0	0	2	0	2	0	1	0	2
Geranium	5	34	1	0	0	3	0	1	0	0	0	1
Pastinaca	4	33	1	1	1	1	0	0	0	1	0	0
Eupatorium	6	32	0	0	1	5	0	0	0	0	0	0
Linum	11	32	7	1	5	3	0	2	0	0	0	0
Lathyrus	8	30	4	1	0	6	0	0	0	0	0	1
Myrica	6	30	0	0	1	5	0	0	0	0	0	0
Veronica	7	30	6	0	0	1	0	3	0	2	0	1
Arctostaphylos	4	28	2	0	1	1	0	0	2	0	0	0
Sinapis	8	28	3	2	1	3	0	2	0	0	0	0
Origanum	3	27	0	0	0	2	0	0	1	0	0	0
Solidago	14	27	1	1	1	12	0	0	0	0	0	0
Aquilegia	2	26	2	0	0	1	0	0	1	0	0	0
Helianthemum	4	26	1	0	1	3	0	0	0	0	0	0
Crassula	4	25	2	0	0	3	0	1	0	0	0	0
Erica	5	25	3	0	2	3	0	0	0	0	0	0
Ajuga	3	24	0	0	0	2	0	1	0	0	0	0

Genus	n	Summed Risk*	Present	Bacteria	Fungi	Insects	Mites	Nema-todes	Oomy-cetes	Phyto-plasmas	Pest Plants	Viruses
Bidens	7	24	1	0	0	4	1	1	0	0	0	1
Bromus	5	24	2	1	1	2	0	0	0	0	0	1
Cardamine	3	24	1	0	0	1	0	0	0	0	0	2
Digitalis	3	24	0	1	0	1	0	1	0	0	0	0
Erigeron	7	24	1	0	1	4	0	1	0	0	0	1
Senecio	13	24	9	0	2	4	0	4	0	2	0	1
Calluna	2	22	1	0	0	1	0	0	1	0	0	0
Cerastium	3	22	1	0	0	0	0	1	0	0	0	2
Sisymbrium	3	22	0	1	0	1	0	0	0	0	0	1
Tanacetum	6	22	4	1	1	2	0	1	0	0	0	1
Leucanthemum	2	21	0	0	0	1	0	0	1	0	0	0
Capsella	6	20	4	0	1	1	0	2	0	0	0	2
Cirsium	3	20	1	0	0	3	0	0	0	0	0	0
Melilotus	4	19	0	1	0	2	0	0	0	0	0	1
Achillea	5	18	1	0	1	4	0	0	0	0	0	0
Dactylis	6	18	2	0	1	3	0	2	0	0	0	0
Galium	2	18	1	0	0	2	0	0	0	0	0	0
Phragmites	4	18	0	0	0	4	0	0	0	0	0	0
Tussilago	3	18	2	0	0	0	0	2	0	1	0	0
Valerianella	2	18	2	0	1	0	0	0	0	0	0	1
Asplenium	5	17	3	0	0	3	0	2	0	0	0	0
Polystichum	3	17	1	0	0	1	0	2	0	0	0	0
Viola	6	17	4	1	1	0	0	3	0	0	0	1
Arctium	2	16	1	0	0	0	0	0	0	0	0	2
Dryopteris	1	16	1	0	0	0	0	0	1	0	0	0
Juncus	3	16	1	0	0	2	0	1	0	0	0	0
Inula	2	15	0	0	0	1	0	0	0	0	0	1

Genus	n	Summed Risk*	Present	Bacteria	Fungi	Insects	Mites	Nema-todes	Oomy-cetes	Phyto-plasmas	Pest Plants	Viruses
Picris	3	15	1	0	0	1	0	0	0	0	0	2
Anagallis	2	14	2	0	0	0	0	1	0	0	0	1
Cytisus	2	14	0	1	0	1	0	0	0	0	0	0
Limonium	3	14	2	1	0	1	0	1	0	0	0	0
Papaver	2	14	0	0	0	0	0	1	0	0	0	1
Ruscus	3	14	1	0	0	1	0	2	0	0	0	0
Buddleja	3	13	1	0	0	2	0	1	0	0	0	0
Nasturtium	3	13	0	0	0	3	0	0	0	0	0	0
Arum	1	12	0	0	0	0	0	0	0	0	0	1
Calystegia	1	12	0	0	0	1	0	0	0	0	0	0
Carex	3	12	0	0	0	3	0	0	0	0	0	0
Ceratophyllum	2	12	0	0	0	1	0	1	0	0	0	0
Liparis	1	12	0	0	0	1	0	0	0	0	0	0
Sagittaria	3	12	1	0	0	1	0	1	0	0	0	0
Salsola	1	12	0	0	0	1	0	0	0	0	0	0
Spergula	1	12	0	0	0	0	0	0	0	0	0	1
Spergularia	1	12	0	0	0	0	0	0	0	0	0	1
Teucrium	1	12	1	0	0	1	0	0	0	0	0	0
Valeriana	2	12	1	1	0	0	0	0	0	1	0	0
Matricaria	3	10	1	0	0	2	0	1	0	0	0	0
Onobrychis	2	10	1	0	1	1	0	0	0	0	0	0
Anthoxanthum	2	9	1	0	0	2	0	0	0	0	0	0
Arabidopsis	1	9	0	1	0	0	0	0	0	0	0	0
Conyza	1	9	0	0	0	1	0	0	0	0	0	0
Eryngium	1	9	0	0	0	0	0	0	0	0	0	1
Myosotis	2	9	1	1	0	1	0	0	0	0	0	0
Sedum	1	9	0	1	0	0	0	0	0	0	0	0

