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# CATALOGUE OF PESTS AND PATHOGENS OF TREES ON THE ISLAND OF IRELAND

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## ABSTRACT

The health and sustainability of trees are increasingly under threat from biotic and abiotic sources, including rising incidences of non-native invasive plant pests and pathogens. The island of Ireland (Ireland and Northern Ireland) is generally understood to have a high plant health status, due to its island status and because of the national and international regulations aimed at protecting plant health. To establish a baseline of the current pest and pathogen threats to tree health for the island of Ireland, the literature and unpublished sources were reviewed to produce a dataset of pests and pathogens of trees on the island of Ireland. The dataset contains 396 records—the majority of pests and pathogens being arthropods and fungi—and indicates potentially more than 44 non-native pest and pathogen introductions. The reliability of many (378) of the records was judged to be high, therefore the dataset provides a robust assessment of the state of pests and pathogens of trees recorded on the island of Ireland. We analyse this dataset and review the history of plant pest and pathogen invasions; in doing so, we discuss (i) notable native and non-native pests and pathogens of trees, (ii) interceptions at borders and (iii) pests, pathogens and climate change. The dataset establishes an important baseline for the knowledge of plant pests and pathogens on the island of Ireland, and will be a valuable resource for future plant health research and policy making.

## INTRODUCTION

The incidences of non-native pests and pathogens of plants are increasing globally, and these pests threaten important ecosystem services (Boyd *et al*. 2013; Crous *et al*. 2016), with this increase mainly attributed to increased globalisation (Desprez-Loustau *et al*. 2010; Liebhold *et al*. 2012; Santini *et al*. 2013) and climate change (Desprez-Loustau *et al*. 2007; Bebber 2015; Ramsfield *et al*. 2016). Reviews in the USA (Aukema *et al*. 2010), New Zealand (Sikes *et al*. 2018) and the UK (Freer-Smith and Webber 2015) have shown an increase in the records of highly damaging non-native pests and pathogens of woody plants since the late twentieth century. One such insect pest causing significant economic and environmental damage is the emerald ash borer (*Agrilus planipennis* Fairmaire), which has been spreading across North America since its introduction there during the 1990s (Herms and McCullagh

2014). This pest is considered a very serious threat to ash (*Fraxinus excelsior*) in Europe (EPPO 2013), where another non-native fungal pathogen (*Hymenoscyphus fraxineus* Baral *et al.*) is causing widespread decline and mortality in the form of ash dieback disease (Kowalski 2006; Gross *et al*. 2014). Ash dieback is estimated to cost many billions of euros in economic damage, with estimates from the UK alone reaching £15 billion (Hill *et al*. 2019). Eradication of these pathogens is difficult (Liebhold and Kean 2019), and bioeconomic modelling indicates that resources are best allocated to activities preventing these invasive species introductions rather than those trying to eradicate or control invasive species (Leung *et al*. 2002). Liebhold *et al*. (2016) identify the need for improved surveillance systems to help eradicate pests through early detection.

Forests provide vital ecosystem services (FAO 2018), but these are under threat from non-native pests and pathogens (Boyd *et al*. 2013). Ireland is one of the least forested countries in the EU (FRA 2015), with forests covering 770,020ha or around 11% of the land area (Anon 2018). Northern Ireland has over 112,000ha of forestry (Department of Agriculture, Environment and Rural Affairs (DAERA) 2018)), equating to roughly 8% of the land area. Historic forest clearance across the island of Ireland (i.e. Ireland and Northern Ireland) led to almost complete deforestation, with estimates of just 1% remaining forest cover in the late eighteenth century (Cross 1998). The forest area in Ireland has increased in recent years, being composed primarily of the exotic species *Picea sitchensis* (Bong.) Carr. (51% of forest area), *Pinus controta* Douglas (10%), *Picea abies* (L.) H. Karst. (4%) and *Larix kaempferi* (Lamb.) Carr. (Anon 2018). In Northern Ireland, almost 62% of the forest area is composed of conifer or conifer mixtures (DAERA 2018). Outside of forests, there are also a large number of trees scattered across the island, with estimates from Northern Ireland indicating that there are more than five million trees in hedgerows (Spaans *et al*. 2018). The low cover of forest across the island of Ireland probably had a significant impact on the numbers of known forest-associated species, such as forest-associated fungi (O'Hanlon and Harrington 2011) and insects (Morris 1993; Reilly 2008), compared to that in similar regions such as England or Scotland. The historically low level of forest cover (as low as 1% in the early 1900s (Rackham 1997 as cited in Cross 2006)) probably also contributed to the development of a depauperate community of forest-associated pests and pathogens, with the forests of the island of Ireland generally known to have less diseases due to pests and pathogens than similarly sized European regions (Grégoire and Evans 2004; McCracken 2013).

The newness of Ireland's forest estate as well as the country's island status confer a strong natural advantage in terms of forest health (Department of Agriculture, Food and the Marine (DAFM) 2014)); and at a European level, Ireland's forests are recognised as being relatively healthy. However, during the 1970s, de Brit and McAree (1977) flagged how such plantations were potentially susceptible to introduced pests and pathogens, due to the structure and composition of Ireland's spruce plantations. In recent years there has been a growing concern over the threat that non-native pests and pathogens pose to tree and forest health on the island of Ireland (McCracken 2013; O'Hanlon 2015) (Figure 1a,b,c,d,e,f). Many of the recently introduced pathogens and pests arrived with trade consignments, such as *Phytophthora ramorum* Werres, De Cock and Man in 't Veld 2001 and the eucalyptus psyllid *Ctenarytaina eucalypti* Maskell on plants for planting (Purvis *et al*. 2002; O'Hanlon *et al*. 2016a). Plants for planting, and wood packaging material such as pallets and crates are known pathways for introducing non-native pests and pathogens worldwide (Kenis *et al*. 2007; Brasier 2008; Humble 2010; Liebhold *et al*. 2012; Eyre *et al*. 2018), and thus are regulated under the plant health regulation (EU 2016/2031) and the related official controls regulation (EU 2017/625) in the EU.

The aim of this article is to provide a list of occurrences of pests of trees on the island of Ireland. Despite having a strong history of plant pathology expertise (Muskett 1976; Kavanagh and Brennan 1993), the island of Ireland has in recent years seen a reduction in the number of practicing forest pathologists, mycologists and entomologists (Copeland and Dowley 2010; Skilling and Batzer 1995; Battisti and Faccoli 2004; Dahlberg *et al*. 2009; O'Hanlon 2016; O'Hanlon *et al*. 2016b). Data from the Tree CD project found that just 2% of forest researchers' time in Ireland was devoted to forest protection compared to 13, 17 and 11% in Austria, Switzerland and the UK, respectively (Bystriakova and Schuck 1999). This is in line with similar recent declines in tree and forest health specialists in Britain (Jones and Baker 2007; Anon 2013c) and more widely in Europe (EPPO 2004). The information and results from years of work in the disciplines of forest pathology and entomology on the island of Ireland is scattered across many sources, both published and unpublished. Collating this type of historic data is important because it offers the opportunity to assess if trends are evident in new pest invasions, or if climate change may be influencing the distribution of pests and pathogens (Jeger and Pautasso 2008).

## PLANT DISEASE, PHYTOSANITARY MEASURES AND THE INTERNATIONAL YEAR OF PLANT HEALTH

The United Nations General Assembly declared 2020 as the International Year of Plant Health (http://www.fao.org/plant-health-2020/home/en/). Governments and organisations across the world have seized on the opportunity to raise global awareness on how protecting plant health can help end hunger, reduce poverty, protect the environment and boost economic development. Plant diseases are caused by biotic and abiotic factors, and in recent years the threat from plant diseases to global food security and environmental sustainability had come to prominence (Boyd *et al*. 2013; MacLeod *et al*. 2016). Protection of plant health worldwide is enshrined in the agreements of the International Plant Protection Convention (IPPC; www.ippc.int). This convention aims to protect the world's plant resources from the spread and introduction of pests and pathogens, while also promoting safe trade. Within the EU the measures to calculate and reduce the risk to plant health are contained in the EU plant health regulation (EU 2016/2031), which replaces the previous Plant Health Directive (2000/29/EC).