Genus	n	Summed Risk*	Present	Bacteria	Fungi	Insects	Mites	Nema-todes	Oomy-cetes	Phyto-plasmas	Pest Plants	Viruses
Suaeda	1	9	0	0	0	1	0	0	0	0	0	0
Alopecurus	2	8	0	0	0	2	0	0	0	0	0	0
Anthemis	2	8	1	0	0	0	0	1	0	1	0	0
Anthriscus	1	8	0	0	0	1	0	0	0	0	0	0
Bellis	1	8	1	0	0	1	0	0	0	0	0	0
Blechnum	2	8	1	0	0	2	0	0	0	0	0	0
Convallaria	1	8	0	0	0	1	0	0	0	0	0	0
Elodea	1	8	0	0	0	1	0	0	0	0	0	0
Geum	2	8	2	0	0	0	0	2	0	0	0	0
Heracleum	2	8	1	0	0	2	0	0	0	0	0	0
Lamium	2	8	2	0	0	1	0	1	0	0	0	0
Phleum	2	8	1	1	1	0	0	0	0	0	0	0
Pimpinella	2	8	0	0	0	2	0	0	0	0	0	0
Polygonatum	1	8	0	0	0	1	0	0	0	0	0	0
Pteridium	1	8	1	0	0	1	0	0	0	0	0	0
Saxifraga	2	8	1	0	0	0	0	1	0	0	0	0
Polygala	2	7	0	1	0	1	0	0	0	0	0	0
Arrhenatherum	2	6	1	0	1	1	0	0	0	0	0	0
Carduus	1	6	0	0	0	1	0	0	0	0	0	0
Carlina	1	6	0	0	0	1	0	0	0	0	0	0
Centaurea	2	6	0	0	0	2	0	0	0	0	0	0
Cladium	1	6	0	0	0	1	0	0	0	0	0	0
Eleocharis	1	6	0	0	0	1	0	0	0	0	0	0
Eriophorum	1	6	0	0	0	1	0	0	0	0	0	0
Fumaria	1	6	1	0	0	0	0	0	0	0	0	1
Gnaphalium	1	6	0	0	0	1	0	0	0	0	0	0
Melampyrum	2	6	0	0	2	0	0	0	0	0	0	0

Genus	n	Summed Risk*	Present	Bacteria	Fungi	Insects	Mites	Nema-todes	Oomy-cetes	Phyto-plasmas	Pest Plants	Viruses
Nymphaea	3	6	1	0	0	3	0	0	0	0	0	0
Pulicaria	1	6	0	0	0	1	0	0	0	0	0	0
Pulsatilla	1	6	1	0	0	1	0	0	0	0	0	0
Scilla	1	6	1	0	0	0	0	1	0	0	0	0
Scirpus	1	6	0	0	0	1	0	0	0	0	0	0
Symphytum	2	6	1	1	0	0	0	1	0	0	0	0
Rhamnus	3	5	0	0	0	3	0	0	0	0	0	0
Acorus	1	4	0	0	0	0	0	1	0	0	0	0
Alisma	1	4	1	0	0	1	0	0	0	0	0	0
Barbarea	1	4	0	0	0	1	0	0	0	0	0	0
Butomus	1	4	1	0	0	1	0	0	0	0	0	0
Cakile	1	4	0	0	0	1	0	0	0	0	0	0
Calamagrostis	1	4	0	0	0	1	0	0	0	0	0	0
Callitriche	1	4	1	0	0	1	0	0	0	0	0	0
Cheiranthus	1	4	0	0	0	1	0	0	0	0	0	0
Echium	2	4	1	0	0	1	0	1	0	0	0	0
Genista	1	4	0	0	0	1	0	0	0	0	0	0
Halimione	1	4	0	0	0	1	0	0	0	0	0	0
Leymus	1	4	0	0	0	1	0	0	0	0	0	0
Lobelia	1	4	0	1	0	0	0	0	0	0	0	0
Lycopus	1	4	0	0	0	1	0	0	0	0	0	0
Nuphar	1	4	1	0	0	1	0	0	0	0	0	0
Polypodium	1	4	0	0	0	1	0	0	0	0	0	0
Potamogeton	1	4	1	0	0	1	0	0	0	0	0	0
Scabiosa	2	4	1	0	0	1	0	1	0	0	0	0
Sparganium	1	4	1	0	0	1	0	0	0	0	0	0
Thelypteris	1	4	0	0	0	1	0	0	0	0	0	0

Genus	n	Summed Risk*	Present	Bacteria	Fungi	Insects	Mites	Nema-todes	Oomy-cetes	Phyto-plasmas	Pest Plants	Viruses
Triglochin	1	4	1	0	0	1	0	0	0	0	0	0
Typha	1	4	1	0	0	1	0	0	0	0	0	0
Aegopodium	1	3	0	0	0	0	0	0	0	0	0	1
Gymnadenia	1	3	0	0	0	1	0	0	0	0	0	0
Pedicularis	1	3	0	0	1	0	0	0	0	0	0	0
Deschampsia	1	2	1	0	1	0	0	0	0	0	0	0
Elymus	1	2	1	0	1	0	0	0	0	0	0	0
Koeleria	1	2	1	0	1	0	0	0	0	0	0	0
Anchusa	1	0	1	0	0	0	0	1	0	0	0	0
Astragalus	1	0	1	0	0	1	0	0	0	0	0	0
Caltha	1	0	1	0	0	0	0	1	0	0	0	0
Campanula	2	0	2	0	0	0	0	1	0	0	0	1
Conium	1	0	0	0	0	1	0	0	0	0	0	0
Crambe	1	0	1	0	1	0	0	0	0	0	0	0
Dipsacus	1	0	1	0	0	0	0	1	0	0	0	0
Galeopsis	1	0	1	0	0	0	0	0	0	0	0	1
Hypochoeris	1	0	0	0	0	1	0	0	0	0	0	0
Lotus	2	0	1	0	0	1	0	1	0	0	0	0
Lythrum	1	0	1	1	0	0	0	0	0	0	0	0
Mercurialis	1	0	1	0	1	0	0	0	0	0	0	0
Osmunda	1	0	1	0	0	0	0	1	0	0	0	0
Petasites	1	0	0	0	0	1	0	0	0	0	0	0
Prunella	1	0	1	0	0	0	0	0	0	0	0	1
Rorippa	1	0	1	0	0	0	0	1	0	0	0	0
Scrophularia	1	0	0	0	0	0	0	1	0	0	0	0
Sium	1	0	0	0	0	1	0	0	0	0	0	0
Torilis	1	0	0	0	0	1	0	0	0	0	0	0

Genus	n	Summed Risk*	Present	Bacteria	Fungi	Insects	Mites	Nema-todes	Oomy-cetes	Phyto-plasmas	Pest Plants	Viruses
Trollius	1	0	1	0	0	0	0	1	0	0	0	0

Supplementary Table 2. UK Pest Risk Register high-impact pests associated with the genera in Scottish plant communities. S is the number of taxa per community, N is the number of associated UKPHRR pests, 'Risk' is UKPHRR Impact x Mitigated Likelihood (scaled 0-25 points) summed across genera, and "In UK" is the number of pests known already to be present; the rest have unknown distributions or have not yet been detected nationally. Remaining columns represent the breakdown of 'N' into pest groups.*

Community	NVC Code	S	N	Risk*	in UK	Bacteria	Fungi	Insects	Mites	Nema-todes	Oomy-cetes	Phyto-plasmas	Pest Plants	Viruses
Quercus robur-Pteridium aquilinum-Rubus fruticosus woodland	W10	690	1971	10365	562	59	273	1102	23	216	54	66	11	164
Fraxinus excelsior-Acer campestre-Mercurialis perennis woodland	W8	1058	1941	10220	582	61	228	1089	26	229	47	65	2	190
Fraxinus excelsior-Sorbus aucuparia-Mercurialis perennis woodland	W9	400	1569	8246	456	49	181	888	17	192	35	59	8	137
Crataegus monogyna-Hedera helix scrub	W21	346	1575	8210	459	50	184	884	19	190	37	53	0	154
Alnus glutinosa-Urtica dioica woodland	W6	363	1488	7866	378	50	157	833	13	175	32	38	8	178
Fagus sylvatica-Mercurialis perennis woodland	W12	324	1402	7399	426	52	143	786	20	176	39	54	0	130
Rubus fruticosus-Holcus lanatus underscrub	W24	239	1464	7379	420	54	134	764	18	206	29	57	0	199
Alnus glutinosa-Fraxinus excelsior-Lysimachia nemorum woodland	W7	450	1290	6832	389	46	128	735	15	155	32	49	0	127
Fagus sylvatica-Rubus fruticosus woodland	W14	84	1171	6295	311	41	147	690	10	124	29	31	8	88
Alnus glutinosa-Carex paniculata woodland	W5	396	1111	5875	298	43	99	623	16	130	29	21	0	147
Epilobium angustifolium community	OV27	275	988	5224	269	36	113	531	9	128	19	23	8	120
Salix cinerea-Betula pubescens-Phragmites australis woodland	W2	290	956	5165	230	37	78	552	13	105	23	19	0	126
Poa annua-Matricaria perforata community	OV19	364	957	4915	258	46	60	449	12	183	4	35	0	165
Quercus spp.-Betula spp.-Deschampsia flexuosa woodland	W16	261	859	4658	233	25	143	501	8	73	34	14	8	52
Quercus petraea-Betula pubescens-Dicranum majus woodland	W17	667	834	4492	247	30	116	495	7	74	32	16	0	62
Salix cinerea-Galium palustre woodland	W1	72	823	4420	213	36	74	453	9	89	21	22	0	116
Pteridium aquilinum-Rubus fruticosus underscrub	W25	155	841	4352	253	29	82	473	8	103	21	29	0	94

Community	NVC Code	S	N	Risk*	in UK	Bacteria	Fungi	Insects	Mites	Nema-todes	Oomy-cetes	Phyto-plasmas	Pest Plants	Viruses
Betula pubescens-Molinia caerulea woodland	W4	344	789	4253	203	25	115	480	4	59	27	13	8	56
Chrysanthemum segetum-Spergula arvensis community	OV4	153	799	4092	228	39	47	370	10	153	5	30	0	144
Quercus petraea-Betula pubescens-Oxalis acetosella woodland	W11	505	720	3924	232	25	106	389	5	73	24	19	2	76
Parietaria diffusa community	OV41	103	720	3758	188	37	50	345	12	137	5	21	0	112
Stellaria media-Capsella bursa-pastoris community	OV13	231	708	3718	195	35	45	318	10	137	3	24	0	135
Fagus sylvatica-Deschampsia flexuosa woodland	W15	225	673	3648	185	17	110	374	6	71	31	10	8	45
Epilobium hirsutum community	OV26	403	706	3633	203	33	45	351	7	109	7	20	0	132
Matricaria perforata-Stellaria media community	OV9	272	701	3552	197	32	40	318	7	133	5	23	0	142
Phragmites australis swamp and reed-beds	S4	159	666	3500	181	29	39	340	8	89	9	22	0	128
Salix pentandra-Carex rostrata woodland	W3	115	673	3499	182	28	50	362	7	84	14	16	0	110
Hippophae rhamnoides dune scrub	SD18	145	682	3485	190	30	49	327	8	100	7	20	0	139
Salix repens-Calliergon cuspidatum dune-slack community	SD15	354	665	3332	187	29	40	332	6	106	7	23	0	120
Juncus subnodulosus-Cirsium palustre fen-meadow	M22	476	631	3286	162	28	34	328	5	101	4	21	0	108
Phragmites australis-Eupatorium cannabinum tall-herb fen	S25	162	608	3098	158	28	39	320	6	80	11	15	0	107
Salix repens-Holcus lanatus dune-slack community	SD16	367	591	3042	193	18	57	307	5	88	13	24	0	77
Phragmites australis-Urtica dioica tall-herb fen	S26	209	590	2989	176	27	37	271	7	95	7	22	0	123
Prunus spinosa-Rubus fruticosus scrub	W22	166	595	2972	190	25	43	308	9	84	11	25	0	89
Urtica dioica-Cirsium arvense community	OV25	178	606	2965	192	22	31	299	8	121	6	24	0	95
Bidens tripartita-Polygonum amphibium community	OV30	36	550	2932	132	25	26	277	6	91	4	16	0	103