Under the IPPC, plant health legislation mainly follows a list-based system of regulation. Pests are assessed using pest risk assessment (PRA), and listed in terms of threat and regulated accordingly. A prerequisite of the listing of any pest or pathogen, is that the organism must be identifiable, and able to spread and cause consistent damage in a plant (FAO 2007). The identifiable requirement is usually fulfilled by the pest being a formally described species. This can pose a difficulty to the rapid regulation of new pests and pathogens, given that some recent epidemics (sudden oak death, ash dieback) in Europe were caused by organisms unknown to science at the time the epidemic started. The sudden oak death pathogen *Phytophthora ramorum* caused a major epidemic in oak forests in California from 1995 onwards (Rizzo *et al*. 2002), but was only formally described as a species in 2001

(Werres *et al*. 2001). Similarly, ash dieback was first noted in Poland in 1996, but the causal organism *Chalara fraxinea* (syn. *Hymenoscyphus fraxineus*) was only formally described in 2006 (Kowalski 2006). Further evidence for the practical issues with needing a formal species description before an organism can be regulated can be seen in some of the sentinel planting research in China and Russia, where many of the disease-causing organisms were undescribed taxa (Eschen *et al*. 2018). Eschen *et al*. (2018) suggest that risk assessments should focus on the commodity (commodity risk assessment) rather than on individual PRA in order to prevent threats, at least until formal species description and pest risk assessment can take place.

There are three types of regulated pests (including pathogens) in the EU plant health regulation: (i) priority pests, (ii) quarantine pests and (iii) regulated non-quarantine pests (RNQP). For the 20 priority pests, EU member states must carry out annual surveys and monitoring as well as put in place contingency plans and information/outreach activities in order to prevent these pests and pathogens establishing in their jurisdiction. Quarantine pests are those whose presence would have an unacceptable economic, social or environmental impact within the EU. These pests include union quarantine pests (n=173) and protected zone (PZ) pests (n=31). Member states are required to conduct one survey every five years for each union quarantine pest, if that pest has the potential to establish in their jurisdiction. Ireland and Northern Ireland enjoy PZ status for many harmful forest pests and pathogens. A PZ is essentially an area in the EU where a pest or pathogen of quarantine significance, established in other parts of the EU, is not present despite favourable conditions for it to establish. Annual surveys for PZ pests must be conducted to prove freedom from the pest, in order to maintain a PZ status. Regulated non-quarantine pests are those pests and pathogens that are spread on plants for planting or planting material, and can cause unacceptable yield or quality losses on those plants. They differ from quarantine pests in being present within the region already.

The EU Plant Health Regulation is administered and implemented by the National Plant Protection Organisations (NPPO), which in Ireland is the Department of Agriculture, Food and the Marine (DAFM). In the UK, plant health is a devolved matter, with the Department of Agriculture, Environment and Rural Affairs (DAERA) being responsible for plant health matters in Northern Ireland. DAERA work closely with the Department of the Environment, Food and Rural Affairs, who act as the NPPO for the UK. The island of Ireland is treated as a single epidemiological unit in the context of plant or animal health. Due to the harmonised approach to plant health on the island (DAFM 2019a) and the EU plant health regulation, there are limited physical checks on plants or plant products moving between Ireland and Northern Ireland, or vice-versa. However, the EU plant health regulation does require that conifer wood that is not bark-free must be accompanied by a plant passport to prove it has been inspected by a professional operator authorised by the NPPO of the exporting country. The UK left the EU in 2020; however, at present the specific plant health rules that the UK will implement are as of yet unclear and will be agreed during the transition period (Spence 2020).

DEVELOPING A DATASET OF PEST DETECTIONS ON THE ISLAND OF IRELAND

This research provides a dataset containing a range of important details of pests and pathogens detected on the island of Ireland (Supplementary Table 1). Pests in this article and dataset are taken to be arthropods, while pathogens include fungi, oomycetes and bacteria. Although viruses and nematodes are also important pests and pathogens of woody plants, the literature on the diseases of woody plants on the island of Ireland caused by these groups is limited (NBDC 2010). For example, in a published dataset of nematode abundances from around the world, no data was available for nematodes of forest sites from the island of Ireland (van Hoogen *et al*. 2020). A number of literature sources were examined for reports of diseases of trees. Some reports of disease on other woody plants, though not generally considered trees, were also included. Many pests that cause disease on woody shrubs can also cause disease on trees, and therefore pose a risk to tree health. In this case a disease is any damage or ill health, which may or may not have been caused by a pest or pathogen. This literature examined included published literature (e.g. *Irish Naturalists Journal*), grey literature (e.g. the annual reports of the respective Departments of Agriculture in Ireland, and Northern Ireland; Table 1), and the private records of the authors and colleagues. A search of the literature was conducted in Google Scholar using the search terms 'pathogen OR pest AND forest OR tree AND Ireland'. The results were reviewed, and relevant literature examined. The *Trees of Great Britain and Ireland* (Elwes and Henry 1906) was also searched for the terms 'pest', 'parasite', 'pathogen', 'insect', 'fungus' and 'disease'.

While developing the dataset for the island of Ireland, other sources were also consulted to compare the detections of pests and pathogens with those in Britain (i.e. England, Scotland and Wales) and Europe. These sources provided information on pest and pathogen detections, risk rating and native status for pathogens (Kloet and Hincks 1945; Moore 1959; Jones and Baker 2007; Freer-Smith and Weber 2015; FRDBI 2020; CABI 2020a; DAERA 2020) and arthropod pests (Browne 1968; BRC 2018; CABI 2020a) in Britain, and for pathogens (Santini *et al*. 2013) and arthropod pests (Day and Leather 1997) in Europe. Pests and pathogens not found in either Britain or the island of Ireland, but with a risk rating >80 on the Northern Ireland health risk register (DAERA 2020) were also included. Information on  the behaviour and ecology of a pest or pathogen in its native range is useful in designing control strategies in areas where it has potential to invade (Webber *et al*. 2012). However, assigning native or non-native status to pests or pathogens—especially microbial pathogens—is not straightforward (Regan *et al*. 2010; Jung *et al.* 2016); therefore this information should be taken as evidence of putative native status. Synonyms were resolved for fungi by means of the Index Fungorum (www.indexfungorum.org), and for arthropod pests using a number of websites (e.g. NBN Atlas 2020). The taxonomic position of the pest or pathogen was also listed from the European and Mediterranean Plant Protection Organisation (EPPO) (2020a), along with the binomial authority for the species. In cases where the year of first detection was not specified, the date of the publication was taken as the date of the detection. There were many relevant pest records reported in Browne (1968), which unfortunately does not assign a year of detection. Therefore, the dataset reflects that many pest records were reported in 1968, though this does not mean these pests were first recorded in 1968. The pest and pathogen detections in surveys and monitoring conducted in Ireland (by, or on behalf of the DAFM and its precursor departments) and Northern Ireland (by, or on behalf of the DAERA and its precursor departments) were split by year of publication in order to provide a measure of a pests' frequency of occurrence. Where available, the host on which the pest or pathogen was detected was also noted.

The records of pest and pathogen detections on the island of Ireland were scored on their reliability, based on the guidelines listed in ISPM 8 (FAO 2017). For reports published by the NPPO, or in peer reviewed scientific journals within the last 20 years, a rank of 1 (the most reliable source) was given. The EPPO reporting service (EPPO 2020b) was the primary source for NPPO reports of pests and pathogens, although the official websites of the NPPO in Ireland also provided several pest and pathogen reports. For reports that were either an official historical record (>20 years old) or published in a non-peer-reviewed scientific journal or a technical journal, a rank of 2 was given. Reports in specialist amateur publications, or in unpublished scientific or technical documents, were categorised as rank 3. Rank 4 (the least reliable source) was applied to reports in non-technical media (e.g. periodicals, newspapers), or to personal communications or unpublished records. Ranking the reliability of records is important to allow readers attach a degree of uncertainty to any analysis that uses these records. The economic consequences of a pest or pathogen presence in a country can be significant, therefore great care should be taken in interpreting these reports. Direct contact with the NPPO via their respective websites in Ireland (https://www.agriculture.gov.ie/farmingsectors/planthealthtrade/) and Northern Ireland (https://www.daera-ni.gov.uk/topics/plant-and-tree-health) is the most reliable way of finding information about the official status of a pest or pathogen in that jurisdiction.

### SOURCES OF NOTABLE PESTS AND PATHOGENS OF TREES ON THE ISLAND OF IRELAND

There is speculative evidence from pollen core and tree-ring radiocarbon dating of a pathogen that contributed to the decline of elm trees in Ireland and the UK around 5,000 years ago (Parker *et al*. 2002; Mitchell 2006). Until the early 1900s, there were few records found of tree pests or pathogens, and these were scattered in periodicals such as *Gardeners Chronicle* and its successor titles. Some of these reports were included in reviews of pests and pathogens of plants and trees in Ireland and the UK (Johnson and Halbert 1902; Massee 1913; Adams and Pethybridge 1910; Brooks 1928; McKay 1952; Muskett 1976; Moore 1959; Peace 1962; Browne 1968; Muskett and Malone 1978, 1980a, 1980b, 1983, 1984, 1985; Phillips and Burdekin 1982; Mangan 2008), while other records appeared sporadically in the more nationally important journals *Irish Naturalists Journal* (previously known as *Irish Naturalist*) and *Irish Forestry*. The first published reports from the government departments responsible for forest health (the name of which changed several times; O'Carroll and Joyce 2004) started in Ireland in 1933, and in Northern Ireland in 1952 (Table 1). These reports continued almost annually and are considered here up until 2015, although the level of detail on the pests and pathogens reported varies widely across the years. The research reports from the horticulture, horticulture and forestry, plant sciences and crop husbandry, and soils divisions of An Foras Taluntais (now known as Teagasc) between 1962 and 2002 were also examined for information on pests and pathogens of woody plants.