Community	NVC Code	S	N	Risk*	in UK	Bacteria	Fungi	Insects	Mites	Nema-todes	Oomy-cetes	Phyto-plasmas	Pest Plants	Viruses
Rumex crispus-Glaucium flavum shingle community	SD1	97	553	2928	136	27	38	250	12	91	3	16	0	113
Carex rostrata-Potentilla palustris tall-herb fen	S27	219	547	2875	146	24	30	278	6	84	6	21	0	96
Carex otrubae swamp	S18	113	550	2789	152	23	33	251	7	87	6	15	0	127
Veronica persica-Veronica polita community	OV7	42	521	2745	144	26	33	222	9	95	3	15	0	117
Festuca rubra-Galium verum fixed dune grassland	SD8	557	539	2723	173	22	33	288	7	101	4	24	0	59
Poa annua-Taraxacum officinale community	OV22	217	535	2658	185	19	32	230	6	112	3	23	0	108
Pinus sylvestris-Hylocomium splendens woodland	W18	301	468	2644	100	5	96	282	3	33	11	7	13	18
Luzula sylvatica-Geum rivale tall-herb community	U17	714	517	2639	184	21	44	267	3	69	11	20	0	80
Festuca ovina-Avenula pratensis grassland	CG2	602	561	2635	213	24	49	260	5	115	5	32	0	71
Typha latifolia swamp	S12	155	481	2551	120	22	27	234	6	72	5	19	0	95
Juniperus communis ssp. communis-Oxalis acetosella woodland	W19	276	497	2451	198	15	60	205	7	82	15	25	0	88
Carex riparia swamp	S6	45	483	2443	129	22	29	230	6	71	7	13	0	104
Arrhenatherum elatius grassland	MG1	484	507	2430	200	20	35	233	3	95	7	24	0	90
Festuca ovina-Hieracium pilosella-Thymus praecox/pulegioides grassland	CG7	458	518	2427	190	21	51	226	6	110	5	32	0	67
Lolium perenne-Dactylis glomerata community	OV23	290	488	2421	161	17	28	232	3	108	3	22	0	75
Armeria maritima-Cerastium diffusum ssp. diffusum maritime therophyte community	MC5	264	458	2414	150	23	28	209	7	109	0	21	0	60
Glyceria maxima swamp	S5	100	447	2386	114	19	25	220	6	69	4	16	0	87
Sparganium erectum swamp	S14	141	443	2347	120	20	24	211	6	73	4	18	0	86
Carex elata swamp	S1	34	443	2336	93	21	26	238	5	59	4	10	0	78
Urtica dioica-Galium aparine community	OV24	145	478	2334	171	20	28	214	4	99	5	19	0	89
Scirpus lacustris ssp. tabernaemontani swamp	S20	76	443	2326	97	20	25	211	7	62	5	19	0	93

Community	NVC Code	S	N	Risk*	in UK	Bacteria	Fungi	Insects	Mites	Nema-todes	Oomy-cetes	Phyto-plasmas	Pest Plants	Viruses
Phalaris arundinacea tall-herb fen	S28	96	455	2303	124	21	29	206	7	70	6	13	0	102
Carex paniculata swamp	S3	37	454	2263	121	21	28	211	6	67	7	12	0	101
Poa annua-Senecio vulgaris community	OV10	269	440	2191	158	22	29	193	5	97	1	19	0	74
Carex acutiformis swamp	S7	42	423	2182	117	19	25	197	5	70	3	13	0	90
Polygonum lapathifolium-Poa annua community	OV33	51	445	2166	150	24	30	204	5	106	0	16	0	60
Glyceria fluitans water-margin vegetation	S22	59	408	2147	98	19	24	194	6	62	4	16	0	82
Cladium mariscus swamp and sedge-beds	S2	67	402	2146	75	19	23	220	5	50	4	9	0	70
Elymus repens salt-marsh community	SM28	57	426	2142	132	13	26	214	5	86	2	21	0	59
Salix repens-Campylium stellatum dune-slack community	SD14	405	444	2128	165	17	34	205	4	80	8	23	0	72
Ammophila arenaria-Arrhenatherum elatius dune grassland	SD9	175	434	2087	166	14	27	200	8	88	6	29	0	62
Dryas octopetala-Carex flacca heath	CG13	240	424	2076	145	19	33	216	3	70	8	17	0	56
Festuca ovina-Agrostis capillaris-Rumex acetosella grassland	U1	530	409	2043	151	16	38	194	1	70	8	16	0	65
Molinia caerulea-Cirsium dissectum fen-meadow	M24	279	418	2021	145	17	32	231	1	58	9	15	0	54
Scirpus lacustris ssp. lacustris swamp	S8	116	379	1996	89	17	20	182	5	64	3	10	0	76
Typha angustifolia swamp	S13	34	377	1984	88	16	21	180	5	62	3	10	0	79
Potentilla anserina-Carex nigra dune-slack community	SD17	345	388	1928	139	15	23	200	1	68	4	12	0	64
Calluna vulgaris-Deschampsia flexuosa heath	H9	184	330	1848	66	5	63	192	0	30	11	7	8	13
Calluna vulgaris-Carex arenaria heath	H11	207	350	1836	99	11	24	199	5	55	8	16	0	31
Festuca ovina-Agrostis capillaris-Thymus praecox grassland	CG10	474	395	1829	158	15	33	181	2	68	8	21	0	66
Gymnocarpium robertianum-Arrhenatherum elatius community	OV38	58	392	1825	155	12	28	163	10	80	12	22	0	64
Holcus lanatus-Deschampsia cespitosa grassland	MG9	223	380	1790	146	13	24	180	1	77	4	16	0	65

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Dryas octopetala-Silene acaulis ledge community	CG14	152	360	1786	130	16	28	178	1	52	9	14	0	60
Festuca ovina-Agrostis capillaris-Alchemilla alpina grass-heath	CG11	313	338	1781	120	12	26	173	1	53	6	19	0	46
Festuca ovina-Carlina vulgaris grassland	CG1	465	353	1780	114	19	29	176	5	70	1	17	0	36
Papaver rhoeas-Viola arvensis community	OV3	52	368	1776	128	13	21	171	2	79	1	18	0	63
Deschampsia flexuosa grassland	U2	109	328	1754	97	9	41	177	2	35	13	9	0	41
Arrhenatherum elatius-Filipendula ulmaria tall-herb grassland	MG2	278	341	1750	127	10	20	182	6	59	5	14	0	44
Festuca rubra-Armeria maritima maritime grassland	MC8	259	327	1727	96	14	17	153	3	87	0	12	0	41
Poa annua-Plantago major community	OV21	215	351	1692	128	12	22	161	3	75	1	16	0	61
Equisetum fluviatile swamp	S10	39	324	1686	68	15	18	151	5	49	3	10	0	72
Ammophila arenaria-Festuca rubra semi-fixed dune community	SD7	419	353	1659	143	17	30	147	4	66	3	18	0	68
Erica tetralix-Sphagnum compactum wet heath	M16	266	295	1648	47	5	47	206	1	19	5	1	8	2
Molinia caerulea-Potentilla erecta mire	M25	250	325	1642	101	13	28	180	1	38	10	10	0	44
Luzula sylvatica-Vaccinium myrtillus tall-herb community	U16	249	299	1618	86	14	27	181	1	28	9	11	0	27
Cymbalaria muralis community	OV42	43	295	1612	97	14	34	148	4	56	4	5	0	29
Festuca rubra-Hyacinthoides non-scripta maritime bluebell community	MC12	101	316	1545	122	14	18	136	4	66	4	12	0	62
Festuca ovina-Alchemilla alpina-Silene acaulis dwarf-herb community	CG12	125	291	1543	97	12	26	149	1	41	6	11	0	43
Calluna vulgaris-Scilla verna heath	H7	355	278	1497	76	12	24	160	2	46	4	9	0	20
Festuca rubra-Plantago spp. maritime grassland	MC10	218	268	1415	87	13	18	147	1	51	2	10	0	25
Festuca ovina-Agrostis capillaris-Galium saxatile grassland	U4	419	275	1397	104	9	20	124	1	54	5	17	0	45

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Ammophila arenaria mobile dune community	SD6	212	292	1384	115	11	23	128	5	52	3	14	0	56
Anthoxanthum odoratum-Geranium sylvaticum grassland	MG3	228	290	1369	126	11	18	124	0	66	1	18	0	51
Filipendula ulmaria-Angelica sylvestris mire	M27	312	301	1364	134	12	22	135	1	63	3	9	0	56
Festuca rubra-Holcus lanatus maritime grassland	MC9	319	277	1364	99	14	20	136	4	57	1	15	0	30
Vaccinium myrtillus-Racomitrium lanuginosum heath	H20	350	226	1303	55	8	28	135	2	21	7	5	0	19
Holcus lanatus-Juncus effusus rush-pasture	MG10	188	259	1302	105	7	14	115	0	65	0	11	0	47
Narthecium ossifragum-Sphagnum papillosum valley mire	M21	148	243	1296	45	4	46	140	0	22	7	6	8	10
Lolium perenne-Cynosurus cristatus grassland	MG6	193	264	1285	92	10	17	131	1	59	0	12	0	34
Calluna vulgaris-Eriophorum vaginatum blanket mire	M19	306	245	1258	80	6	27	128	2	25	12	8	0	37
Salix lapponum-Luzula sylvatica scrub	W20	109	232	1223	71	9	19	129	1	30	7	10	0	25
Festuca arundinacea grassland	MG12	153	242	1220	88	6	12	111	1	54	0	9	0	49
Sagina nodosa-Bryum pseudotriquetrum dune-slack community	SD13	134	240	1189	81	9	15	126	1	34	4	5	0	45
Poa annua-Myosotis arvensis community	OV12	105	224	1188	90	8	11	85	2	57	0	11	0	50
Carex rostrata-Calliergon cuspidatum/giganteum mire	M9	269	215	1185	59	8	14	145	1	25	2	4	0	15
Cynosurus cristatus-Centaurea nigra grassland	MG5	298	246	1170	99	9	15	117	0	50	1	15	0	39
Poa annua-Sagina procumbens community	OV20	94	251	1170	89	8	15	114	2	60	0	12	0	40
Agrostis stolonifera-Ranunculus repens community	OV28	89	220	1166	86	7	10	91	1	55	0	9	0	47
Calluna vulgaris-Ulex gallii heath	H8	254	241	1165	90	12	29	105	1	35	8	8	0	43
Deschampsia cespitosa-Galium saxatile grassland	U13	197	212	1158	60	7	18	122	1	26	6	6	0	24