Monitoring for forest pests and pathogens during the period from 1938 to 1956 was commissioned by the Department of Agriculture Ireland and carried out by scientists from University College Dublin (Forest and Wildlife Service 1938; 1943). Between 1986 and 2006 a European forest health monitoring scheme known as the International Co-operative Programme (ICP) was established as part of an EU-wide programme to monitor forest conditions in response to concerns over increasing atmospheric pollution. These plots were established across Ireland, with results reported sporadically (Keane *et al*. 1989; McCarthy 1993; Ward and Keane 1993; Anon 2006a, 2007a, 2008a). Recording focussed on disease symptoms rather than causal organisms (i.e. pests and pathogens), limiting the use of the data for the purposes of this pest and pathogen list. There were no ICP plots established in Northern Ireland (Brown *et al*. 2019). The National Forest Inventory of Ireland recorded the presence of forest damage in the assessment plots during its three previous cycles (Anon 2007, 2013, 2018). In the most recent inventory, 24% of the forests had obvious damage due to biotic causes, including over 6,000ha of damage due to pests and pathogens. The methodology for recording damage from pests and pathogens was based on the presence of symptoms of the pests and pathogens *Heterobasidion. annosum*, *Armillaria* spp., *Rhizina undulata* Fr., *H. fraxineus*, *P. ramorum*, *Phytophthora alni* Brasier and S.A. Kirk, *Dothistroma* sp., *Hylobius abietis* (L.), *Elatobium abietinum* (Walker), *Rhyacionia buoliana* (Denis and Schiffermüller).

Figure 1, a-f. Symptoms of pests and pathogens of woody plants and trees recorded on the island of Ireland. Figure 1a, *Phytophthora lateralis* dieback in Lawson cypress (*Chamaecyparis lawsoniana*) in Co. Antrim, Northern Ireland. The trees with the sparse crowns and foliage in the centre of the figure are affected by *P. lateralis* trunk canker and root rot. Figure 1b, Ash dieback disease on European ash (*Fraxinus excelsior*) in Co. Fermanagh, Northern Ireland. The diamond shaped lesion (marked with a red arrow) emanating from the small side shoot in the centre of the figure is characteristic of ash dieback disease caused by *Hymenoscyphus fraxineus*. Figure 1c, aerial view of roadside Sitka spruce (*Picea sitchensis*) damage caused by green spruce aphid (*Elatobium abietinum*) in Co. Antrim, Northern Ireland. The grey coniferous trees in the centre of the figure are diseased due to E. abietinum (copyright DAERA). Figure 1d, *Heterobasidion annosum* on a Sitka spruce root. Figure 1e, Ash sawfly (*Tomostethus nigritus*) caterpillar feeding on a European ash tree. Figure 1f, *Ips typographus* galleries on Norway spruce (*Picea abies*) in Kent, England.

There have been several initiatives nationally and internationally to increase plant health expertise and knowledge sharing. The Society of Irish Plant Pathologists (SIPP) was founded in 1968, and organised seminars on plant health almost every year since its inception. Reports of forest pathology activities can be found in several SIPP newsletters, including details of the involvement of SIPP members in the informal Forest Pathology group, which included experts from Ireland and the UK. The group met regularly from 1960 to 1996 (SIPP 1970, 1975, 1982, 1987), and even hosted a joint meeting with members of the British Mycological Society in 1969 (SIPP 1970). A herbarium for forest disease and mycorrhizal fungi was set up in 1981 in an attempt to establish a forest health resource for future research and diagnostics (Forest and Wildlife Service 1982). This herbarium was maintained and expanded in 1985 and 1987 (Anon 1986b, 1988). Other large forest pathology initiatives included the development of an All-island Plant Health and Research Strategy in 2005 (Anon 2006a), and the All-Ireland Chalara Control Strategy in 2013 (Anon 2013a). Close cooperation between the NPPO in Ireland and Northern Ireland is fostered through the North South Ministerial Council (https://www.northsouthministerialcouncil.org/).

Table 1 Details of the annual plant health survey information published by the responsible government department in Ireland and Northern Ireland and included in this review. The data from these reports are included in the dataset (Supplementary table 1).

| Region | Years | Reference |
|---|---|---|
| Ireland | 1933–75 | Report of the Minister for Lands on Forestry |
| | 1971–85 | Forest and wildlife service reports |
| | 1986–88 | Forest service reports |
| | 1991–2011 | DAFF annual report |
| | 2012–15 | DAFM annual report |
| Northern Ireland | 1952–67 | *Record of agricultural research* |
| | 1963–69 | Annual progress report on research and technical work |
| | 1963 | Ministry of Agriculture NI |
| | 1970–87 | Annual report NI |
| | 1995–2017 | AFBI records |

## THE DATASET OF PESTS AND PATHOGENS OF TREES ON THE ISLAND OF IRELAND

A total of 396 pests and pathogens were recorded on trees on the island of Ireland. Also included in the dataset are 49 cases from the island of Ireland where the pest or pathogen could not be identified, and are indicated in the dataset by '?' preceding the name. The dataset also includes a further 57 pests and pathogens that have not been detected on the island of Ireland but were judged to pose a high threat. These were included either because they were recorded in Britain or have a risk rating of 80 or above on the Northern Ireland Plant Health Risk Register. There is evidence that 45 of the pests and pathogens recorded on the island of Ireland are potentially native, with a further 129 of the pests and pathogens being native to at least some parts of Europe. The literature suggests that 12 pests and pathogens are non-native to the island of Ireland, while 31 are non-native to Europe. A further twelve pests or pathogens have a cryptic biology and so their native status is not easy to determine. No information could be found on the native status of the remaining 216 pests and pathogens. A total of 294 of the pests and pathogens recorded on the island of Ireland have a host associated with them. The hosts most frequently recorded (i.e. more than 20 pests or pathogens associated with them) were species of *Larix, Populus, Quercus, Alnus, Betula, Picea, Pinus* and *Salix*. Of the 396 pests and pathogens detected in Ireland, 378 have a reliability rating of 1 or 2, indicating a high degree of certainty in their detection.

A total of 33 of the pests and pathogens listed in the dataset are regulated under the EU Plant Health Regulation, of which 23 have been recorded on the island of Ireland, with 5 of these as interceptions at ports and 12 being RNQP. None of the priority pests have ever been recorded on the island of Ireland. Of the 123 pathogens listed as threatening to forests in

Europe (Santini *et al*. 2013), 41 have been recorded in Ireland. A total of 63 of the 99 pests listed by Day and Leather (1997) as major forest pests in Europe have been recorded on the island of Ireland.

The 396 recorded pests and pathogens included 11 bacteria, 20 oomycetes, 150 fungi and 215 arthropods. It is likely that all of these groups have been under-recorded in Ireland and Northern Ireland. A dearth of scientific expertise—and consequently a lack of surveys—for certain groups of pests and pathogens including insects and bacteria (NBDC 2010; Regan *et al*. 2010), fungi (Dahlberg *et al*. 2009; O'Hanlon and Harrington 2011; O'Hanlon 2016) and oomycetes (O'Hanlon *et al*. 2016b) is evident in Ireland and Northern Ireland. Between 1970 and 2004, Jones and Baker (2007) examined records from several sectors (including horticulture, agriculture and forestry) and recorded 234 pathogens in Britain, while only 42 were recorded during the same period on the island of Ireland. It is also likely that the number of microbial (bacteria, fungal and oomycete) pathogens are under-recorded because of inherent difficulties in detecting and identifying these (Brasier 2008; Morales *et al*. 2019), and their ability to infect plants asymptomatically (e.g. Migliorini *et al*. 2015). Recent studies by O'Hanlon *et al*. (2016a) and McEvoy *et al*. (2016) used molecular analysis to identify thirteen new records of plant pathogenic microorganisms for Ireland. Similarly, analysis of *P. sitchensis* needle endophytes in four sites in Scotland identified thirteen taxa of fungi (Stewart *et al*. 2018), of which none have been recorded from conifers on the island of Ireland. This lack of understanding of the fungal and bacterial communities of plants in Ireland is worrying as these are some of the most threatening pathogens to tree and plant health globally (Wingfield *et al*. 2001; Crous *et al*. 2016).