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Scirpus maritimus swamp	S21	235	204	1153	74	6	13	97	2	35	2	10	0	39
Nardus stricta-Carex bigelowii grass-heath	U7	258	217	1150	50	8	19	142	0	20	7	5	0	15
Festuca rubra-Agrostis stolonifera-Potentilla anserina grassland	MG11	202	227	1137	88	6	16	100	1	50	0	9	0	45
Pteridium aquilinum-Galium saxatile community	U20	219	220	1132	81	7	18	100	1	43	5	14	0	32
Juncus effusus/acutiflorus-Galium palustre rush-pasture	M23	233	225	1119	98	8	11	96	0	56	0	12	0	42
Schoenus nigricans-Juncus subnodulosus mire	M13	365	217	1113	75	9	14	117	0	38	1	10	0	28
Calluna vulgaris-Arctostaphylos alpinus heath	H17	151	204	1109	46	7	29	125	1	17	9	5	0	10
Alchemilla alpina-Sibbaldia procumbens dwarf-herb community	U14	78	205	1102	58	7	18	120	0	26	5	6	0	21
Lolium perenne leys and related grasslands	MG7	214	219	1060	84	8	15	98	0	47	0	9	0	42
Iris pseudacorus-Filipendula ulmaria mire	M28	224	202	1059	84	7	12	97	1	42	0	4	0	39
Cynosurus cristatus-Caltha palustris grassland	MG8	70	214	1055	86	7	12	99	0	51	1	12	0	32
Carex bigelowii-Racomitrium lanuginosum moss-heath	U10	307	202	1047	49	8	19	126	0	21	5	5	0	17
Carex arenaria-Festuca ovina-Agrostis capillaris dune grassland	SD12	148	218	1042	94	6	14	106	0	47	1	13	0	31
Vaccinium myrtillus-Deschampsia flexuosa heath	H18	286	203	1031	72	6	19	98	1	32	7	11	0	29
Atriplex prostrata-Beta vulgaris ssp. maritima sea-bird cliff community	MC6	20	182	1014	54	7	9	75	4	44	0	4	0	39
Juncus maritimus salt-marsh community	SM18	138	197	1009	64	4	10	102	1	34	1	12	0	33
Calluna vulgaris-Vaccinium myrtillus-Sphagnum capillifolium heath	H21	234	191	1005	54	7	36	95	2	20	9	5	0	17
Nardus stricta-Galium saxatile grassland	U5	416	188	999	69	7	16	82	0	36	5	15	0	27
Calluna vulgaris-Vaccinium myrtillus heath	H12	275	186	979	66	8	34	85	1	23	8	8	0	19

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Calluna vulgaris-Arctostaphylos uva-ursi heath	H16	230	180	974	59	6	22	96	1	21	8	8	0	18
Crithmum maritimum-Spergularia rupicola maritime rock-crevice community	MC1	86	177	972	50	7	8	84	4	41	1	7	0	25
Lythrum portula-Ranunculus flammula community	OV35	34	169	972	54	8	8	104	1	22	2	7	0	16
Carex demissa-Saxifraga aizoides mire	M11	238	170	961	57	7	14	96	0	25	2	2	0	22
Calluna vulgaris-Cladonia arbuscula heath	H13	220	161	926	39	6	18	99	0	14	8	5	0	10
Vaccinium myrtillus-Rubus chamaemorus heath	H22	142	186	901	65	6	18	86	1	22	10	8	0	35
Cratoneuron commutatum-Carex nigra spring	M38	101	173	899	71	7	11	76	0	41	0	10	0	27
Juncus trifidus-Racomitrium lanuginosum rush-heath	U9	132	157	896	36	6	15	97	0	16	5	5	0	12
Schoenus nigricans-Narthecium ossifragum mire	M14	39	169	894	26	1	37	105	0	13	3	1	8	1
Saxifraga aizoides-Alchemilla glabra banks	U15	100	174	884	69	6	10	75	1	43	1	8	0	29
Vaccinium myrtillus-Cladonia arbuscula heath	H19	237	153	876	35	6	15	96	0	14	6	5	0	10
Hypericum elodes-Potamogeton polygonifolius soakway	M29	61	158	876	46	8	10	103	1	17	2	7	0	9
Ulex europaeus-Rubus fruticosus scrub	W23	133	194	865	88	9	17	79	1	36	5	7	0	40
Carex bigelowii-Polytrichum alpinum sedge-heath	U8	116	151	853	34	6	15	93	0	15	5	5	0	10
Calluna vulgaris-Erica cinerea heath	H10	322	164	825	58	9	21	81	0	21	5	7	0	20
Carex rostrata-Sphagnum warnstorfii mire	M8	120	152	825	53	7	15	92	0	21	2	4	0	10
Thelypteris limbosperma-Blechnum spicant community	U19	60	155	816	61	5	16	68	1	26	5	9	0	25
Honkenya peploides-Cakile maritima strandline community	SD2	31	165	814	57	4	13	68	3	41	0	3	0	33
Carex curta-Sphagnum russowii mire	M7	158	175	813	66	8	18	68	1	29	7	8	0	35

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Phleum arenarium-Arenaria serpyllifolia dune annual community	SD19	45	157	812	55	9	11	77	3	31	0	9	0	17
Myosotis scorpioides-Ranunculus sceleratus community	OV32	46	157	787	61	3	5	78	1	41	0	9	0	20
Calluna vulgaris-Racomitrium lanuginosum heath	H14	237	144	784	38	5	26	73	1	15	9	5	0	10
Juncus squarrosus-Festuca ovina grassland	U6	201	148	780	43	4	13	73	0	27	5	11	0	15
Calluna vulgaris-Juniperus communis ssp. nana heath	H15	49	146	769	40	6	27	71	1	17	8	5	0	11
Other water-margin vegetation	S23	48	142	766	61	5	7	69	1	31	1	9	0	19
Eriophorum vaginatum blanket and raised mire	M20	124	159	754	58	6	16	64	1	22	8	8	0	34
Erica tetralix-Sphagnum papillosum raised and blanket mire	M18	165	160	752	59	6	18	65	1	20	8	8	0	34
Carex saxatilis mire	M12	95	138	747	38	5	8	84	0	21	1	1	0	16
Eleocharis palustris swamp	S19	116	136	742	51	5	4	70	0	32	0	7	0	18
Festuca ovina-Minuartia verna community	OV37	148	158	729	61	5	15	77	0	35	1	8	0	17
Festuca rubra salt-marsh community	SM16	186	138	724	41	4	5	74	1	25	1	10	0	18
Molinia caerulea-Crepis paludosa mire	M26	166	145	719	61	6	5	71	0	30	0	13	0	20
Elymus farctus ssp. boreali-atlanticus foredune community	SD4	29	141	718	41	6	12	69	4	18	1	3	0	28
Stellaria media-Rumex acetosa sea-bird cliff community	MC7	26	145	714	53	4	7	61	1	36	0	8	0	28
Carex echinata-Sphagnum recurvum/auriculatum mire	M6	229	129	666	43	4	16	61	0	20	4	6	0	18
Eleocharis uniglumis salt-marsh community	SM20	29	125	666	32	3	5	73	1	20	1	9	0	13
Artemisia maritima salt-marsh community	SM17	27	128	654	28	5	9	76	1	19	2	3	0	13
Rorippa palustris-Filaginella uliginosa community	OV31	35	117	641	43	5	4	54	1	25	0	1	0	27
Scirpus cespitosus-Erica tetralix wet heath	M15	419	119	632	36	5	17	60	0	16	5	5	0	11

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Carex dioica-Pinguicula vulgaris mire	M10	318	109	621	46	5	12	51	0	16	0	4	0	20
Cryptogramma crispa-Deschampsia flexuosa community	U21	56	112	614	35	4	15	50	1	16	5	5	0	16
Cryptogramma crispa-Athyrium distentifolium snow-bed	U18	66	117	609	38	4	13	50	1	19	5	5	0	19
Blysmus rufus salt-marsh community	SM19	31	116	604	31	3	5	68	0	20	1	9	0	10
Agrostis stolonifera-Alopecurus geniculatus grassland	MG13	44	115	575	47	4	9	53	1	25	0	2	0	21
Polytrichum sexangulare-Kiaeria starkei snow-bed	U11	123	102	570	23	5	7	72	0	12	1	0	0	3
Asplenium trichomanes-Asplenium ruta-muraria community	OV39	139	118	568	39	5	9	66	1	26	0	5	0	5
Scirpus cespitosus-Eriophorum vaginatum blanket mire	M17	284	102	560	29	4	16	49	0	13	5	5	0	10
Alopecurus geniculatus-Rorippa palustris community	OV29	31	108	534	43	4	7	47	1	24	0	1	0	24
Nuphar lutea community	A8	139	92	519	42	2	3	44	1	19	1	9	0	12
Juncus maritimus-Triglochin maritima salt-marsh community	SM15	28	100	518	20	4	5	66	1	7	2	3	0	12
Salix herbacea-Racomitrium heterostichum snow-bed	U12	137	89	515	16	4	6	70	0	7	1	0	0	0
Ranunculus omiophyllus-Montia fontana rill	M35	44	107	504	41	3	3	51	0	28	0	7	0	15
Philonotis fontana-Saxifraga stellaris spring	M32	208	104	497	51	3	7	39	0	29	0	3	0	22
Matricaria maritima-Galium aparine strandline community	SD3	28	87	479	32	2	7	35	1	16	0	0	0	26
Sphagnum cuspidatum/recurvum bog pool community	M2	96	86	468	24	3	14	39	0	10	5	5	0	10
Spergularia marina-Puccinellia distans salt-marsh community	SM23	22	79	465	20	2	6	45	1	8	1	3	0	13

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Cratoneuron commutatum-Festuca rubra spring	M37	60	79	421	27	1	5	36	0	18	0	1	0	17
Puccinellia maritima salt-marsh community	SM13	149	71	418	18	3	5	40	1	7	1	3	0	11
Carex rostrata-Sphagnum squarrosum mire	M5	53	83	407	36	3	6	38	0	19	0	1	0	16
Halimione portulacoides salt-marsh community	SM14	74	77	393	17	3	4	53	0	2	2	3	0	10
Carex arenaria dune community	SD10	66	80	382	31	2	9	35	0	15	0	2	0	17
Leymus arenarius mobile dune community	SD5	66	65	378	21	0	5	27	1	9	0	0	0	23
Potamogeton pectinatus-Myriophyllum spicatum community	A11	194	66	372	28	3	2	32	1	11	1	7	0	9
Potamogeton perfoliatus-Myriophyllum alterniflorum community	A13	171	66	372	28	3	2	33	1	10	1	7	0	9
Carex vesicaria swamp	S11	88	72	367	34	4	4	33	0	17	0	4	0	10
Carex arenaria-Cornicularia aculeata dune community	SD11	130	73	357	32	5	7	33	0	14	1	2	0	11
Carex rostrata-Sphagnum recurvum mire	M4	53	73	356	30	2	5	32	0	19	0	0	0	14
Ranunculus aquatilis community	A19	18	57	338	24	2	2	25	1	10	1	7	0	9
Rayed Aster tripolium stands	SM12	21	55	332	12	1	3	34	1	1	1	3	0	11
Anthelia julacea-Sphagnum auriculatum spring	M31	46	56	330	22	3	4	17	0	14	0	1	0	16
Carex rostrata swamp	S9	75	59	326	24	3	3	31	0	13	0	1	0	8
Spartina anglica salt-marsh community	SM6	18	54	324	12	2	3	32	1	1	1	3	0	11
Lemna minor community	A2	40	56	307	23	2	2	25	2	9	1	7	0	8
Armeria maritima-Ligusticum scoticum maritime rock-crevice community	MC2	19	53	307	16	3	3	22	1	10	0	0	0	14
Pohlia wahlenbergii var. glacialis spring	M33	26	60	276	29	1	6	18	0	18	0	2	0	14
Rhodiola rosea-Armeria maritima maritime cliff-ledge community	MC3	18	49	269	20	4	3	21	0	9	0	2	0	10