The Irish forest estate was relatively free from serious diseases caused by pests and pathogens during the twentieth century, as evidenced by the low number of publications dealing with plant health in the primary technical journal for Irish foresters, *Irish forestry* (Quirke 1946; Clear 1951; McKay and Clear 1953, 1957; de Brit 1967; McAree 1975, 1987; de Brit and McAree 1977; Keane 1986). Indeed, several other sources highlight the relatively low impact of disease in Irish forests during the twentieth century (Anon 1920; Quirke 1946; McCarthy 1993). In recent years, pest and pathogen reports have continued to increase at a relatively steady rate (Fig. 2). This is in line with records of new non-native pathogens (Jones and Baker 2007) and arthropod pests (Smith *et al*. 2007) in Britain. The large spike (71 new arthropod pests) in records in the year 1968 (Fig 2) in the dataset is due to the publication of a large number of reports in Browne (1968). Given that Browne (1968) did not provide the source of the records, the date of publication of the book (i.e. 1968) is used as the first report. During the five decades starting in the 1970s, the number of new pest and pathogen reports was 26, 27, 16, 37 and 28 up to 2017. Similar trends have been seen in the number of new pest and pathogens in recent years in other regions, including Britain (Freer-Smith and Webber 2015), New Zealand (Sikes *et al*. 2018) and the USA (Aukema *et al*. 2010).

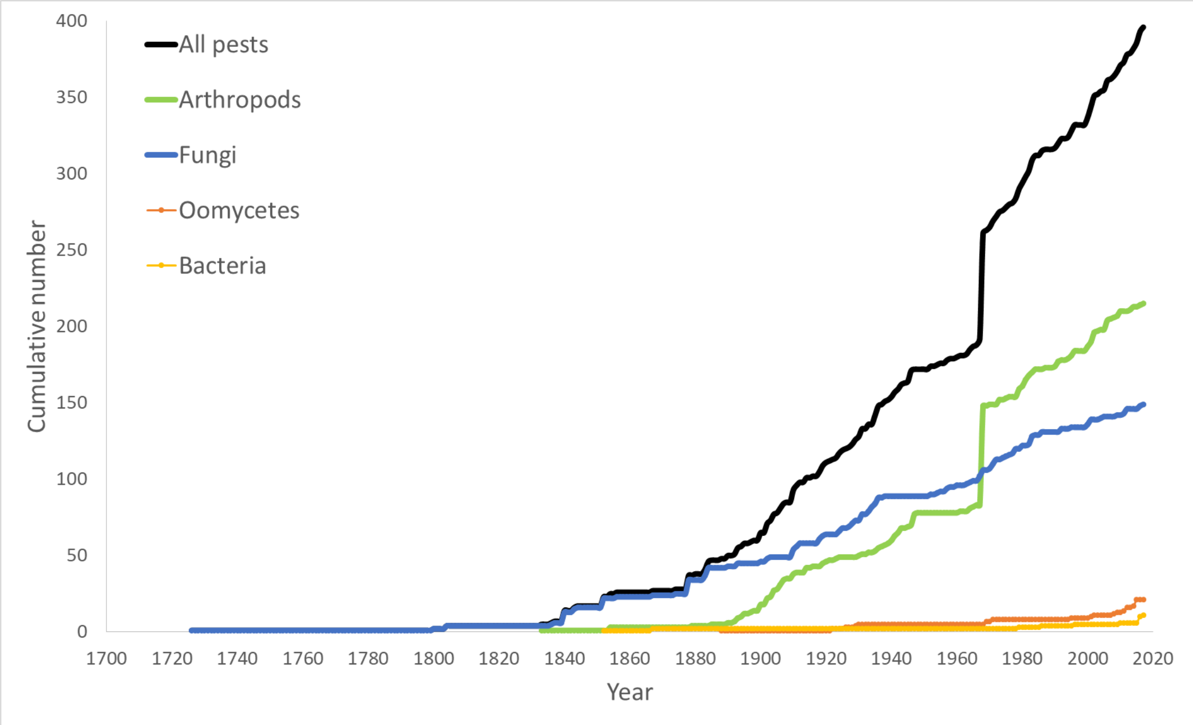


Figure 2 Species accumulation curve for the pests and pathogens reported from trees on the island of Ireland.

The dataset includes records from many print-only publications. For example, 127 official reports of the respective Departments of Agriculture in Ireland and Northern Ireland were reviewed (Table 1), most of which are only available in print format. These valuable data sources should be digitised into searchable formats and shared online to enable researchers gain access to this data. The data could also then be added to online pest list sources, such as the EPPO global database (EPPO 2020a) and the CABI plantwise knowledge bank (CABI 2020b).

## IMPORTANT DISEASES CAUSED BY NATIVE PESTS AND PATHOGENS

Native plants develop mechanisms to reduce the amount of disease from native pests and pathogens through co-evolution. However, in certain circumstances native pests and pathogens gain an advantage over native plants, allowing them to cause increased disease. Several examples of this are reviewed in Riggins and Londo (2009), including an increased amount of damage caused by the oak pinhole borer, *Platypus cylindrus* (Fabricius) in Britain following several years of favourable breeding conditions for the pest. In southwest Western Australia, the native fungal pathogen *Quambalaria coyrecup* has been causing increasing amounts of disease to native marri trees (*Corymbia calophylla*) in response to anthropogenic disturbance and other predisposing factors (Paap *et al*. 2017). Diseases caused by native pests and pathogens on non-native hosts are probably more threatening, as there is probably a lack of co-evolution in the host (Wingfield *et al*. 2010). Liebhold (2012) identified non-native forest plantations as high risk and prone to catastrophic damage from both native and non-native pests. More than 60% of the forest estate in Ireland is composed of two non-native tree species (*P. sitchensis* and *P. contorta*), therefore pests and pathogens pose a major threat to the Irish forest industry. Species diversification and the use of alternative silvicultural systems (e.g. uneven aged silviculture) have been identified as ways to buffer against large scale pest and pathogen epidemics in forests (Ennos 2015; Jactel *et al*. 2017, 2020; Roberts *et al*. 2020).

The dataset contains reports of 77 native pests and pathogens associated with native genera of trees and woody plants, and 51 native pests and pathogens associated with non-native genera of trees and woody plants. Reports of large-scale disease caused by native pests and pathogens on native trees are generally rare. Quirke (1946) noted the pathogenic fungi *Armillaria mellea* (Vahl) P. Kumm. to be damaging to various native broadleaf trees, and *Neonectria ditissima* (Tul. and C. Tul.) Samuels and Rossman causing disease on native *Betula* and *Fraxinus*. Large native bracket forming fungi such as *Ganoderma*, *Inonotus* and *Porodaedalea* (previously *Phellinus*) are probably a factor in the death of many mature native trees, however they are generally known as secondary or destabilising pathogens and are not suited to causing large epidemics in native trees (Hansen and Goheen 2000). Disease caused by native pests and pathogens on non-native trees are more frequently reported. Damage caused by the gall adelgid (*Adelges cooleyi* [Gillette]) pest in 1930s and 1940s led to Douglas fir (*Pseudotsuga menzeisii* [Mirbel] Franco) falling out of favour with many Irish foresters (Clear 1951). The pest *R. buoliana* has been an issue for Irish forestry for many years. Regular surveys were carried out, using pheromones traps in Northern Ireland in the early 1980s (Department of Agriculture for Northern Ireland 1982; Forest and Wildlife Service 1983).

Group dying of conifers (especially *P. sitchensis*) caused by the fungal pathogen *Rhizina undulata* (Schaeff.) Sacc. was first noted (under the synonym *Rhizina inflata*) in Ireland in 1952 (McKay and Clear 1953, 1955), after similar reports in Britain in 1936 (Murray 1953). The pathogen that causes the disease was noted to fruit prolifically on fire sites, and restrictions on burning fires in forest sites has led to the disease being controlled (Joyce and O'Carroll 2002). Quirke (1946) listed several pests and pathogens of importance to Irish forestry, including those of broadleaves (*N. ditissima*, and *Prays fraxinella* Bjerkander) and conifers (*R. buoliana*, *E. abietinum*, *A. mellea,* and *H. annosum*). The fungal pathogen *H. annosum* causes annosus root disease in many trees, and is listed as the most significant pathogen for forestry in Ireland (Joyce and O'Carroll 2002). Records of this fungus go back as far as 1836, while records of *A. mellea* go to back 1843 (Muskett and Malone 1980), indicating that both are probably native. Reviews by de Brit (1968), McAree (1975) and de Brit and McAree (1977) discussed several of these pathogens and their significance on the island of Ireland. These pathogens have also affected forestry practices on the island of Ireland, with the forest service in Northern Ireland stopping the use of chemical thinning in coniferous forests over concerns that this encouraged *H. annosum* (Department of Agriculture for Northern Ireland 1992).