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Transitional low-marsh vegetation with Puccinellia maritima, annual Salicornia species and Suaeda maritima	SM10	14	40	209	10	1	3	28	0	1	1	3	0	3
Annual Salicornia salt-marsh community	SM8	10	35	179	7	0	3	26	0	0	1	3	0	2
Suaeda maritima salt-marsh community	SM9	10	35	179	7	0	3	26	0	0	1	3	0	2
Asplenium viride-Cystopteris fragilis community	OV40	35	31	172	13	0	3	18	0	8	0	0	0	2
Spartina alterniflora salt-marsh community	SM5	4	33	166	7	0	3	24	0	0	1	3	0	2
Ranunculus fluitans community	A18	12	25	150	13	0	1	13	0	6	0	1	0	4
Ranunculus penicillatus ssp. pseudofluitans community	A17	11	28	145	16	0	0	13	0	7	0	3	0	5
Elodea canadensis community	A15	21	25	128	13	0	0	15	0	5	0	1	0	4
Ranunculus peltatus community	A20	16	23	123	12	0	0	14	0	4	0	1	0	4
Potamogeton pectinatus community	A12	15	20	114	10	0	0	10	0	5	0	1	0	4
Ceratophyllum demersum community	A5	39	22	105	11	1	0	13	0	4	0	1	0	2
Sphagnum auriculatum bog pool community	M1	32	20	99	5	0	3	16	0	1	0	0	0	0
Polygonum amphibium community	A10	14	18	93	8	0	0	13	0	3	0	0	0	2
Potamogeton natans community	A9	46	20	91	11	1	0	13	0	3	0	1	0	2
Littorella uniflora-Lobelia dortmanna community	A22	50	16	79	6	1	0	9	0	3	0	1	0	2
Carex demissa-Koenigia islandica flush	M34	25	16	73	8	0	1	7	0	4	0	1	0	2
Myriophyllum alterniflorum community	A14	16	14	69	8	1	0	7	0	3	0	1	0	2
Eriophorum angustifolium bog pool community	M3	18	13	66	5	1	3	6	0	3	0	0	0	0
Ranunculus baudotii community	A21	14	12	59	8	0	0	6	0	3	0	1	0	2
Isoetes lacustris/setacea community	A23	20	9	46	4	1	0	7	0	1	0	0	0	0
Nymphaea alba community	A7	39	10	42	5	0	0	9	0	1	0	0	0	0
Juncus bulbosus community	A24	48	8	38	4	1	0	6	0	1	0	0	0	0
Callitriche stagnalis community	A16	18	4	20	2	0	0	3	0	1	0	0	0	0
Eleocharis parvula salt-marsh community	SM3	1	1	6	0	0	0	1	0	0	0	0	0	0

Community	NVC Code	S	N	Risk*	in UK	Bacteria	Fungi	Insects	Mites	Nema-todes	Oomy-cetes	Phyto-plasmas	Pest Plants	Viruses
Zostera communities	SM1	15	0	0	0	0	0	0	0	0	0	0	0	0
Ruppia maritima salt-marsh community	SM2	1	0	0	0	0	0	0	0	0	0	0	0	0

Supplementary Table 3. Factors in plant health vulnerability suggested by stakeholders

Survey	trait	Importance
Plant species or population		
4	wide host range	10
4	asymptomatic spread	7
7	international trade in plants and plant products is the biggest factor. Seeds are also vectors of pathogens & pests	
8	species plasticity and adaptability to disease	10
8	ability to develop resistance to disease	10
8	species adaptability to climate change	10
11	Pressure from invasive species	9
12	degree of monoculture, e.g. heather, Sitka spruce	
37	Native species planted outside natural range -> less suitable sites leading to stress (such as oak)	
Plant community or environmental		
1	Added value for local sourcing	7
2	Planting of non-native species that introduce novel pests/allow pest build-up	10
3	Popularity w/ public relative to increased/decreased funding or participation for conservation	
4	wide range of susceptible species	10
5	garden waste dumping (fly tipping)	4
6	Vulnerability to other plant health pressures, e.g. overgrazing in woodland	7
6	lack of pre-existing research information about hosts and disease	6
6	being part of a wider environment community i.e. no immediate business impact	8
8	species genetic diversity	10
8	species diversity high	10
8	plant structural diversity mixed landscape	8
8	biosecurity and international movement of plants and soil	10
10	Border pressures and checks	
10	Recreational use, including mountain biking, horse riding, and dog walking	
10	Supermarkets and garage [illegible] -- less regulated?	
10	Trends in gardening etc e.g. celebrity endorsements of olive trees	
12	presence/absence of parasitoids	
12	management regime	
12	managability/acceptability of pesticide	
12	length of time over which resilience can be built	
13	landscaping specifications -- desire for instant plantings	8
36	Bulk selling cheap plant material by Euro-supermarkets	10
36	Movement of plant material to Europe to 'harden off'	10
36	recreation in forestry areas without control to unknown infected sites	10

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