Ever since the establishment of plantation forestry in Europe, the large pine weevil (*Hylobius abietis* L.) has been a major pest (Munro, 1927). In newly clear-felled stands adult female weevils are attracted by the volatiles and oviposit just under the bark of the stumps. Weevil larvae subsequently develop in the protected environment under the bark for one to three years depending on temperature (Leather *et al*. 1999; Inward *et al*. 2012). Following emergence, adults feed on the bark of young trees and replanted sites can suffer up to 100% mortality of newly planted trees if no control measures are taken. Pine weevil was estimated to cost the UK economy £2 million *per annum* (Weslien 1998; Leather *et al*. 1999). Current control measures include the synthetic chemicals alpha cypermethrin or cypermethrin, which are administered in nursery pre-treatment either via electrodyne application or dipping of young trees prior to planting and/or through on-site post-planting spray. However, with concerns over potential environmental impacts, cypermethrin is being phased out across Europe (E.C. 2012). Under Forest Stewardship Council (FSC) guidelines, alpha cypermethrin and cypermethrin are considered 'highly hazardous chemicals' applied only under derogation, so there is an obligation on FSC-certified companies to find alternatives to chemical control. Furthermore, current pesticides have a repellent effect on the pine weevil and, while this protects young plants, it does little to impact on the local populations of the pest (Torr *et al*. 2005; Leather *et al*. 1999).

In Ireland there has been much work on the use of biological control agents to help mitigate the pine weevil problem. There have been many studies assessing the efficacy of entomopathogenic nematodes (EPN) in the control of pine weevil (Brixey *et al*. 2006; Dillon *et al*. 2006; Dillon *et al*. 2007; Dillon *et al*. 2008; Torr *et al*. 2007). Williams *et al*. (2013a) in a meta-analysis of EPN efficacy found, for two EPN species, *Steinernema carpocapsae* (Weiser) and *Heterorhabditis downesi* Stock, Griffin and Burnell, that efficacy was greater on sites with a peaty substrate than sites with a mineral substrate. The species of the tree stump did not affect efficacy and there was no density-dependence. A more recent study by Kapranas *et al*. (2017) found site specific differences were more important than substrate type. More recently there has been a focus on entomopathogenic fungi (EPF) with *Beauveria bassiana* (Bals.-Criv.) Vuill., *Metarhzium anisopliae* (Metchnikoff) Sorokin and *Beauveria caledonica* Bissett and Widden being used in combination with EPNs (Williams *et al*. 2013b and McNamara *et al*. 2018).

### IMPORTANT DISEASES CAUSED BY NON-NATIVE PESTS AND PATHOGENS

The first reported outbreak in the dataset of a non-native pest or pathogen of trees in Ireland was that of Dutch elm disease. This disease is caused by fungi from the genus *Ophiostoma* (namely *Ophiostoma ulmi* (Buisman) Melin and Nannf. and *Ophiostoma novo-ulmi* Brasier), which are vectored by bark beetles of the genus *Scolytus*. The first outbreak in Ireland was caused by the relatively less pathogenic *O. ulmi* in 1958 (Mangan and Walsh 1980), after a similar outbreak in Britain in 1927 (Moore 1959). Following further reports of widespread elm decline in Britain in the late 1960s, the more aggressive pathogen *Ophiostoma novo-ulmi* Brasier was detected in Britain in 1965 (Potter *et al*. 2011) and in Ireland in 1977 (Walsh and Mangan 1977). The pathogen was recorded as causing large amounts of mortality to *Ulmus* in Northern Ireland throughout the 1970s. The vectors of *O. ulmi* and *O. novo-ulmi* on the island of Ireland are the non-native elm bark beetles (*Scolytus multistriatus* Marsham and *Scolytus scolytus* Fabricius), which were first reported in Ireland in 1980 and 1943, respectively (O'Callaghan 1982; Quirke 1943).

The link between pest and pathogen findings in Britain and Ireland has been indicated previously (O'Hanlon 2015; O'Hanlon *et al*. 2016b). The pests *Cameraria ohridella, Cinara kochiana, Cinara cupressi* and *Pulvinaria regalis*; and pathogens *Blumeriella jaapii, Chondroplea populea, Cylindrocladium buxicola, Gymnosporangium asiaticum, Hymenoscyphus fraxineus, Kabatina juniperi, O. novo-ulmi, Pseudomonas syringae* pv. *aesculi, P. ramorum, Phytophthora kernoviae, Phytophthora lateralis* and *Seiridium cardinal* and are all non-native organisms established in Britain after 1960 and have since become established on the island of Ireland. The average delay in these pests and pathogens being recorded on the island of Ireland after their detection in Britain is ten years. Pests and pathogens that have established in Britain pose a higher risk to plant health on the island of Ireland due to the similar conditions (suitable environment, similar hosts), close geographic proximity, and the high amounts of movement of consignments and travellers between the two regions. In 2018 an estimated 30,000 tonnes of conifer roundwood from Scotland was moved into Northern Ireland for processing (Smith 2019).

The fungal pathogen that causes larch canker (*Lachnellula willkommii* (Hartig) Dennis) has been noted as native to parts of Europe (Yde Anderson 1979; Santini *et al*. 2013) and was first recorded in Ireland in 1840 (Muskett and Malone 1983), having been recorded in Britain since 1800 (Oppermann 1923 as cited in Yde Anderson 1979). *Lachnellula willkommii* is specific to *Larix* and *Pseudolarix* (Yde Anderson 1979; CABI 2020a; FRDBI 2020). During the 1970s and 80s investigations into *Pinus controta* shoot dieback identified a causal relationship with the fungal pathogens *Sydowia polyspora* (Bref. and Tavel) E. Müll. (syn. *Sclerophoma pithyophilla* V. Hohn.) and *Ramichloridium pini* de Hoog and Rhaman. Further testing and assessments during the 1980s confirmed *Ramichloridium pini* was the main cause of the shoot dieback of lodgepole pine (Anon 1986b). Whether *S. polyspora* and *R. pini* are native is unclear. Santini *et al*. (2013) noted that the cryptic lifestyle of *R. pini* made it difficult to say if it was native to Europe. *Sydowia polyspora* has been detected on healthy pine plants and seeds in the USA (Ridout and Newcombe 2018), possibly identifying the trade in seed as a pathway for this pathogen into Ireland, if indeed the pathogen is not native.

The next major outbreak of a non-native pathogen of trees and woody plants was that of the bacterium *Erwinia amylovora* (Burrill) Winslow *et al*. in 1986 (Hume and Conway 1993), which causes a disease of woody plants called fireblight. The pathogen had previously been detected in Northern Ireland on plants (*Stranvaesia* sp. and *Crataegus* sp.) imported from the Netherlands in 1985 (Department of Agriculture for Northern Ireland 1985). This outbreak led to a strict eradication programme being instigated, with a fireblight prevention programme launched in 1986 (Anon 1990). In 1992, both Ireland and Northern Ireland were granted PZ status for *E. amylovora*, with Northern Ireland relinquishing this in 2016 in favour of restricted buffer zone status due to the increased spread of the pest in the wider environment (DAERA 2016). Most of Ireland, except Galway city, retains a PZ for *E. amylovora* to mid-2020. Efforts to eradicate the pathogen in the Galway city area between 2005 and 2013 were not successful. The pathgoen is regulated as an RNQP under the EU Plant Health Regulation. Genotypic analysis of the *E. amylovora* isolates detected in Ireland showed no clear genetic structuring in relation to host or location (Brennan *et al*. 2002), possibly indicating that multiple genotypes had been introduced into Ireland. Indeed, *E. amylovora* infected plants have been intercepted at the Irish border on several occasions (EUROPHYT 2016).

McAree and MacKenzie (1993) listed eight forest pests and pathogens (*Bupalus piniaria* [L.], *Cephalcia lariciphila* Wachtl, *Dendroctonus micans* (Kugelann), *Gilpinia hercyniae* (Htg.), *Ips cembrae* (Heer), *Ips sexdentatus* (Börner), *Pristiphora abietina* (Christ), and *G. abietina* (Lagerberg) Morelet) that were present in Britain, but absent from the island of Ireland. *Bupalis piniaria*, *P. abietina* and *G. abietina* have since been recorded on the island of Ireland. *Gremmeniella abietina* is a threat to several coniferous trees, especially

*Pinus* (Jeger *et al*. 2017a), and up until recently, both Ireland and Northern Ireland have PZ for *G. abietina*. This history of detections of *G. abietina* in Northern Ireland provides a useful insight into the process for official detections of plant health pests. Official detections of pests should follow international legislation and should work according to international or regional guidance. For many regulated pests and pathogens, official diagnostic standards exist, either published by international (i.e. International Standards for Phytosanitary Measures, ISPM; FAO 2020) or regional (EPPO) organisations. For *G. abietina*, the EPPO standard (EPPO 2009) relies on morphological detection of the pathogen, and although molecular identification methods did exist when the standard was agreed, these were not deemed suitable due to confusion over the taxonomy of the pest. In 2008 in Northern Ireland, samples from three sites indicated the presence of the pathogen using a nested PCR method (Zeng *et al*. 2005), however no morphological structures of the fungus were observed. In 2009, DNA sequencing of extracts of fungal DNA from symptomatic *Pinus* samples indicated a match to the type culture of *G. abietina*. The records in 2008 and 2009 did not satisfy the EPPO standard and so were not officially recognised. Apothecia (i.e. fruiting structures) of the pathogen were first visually observed on *Pinus* in Northern Ireland in the 2012, and hence count as the first valid official record of the pest. Isolation of the fungus into pure culture, which is another acceptable identification method, was achieved in Northern Ireland in 2015. These findings of *G. abietina* in Northern Ireland have led to removal of the PZ in that jurisdiction, while the pathogen has not been confirmed in Ireland and the PZ status is maintained. Findings of the RNQP needle blight pathogen *Lecanosticta acicola* () in Ireland (Mullett *et al*. 2018) in recent years warrant further surveys to delimit the distribution of this pathogen on the island of Ireland. The case of *G. abietina*, *L. acicola* and *P. kernoviae* represent detections of pathogens in one jurisdiction, but not in the other. The case of the distribution of the phylogenetic lineages of *P. ramorum* on the island of Ireland is another example of a clear difference between Ireland and Northern Ireland. In Ireland, only the EU1 lineage has been detected, while in Northern Ireland both the EU1 and EU2 lineages have been detected, though the EU1 has never been detected in the wider environment (O'Hanlon *et al*. 2016b). Ireland has 15 PZ and Northern Ireland has 14 PZ in place for pests and pathogens of woody plants and trees (Table 2).

Table 2 Protected zone status of pests and pathogens of woody plants and trees in Ireland and Northern Ireland as per Commission Implementing Regulation (EU) 2019/2072

| Pest or pathogen | Ireland PZ | Northern Ireland PZ |
|---|---|---|
| *Erwinia amylovora* | Yes | |
| *Xanthomonas arboricola pv. pruni* | | Yes |
| *Cryphonectria parasitica* | Yes | Yes |
| *Entoleuca mammata* | Yes | Yes |

| | | |
|---|---|---|
| *Gremmeniella abietina* | Yes | |
| *Cephalcia lariciphila* | Yes | Yes |
| *Dendroctonus micans* | Yes | Yes |
| *Dryocosmus kuriphilus* | Yes | Yes |
| *Gilpinia hercyniae* | Yes | Yes |
| *Ips amitinus* | Yes | Yes |
| *Ips cembrae* | Yes | Yes |
| *Ips duplicatus* | Yes | Yes |
| *Ips sexdentatus* | Yes | Yes |
| *Ips typographus* | Yes | Yes |
| *Thaumetopoea pityocampa* | Yes | Yes |
| *Thaumetopoea processionea* | Yes | Yes |

Since the beginning of the twenty-first century, there have been a number of pest and pathogen epidemics of trees and forestry. One particular group of plant pathogens—the genus *Phytophthora*—is a serious risk to plant health globally (Martin *et al*. 2012; Jung *et al*. 2018) and has been reasonably well studied in agricultural settings on the island of Ireland (O'Hanlon *et al*. 2016b). The outbreak of *P. ramorum* in 2002 initially started as a pathogen of the horticulture and ornamental plant industries (EPPO 2020b), which was followed by findings in invasive rhododendron in forests. The pathogen became a major threat to the forest estate in 2010 when found causing disease on Japanese larch (*Larix kaempferi*) (EPPO 2020b). Since the original detection on imported *Rhododendron* spp. and *Viburnum* spp. in Ireland in 2002 (EPPO 2020b), the pest has caused disease on 30 different hosts in both horticultural and forest environments (O'Hanlon *et al*. 2016a). Current disease control actions in forest outbreaks concentrates on removal of infected and susceptible hosts, a control method that has been shown to be effective, at least at a local scale (O'Hanlon *et al*. 2018). The introduction of *P. ramorum* was followed by the detection of other non-native *Phytophthora* species, including *Phytophthora kernoviae* Brasier in 2008 (not detected in Northern Ireland) and *P. lateralis* Tucker and Milbrath in 2011 (O'Hanlon *et al*. 2016a). Detected on *Larix* and *Nothofagus* in Ireland, *Phytophthora pseudosyringae* has also been found in the last decade in the course of DAFM official surveys. This pathogen is also damaging to *Nothofagus* species in the UK (Scanu *et al*. 2012). The pathogen *Phytophthora cinnamomi* is one of the ten most threatening oomycetes globally (Kamoun *et al*. 2014), causing significant disease in Mediterranean type climates (Burgess *et al*. 2017). This pathogen has caused minor issues to woody plants and trees on the island of Ireland, mainly in the plant nursery industry (Department of Agriculture for Northern Ireland 1969, 1975; Shafizadeh and Kavanagh 2005). *Phytophthora* disease of alder (caused by several different *Phytophthora* species) is causing many issues across Europe (Bjelke *et al*. 2016), and this was confirmed in Ireland in 2001 (Clancy and Hamilton 2001), while evidence of the disease was noted as far back as 1995 (McCracken 1996). In 2019, alder disease caused by *Phytophthora plurivora* was recorded along the river Lagan in Belfast, Northern Ireland (O'Hanlon *et al*. 2019). It is likely that there a many *Phytophthora* species present but have not yet been recorded, as O'Hanlon *et al*. (2016b) suggested that based on the species richness in Britain, at least eleven more species of *Phytophthora* are potentially to be discovered on the island of Ireland.

More recently, the ash dieback fungal pathogen *Hymenoscyphus fraxineus* (T. Kowalski) Baral, Queloz and Hosoya has spread across Europe from Poland in the 1990s (Gross *et al*. 2014) finally being confirmed in Ireland and Northern Ireland in 2012 (EPPO 2020b; DAERA 2017). Notable attempts to eradicate the pathogen from the island of Ireland were made early in the invasion, with clear efforts at cooperation established via the All-Ireland Chalara control strategy (Anon 2013a). The pathogen causes dieback of European ash (*Fraxinus excelsior*) and is now recorded in every county in Northern Ireland and Ireland (DAERA 2017; Ryan 2018). The pathogen has the potential to cause major negative economic, environmental and social consequences on the island of Ireland. The economic consequences are likely to cost many millions of euro, with over 13,000ha of ash grant-aided by government in Ireland between 1992 and 2012 (McCracken *et al*. 2017). The negative environmental consequences of ash dieback are also major, with estimates of more than 2.9 million ash trees in Northern Irish hedgerows (Spaans *et al*. 2019) now under serious threat from by *H. fraxineus*. As well as the large economic losses incurred because of ash dieback in Britain (Hill *et al*. 2019), the disease also threatens biodiversity associated with ash trees, with over 1,000 species thought to be associated with ash trees in the UK (Mitchell *et al*. 2014). Ash dieback disease causes high levels of mortality in European ash in forests (Gross *et al*. 2014), though recent evidence suggests that survival of solitary trees and those isolated from other ash trees may be better than previously expected (Grosdidier *et al*. 2020).

Another recent non-native pest (though only locally important) on trees has been the outbreak of horse chestnut leaf miner *Cameraria ohridella* Deschka and Dimić on horse chestnut (*Aesculus hippocastanum* L.) in Dublin in 2013 (Moths Ireland 2020). Symptoms of the pest have now been reported from several counties along the east of Ireland and Northern Ireland. The damage due to *C. ohridella*, combined with other present threats to horse chestnut, namely bacterial canker of horse chestnut (caused by *Pseudomonas syringae aesculi*) and Guignardia leaf blotch (caused by the fungus *Guignardia aesculi*), mean that the health of horse chestnut is under increasing threat. Horse chestnut is a commonly planted tree in urban environments, with 684 present within the Belfast city area, of which 171 are in poor health (Belfast Trees 2020). The ash sawfly (*Tomostethus nigritus* [Fabricius]), which was first detected in Northern Ireland in 2016 (Jess *et al*. 2017), led to defoliation of hundreds of trees in 2017 in urban areas in south Belfast (Ian Rea unpublished data). Recent work has highlighted the threat to these and other urban trees from disease (biotic and abiotic), with a need to diversify urban tree species (Stevenson *et al*. 2020)

## PEST AND PATHOGEN INTERCEPTIONS AT BORDERS

The two most recognised pathways for introduction of exotic plant pests are (i) wood packaging material (Eyre *et al*. 2018; Meurisse *et al*. 2019) and (ii) plants for planting (Liebhold *et al*. 2012), while pathogens are primarily understood to be introduced on plants for planting. Although phytosanitary treatments are in place for both pathways, there are a number of examples where pests have been transported on commodities despite controls. Haack (2006) reviewed 25 new beetle (Coleoptera) pest records in the USA and found that most were associated with wood packaging material. Similarly, Brockerhoff *et al*. (2006) examined interception data from the USA and New Zealand and found that 82% of the most frequently intercepted pests have become established as invasive plant pests worldwide. Inward (2019) highlighted potential shortcomings in debarking of roundwood as an effective treatment for regulation of plant pests in the ambrosia beetles group, and concluded that appropriate heat treatment, fumigation or irradiation are more effective measures than debarking alone. Freedom from bark (not to be confused with debarking) is also used as a phytosanitary measure for controlling pests and pathogens, such as the bark beetle *I. typographus* and fungal pathogen *Cryphonectria parasictica*. For example, wood of conifers needs to be either bark-free, from a pest free area or kiln dried to below 20% moisture content before it can be imported into Ireland or the UK (EU 2019/2072) from other EU member states.

It is the remit of the NPPO of each country to survey for and apply controls for quarantine pests and pathogens. These pests and pathogens are usually identified using a risk-based approach, such as the Northern Irish Plant Health Risk Register (DAERA 2020) in Northern Ireland. In the EU, the importation of commodities that have threatening pests or pathogens present are reported to the country of export via the Europhyt reporting system (EUROPHYT 2016). Europhyt records information on consignments received by EU member states that violate any of the EU's plant health requirements. Reports of pests and pathogens found in Northern Ireland are included in the overall UK reports. Based on the Europhyt data between the dates February 2006 and November 2016, inspections of imports into the UK and Ireland intercepted numerous pests and pathogens, including the following: *Anoplophora chinensis* (Forster) (in 2006, 2007, 2008, 2010), *Anoplophora glabripennis* (Motschulsky) (2016), *H. fraxineus* (2012), *Ips typographus* (L.) (2009), *Oemona hirta* Fabricius (2010), *Opogona sacchari* (Bojer) (2010), *Monochamus alternatus* Hope (2013, 2015), *Phytophthora ramorum* (2006–2016), and *Thaumetopoea processionea* (L.) (2016)(EUROPHYT 2016). *Anoplophora chinensis* was also intercepted in Britain in 2005 (EPPO 2020b). There are potentially many more pests and pathogens going undetected, as a recent analysis by Eyre *et al*. (2018) indicated that the surveillance systems in place in most EU countries are not sufficient to detect all of the potential pests on wood packaging material. Brockerhoff *et al*. (2003) also highlight the threat of wood and wood packaging material for transferring pests, listing 1,468 records of interceptions of at least 98 plant pest beetles into New Zealand between 1952 and 2000. While it would be extremely difficult to inspect all wood packaging imported, in recent years an EU-wide monitoring programme has focussed on wood packaging associated with imports of high-risk commodities such as stone from China (EU Commission decision 2013/92/EU). Under the new EU plant health regulation, member states are required to implement a risk-based surveillance regime on wood packaging imports.

Ashe *et al*. (2002) published findings of beetles imported into Ireland on commodities from China, finding *M. alternatus* and *Cryptorhynchus rufescens* Roelofs. The former is very threatening due to its ability to vector the Pine wood nematode *Bursaphelenchus xylophilus* (Steiner and Buhrer) Nickle*,* currently causing a large epidemic in Portugal and Spain (Futai 2013). There is no evidence to indicate that *Monochamus* spp. are native to the island of

Ireland, though Kloet and Hincks (1945) judged *Monochamus sutor* to be at least native to parts of Europe. Interestingly, one adult of *M. sutor* was detected in a furniture shop in Northern Ireland in 2017, presumably emerging as an adult having pupated for several years inside a wooden piece of imported furniture (A.K. Murchie unpublished data). Further detections of arthropods pests present on imported wood and wood packaging into Ireland included *Dendroctonus rufipennis* Kirby, *Dryocoetes affaber* (Mannerheim), *Ips acuminatus* (Gyllenhal) and *Ips typographus* as part of the 'Insects imported into Ireland' series of articles (O'Connor and Nash 1979, 1982, 1983). There is no evidence that any of the latter insect pests have become established in Ireland or Northern Ireland. O'Connor *et al*. (1991) identified insect pests (specifically Scolytids) that had been found in Britain, but which were not present on the island of Ireland; these included *Dendroctonus micans*, *Ips amitinus* (Eichhoff), *Ips cembrae* and *Ips sexdentatus*. These pests are the subject of longstanding annual PZ surveys. Furthermore, phytosanitary checks and monitoring are carried out on imports of unprocessed conifer wood (a high risk for transporting bark beetles) from Scotland. These imports are only allowed if the wood has come from an officially designated area that has been surveyed by the NPPO and shown to be free from the pest *D. micans*. It is likely, however, that great spruce bark beetle, *D. micans,* is the most imminent insect pest threat to Northern Irish forestry since it is present in Dumfries and Galloway, approximately 70km from Northern Ireland, and is expanding its range in Scotland (Jeger *et al.* 2017b; Forest Commission Scotland 2019). To counter this, a contingency plan is currently being drawn up by DAERA. In addition to plant health biosecurity measures, the contingency plan also considers the release of the predatory beetle *Rhizofagus grandis* Gyllenhal, which has been used successfully to control *D. micans* in Great Britain (Fielding and Evans 1997; Jeger *et al.* 2017b).

To prevent the establishment of high-risk pests, early detection and eradication is vital. There have been two major eradication campaigns against insect pests in England in the last ten years: the first was the Asian longhorn beetle (*Anoplophora glabripennis*) in 2012, and the second *Ips typographus* in 2018. The eradication operation for the *A. glabripennis* was recently concluded in England (Anon 2019a), successfully eradicating the outbreak in 2019 (EPPO 2020b). Detailed research at the site has indicated that the beetle probably arrived at the site around 2000, and from there colonised the surrounding trees. In total, the cost of monitoring and eradication actions for *A. glabripennis* was estimated at £2 million (Straw *et al*. 2016). This pest has often been intercepted in the UK associated with *Acer* plants for planting (EPPO 2020b) and wood packaging material from China (EPPO 2020b). This pest was first found in Europe in 2001, after which it has since been detected in ten EU countries. Genetic testing of the European populations indicates that there were most likely several introductions of this pest into Europe, probably originally on wood and/or wood packaging material before moving within Europe by similar pathways (Javal *et al*. 2019). The related Citrus longhorn beetle *Anoplophora chinensis* has never been intercepted on the island of Ireland, but there have been several interceptions in England. This pest has also been discovered causing infestations in several countries in Europe, notably on 36 occasions in Italy (Hérard and Maspero 2019).

A population of the eight-toothed spruce bark beetle *Ips typographus*, a PZ pest, was discovered in Kent, England in November 2018. A demarcated area was set up and intensive monitoring and eradication actions are ongoing (Forestry Commission 2019). This being the first established population of *I. typographus* in the British Isles, it represents an increased threat from this damaging pest to spruce forests on the island of Ireland and has prompted increased risk-based surveys and monitoring to bolster existing surveys for the beetle. Considered as the most damaging insect pest of spruce, *I. typographus* has a widespread distribution throughout continental Europe and northern Asia. The summers of 2018 and 2019 were hot and dry, which stressed trees and led to *I. typographus* outbreaks across much of the spruce-growing parts of Europe (Jonsson 2020); for example, the Czech Republic witnessed an increase in salvaged timber from bark beetle outbreaks from 5.3 million $m^3$ in 2017 to 18 million in 2018 (Hlásny *et al.* 2019). Although not conclusive, it is thought that the incursion into Kent was from windborne migratory beetle flight and may have occurred several years earlier, with beetle populations only becoming detectable following a second generation during the hot summer of 2018 (Forest Research, pers. comm.). For the island of Ireland, importation of timber and bark remain the most likely pathway for introduction of *I. typographus*. In February 2004, 9,000$m^3$ of wood bark from Estonia were detained at Belfast Port following a routine examination for quarantine pests. Despite having the necessary documentation indicating evidence of fumigation by methyl bromide, living invertebrates (larval Diptera, Coleoptera, mites and rhabditid nematodes) were found, along with galleries typical of *I. typographus*. The consignment was reloaded onto the ship and fumigated at sea, at a cost exceeding €170,000. Subsequently, two live adult *I. typographus* were reared from incubated bark samples (S. Clawson, pers. comm.).

While wood and wood packaging material are known as the main vectors for insect pests (Humble 2010), plants for planting is the commodity most often associated with the transfer of non-native plant pathogens (Jones and Baker 2007; Liebhold *et al*. 2012). Migliorini *et al*. (2015) tested plants from two large nurseries in Italy and found that 70% of the asymptomatic plants contained a plant pathogenic *Phytophthora* species. The records from the island of Ireland for harmful pathogens being intercepted during border inspections are less frequent than those of arthropod pests, probably because pathogens often have cryptic life stages that make them difficult to detect. The pathogen *Gymnosporangium haraerum* was reported on Japanese bonsai juniper plants imported into Northern Ireland in 1974 (Department of Agriculture for Northern Ireland 1974), while the pathogen *Discula destructiva* (Fr.) Munk ex H. Kern was reported on dogwood (*Cornus* sp.) in Northern Ireland in 1995 (McCracken 1996). Apart from the already noted cases of *E. amylovora*, *P. ramorum* and *H. fraxineus* on imported plants for planting to the island of Ireland, the low level of reports of pathogens on imported consignments is most likely due to pathogens often having cryptic lifecycles (see Migliorini *et al*. 2015), and the difficulty in surveying for plant pathogenic microorganisms in general (Morales *et al*. 2019). Furthermore, the use of pesticides on plants for planting can often mask symptoms of disease caused by pathogens, leading to the pathogen not being detected during border surveillance (Brasier 2008). Tjosvold *et al*. (2008) found that fungicides reduced the symptoms of *P. ramorum* blight on rhododendron, but that the pathogen could still be isolated from the infected leaf material. They caution that the use of these fungicides would confound visual inspection attempts. New technologies, such as those based using high throughput sequencing offer the potential to identify the presence of even latent microbial pests in plants (Tedersoo *et al*. 2018), though the application of these techniques for phytosanitary and biosecurity purposes is not straightforward (e.g. McTaggart *et al*. 2016; Holdaway *et al*. 2017).

The global trade in tree seed has recently been identified as a plant health risk (Cleary *et al*. 2019; Franic *et al*. 2019). The latter two references sampled seed of three conifer and one broadleaf tree genera and detected potential pests of the genus *Megastigmus* and pathogens from the genera, *Diaporthe*, *Fusarium*, *Giberella*, *Pestalotiopsis*, *Neonectria*, and *Diplodia*. The hymenopteran genus *Megastigmus* is a known plant pest with potential to be spread by seed trade, with 11 of the 21 seed wasp species in the genus *Megastigmus* being introduced to Europe (Roques and Skrzypczyńska 2003). Seeds of trees are regulated under the same rules as all other plant material in the EU. At present, seeds of the trees in the genus *Pinus* and *Pseudotsgua menziesii* can be imported into and moved within the EU only if they have official certification to show that they are free of the pitch canker pathogen of pine *Fusarium circinatum* Nirenberg and O'Donnell. Franic *et al*. (2019) concluded that seeds of trees represented a large threat to plant health in the EU.

The regulation of plant health at the international level has been criticised by many plant health scientists as being unsuitable for preventing pest and pathogen movements in traded commodities (Brasier 2008; Liebhold *et al*. 2012; Santini *et al*. 2012; Eschen *et al*. 2015; Jung *et al*. 2016; Meurisse *et al*. 2019). Many of the issues with the legislation have been discussed already above, and include (i) a reliance on visual inspections on plants and plant products which can miss asymptomatic infections, (ii) limited resources in NPPOs meaning that only a proportion of commodities can be inspected, (iii) the use of fungicides which mask pathogen symptoms in plants for planting, (iv) pest list-based regulation that overlooks undescribed organisms and (v) variation in the implementation of phytosanitary procedures. Until these issues are addressed it is likely further increases in the numbers of non-native pests and pathogens of trees will increase.

## PESTS AND PATHOGENS AND CLIMATE CHANGE

The island of Ireland is expected to have fewer frost days, more rain in winter, increased chance of drought in summer and increased average annual temperatures by up to 2°C by the mid-twenty-first century (Sweeney and Fealy 2002). These changes are likely to affect the amounts of damage caused by pests and pathogens in trees, through a combination of effects related to range shifts in pests and pathogens and their natural enemies, adapted physiological or behavioural responses in pests and pathogens and phenological changes in host (Zvereva and Kozlov 2006; Cornelissen 2011). Across Europe, Neumann *et al*. (2017) found that recent variations in climate have led to large scale tree mortality. Research has shown that recent outbreaks of bark beetles such as *Ips typographus* in continental Europe and defoliating insects could be linked to climate change (Heliovaara Peltonen 1999; Pureswaran *et al*. 2018). Similarly, outbreaks of the weevil *Hylastes ater* Paykull (Leahy *et al*. 2007) and green spruce aphid *E. abietinum* (Westgarth-Smith *et al*. 2007) may increase under warming conditions. This could be due to milder winter temperatures that can result in reduced arthropod mortality and decreased diapause, thus directly affecting arthropod abundance (Ramsfield *et al*. 2016). Indirectly, more frequent weather extremes (e.g. drought) could lead to compromised tree host defences and increased frequency of arthropod damage. Secondary pests such as *E. abietinum* are likely to become primary pests causing mortality of trees when the tree is suffering from drought conditions as is predicted for future summer months in Ireland with climate change (Sweeney and Fealy 2002).

The threat from pathogens of plants may also change under different climate scenarios, including bacterial (Wainhouse *et al*. 2016), oomycete (Jung *et al*. 2018) and fungal pathogens (La porta *et al*. 2008; Pautasso *et al*. 2012). Jung *et al*. (2018) suggest that disease in oaks (*Quercus* spp.) in Europe due to *Phytophthora* will increase under future climate scenarios. Several pathogens may become more of a threat to the forest health in Ireland under future climate scenarios, including the low temperature sensitive pathogens *Phytophthora kernoviae* and *Phytophthora cinnamomi*. The dataset should be useful in tracking the effects of climate change on damage caused by pests and pathogens. For example, the fungus *Neonectria fuckeliana* (C. Booth) Castl. and Rossman is currently associated with widespread damage to Sitka spruce forests in Northern Ireland (O'Hanlon and Fleming 2018). Whether this is a new or re-emerging disease is not clear, as records of other similar *Nectria*/*Neonectria* taxa (the genus has been through several taxonomic changes) causing frequent damage on conifers in Wicklow in 1984 (Forest and Wildlife Service 1985).

The tree species planted in forests on the island of Ireland in the coming years will need to be resilient against the pressures of future climate and pest and pathogen threats. Building resilience through greater species and structural diversity would seem to be a useful strategy (Ennos 2015). DAFM currently supports the grant-aided forest planting of over thirty species of conifers and broadleaves (DAFM 2016), yet from 2012 to 2018 Sitka spruce dominated the species mix being planted under DAFM grant-aided afforestation schemes and its proportion increased significantly (DAFM 2019b). This is likely linked with the removal of ash (*Fraxinus*) and larch (*Larix*) from the list of grant-aided species but increasing reliance on Sitka spruce should consider the biotic threats to that species (Cameron 2015; Tuffen and Grogan 2019). Tree suitability modelling in Ireland has shown that some conifers from the pacific northwest of America have potential to replace larch in future planned Sitka spruce forest mixtures (Walsh *et al*. 2017).

## CONCLUSIONS

The forests of Ireland have generally suffered less damage from pests and pathogens than mainland European countries, but this trend is changing with increased damage occurring in recent years. Until quite recently pest and pathogen management in Irish forestry focussed largely on control of *H. abietis* and *Heterobasdion annosum*. In the last decade however, the greatest risk to trees and forests on the island of Ireland is the introduction of non-native pests. Evidence indicates that eradication efforts against non-native tree pests globally are rarely successful unless the eradication is attempted soon after the pest has arrived (Pluess *et al*. 2012; Liebhold *et al*. 2016). The resilience of a forest to pest outbreaks is also important in protecting forest estates. Good silviculture has always been about planting the right trees in the right places but today foresters are faced with increasingly complex planting decisions due to the uncertainties surrounding climate change and threats from pests over the lifetime of a forest crop.

This dataset of pests of trees on the island of Ireland sets an important baseline for pest frequency; such datasets provide a valuable resource for future research and policy making in plant health (Shivas *et al*. 2006). As is the case with pest lists from other countries (Kenis 2005; Jones and Baker 2007; Smith *et al*. 2007; Martinez and Malausa, 2000 as cited in Smith *et al*. 2007), this list can be taken as a starting point for developing regular assessments of the threat to tree and forest health on the island of Ireland. These regular assessments need to be underpinned by scientific capacity in specialisms such as mycology, entomology, plant pathology and in broader areas including plant health diagnostics, taxonomy and risk-based surveillance. An educational resource for equipping graduates with plant health training is needed in order to produce the plant health experts of the future (Anon 2019b). For effective protection of plant health on the island of Ireland, continued cross-border work in partnership with all stakeholders (government, industry, academia, NGOs and the public) is vital to safeguarding Ireland's trees.

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