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Current, emerging and potential pest threats to Sitka spruce plantations and the role of pest risk analysis in preventing new pest introductions to Ireland

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Sitka spruce (*Picea sitchensis*) is the predominant tree species used in Irish forestry, comprising over 50 per cent of the forest estate. The island of Ireland is free of many of the most damaging pests and diseases of spruce present in Europe, and consequently forest stands of Sitka spruce are generally healthy and productive. FORM is a research project with the aim to enhance productivity and pest and disease resistance to key forest species in Ireland. It includes a work package to identify and risk analyse threats to Sitka spruce. A global pest list of spruce was compiled and identified over 1000 pests and potential pests of spruce. Using the pest list as a starting point, this review examines the major pests of Sitka spruce both in its native range in the Pacific Northwest of North America and within Europe where it is grown as an exotic. It also reviews emerging pests and diseases of spruces in general that may threaten Sitka spruce plantations in Ireland. Details of how pest risk analysis of these threats can aid in their continued exclusion are discussed.

Introduction

Sitka spruce (*Picea sitchensis* (Bong.) Carrière) is the most important commercial forest tree species in Ireland. In 2013, it comprised 52.5 per cent of the forest area (Forest Service, 2013). The species thrives in Ireland, where the maritime climate matches that of its native range in the Pacific Northwest of North America. Invertebrate pests and disease causing agents (referred to collectively as pests throughout this article) can cause massive economic losses to forestry, as well as impacting on ecosystems and biodiversity. Non-native pests can be particularly damaging. In the US, it was estimated that local governments spend $1.7 billion each year dealing with the impacts of exotic wood borers. Death and destruction of trees also have a major impact on property values, estimated at losses of $830 million a year (Aukema et al., 2011). In recent years, Ireland has suffered a number of outbreaks of invasive forest pests. The oomycete *Phytophthora ramorum* Werres, De Cock & Man in 't Veld is causing an epidemic of Ramorum disease of larch (*Larix* Miller) in Ireland and the UK. From 2010 to 2016, over 18 000 ha of Japanese larch (*L. kaempferi* (Lambert) Carrière) were affected by the eradication measures put in place to control the pest (O'Hanlon et al., 2017). Ash dieback, caused by the fungal pathogen *Hymenoscyphus fraxineus* (T. Kowalski) Baral, Queloz & Hosoya, has caused extensive mortality of ash (*Fraxinus excelsior* Linnaeus) across Europe, and over 2.1 million trees were destroyed in Ireland as a part of an eradication programme (McCracken et al., 2017). Invertebrate pests introduced to the island of Ireland in recent years include the *Eucalyptus* leaf beetle, *Paropsisterna selmani* Reid & de Little, which, by defoliating new flush foliage, is impacting on both *Eucalyptus* grown for forestry and cut foliage production in Ireland (Fanning and Baars, 2014).

Pests and diseases of Sitka spruce were previously reviewed by de Brit and McAree (1977) and a later overview was given by Joyce and OCarroll (2002). To maintain the health and productivity of Irish Sitka spruce forests, it is necessary to have regulations in place to prevent introduction of pests from Europe, North America and beyond. The island of Ireland has succeeded in excluding many serious spruce pests present in Continental Europe, such as the European spruce bark beetle *Ips typographus* (Linnaeus), through the use of Protected Zone legislation. The Protected Zone legislation means other EU member states recognize Ireland as free from specific pests and apply phytosanitary treatments to commodities that may carry the pest, such as removing bark from imported coniferous timber to prevent the introduction of bark beetles. In the light of recent detrimental forest pest introductions, the Irish government funded a research project through the National Research Stimulus Fund called FORestry Management (FORM). The aim of FORM is to enhance productivity and pest resistance in key forest species (http://form.ucd.ie/the-project/). Work package 4 is focused on identifying potential risks to Sitka spruce plantations on the island of Ireland, the results of which are presented here.

In the initial stages of work package 4, a pest list for spruce was compiled. Over 600 pests of spruce were identified, and an additional 400 potential pests. This review covers pests of Sitka spruce in its exotic and native range and also examines new and emerging pest threats identified during the production of the pest list. Finally, it discusses how pest risk analysis (PRA) can be utilized to help protect Irish forestry, such as by providing the evidence required to establish and maintain new Protected Zones.

Methods

An extensive literature search was performed to identify pests of all species of spruce in the genus *Picea* Miller at a global level. The literature search concentrated on identifying pests whose known hosts included species of spruce. During the production of the pest list, a number of pest species were added that infested multiple genera of conifers (Pinophyta) irrespective of records on spruce. This was to account for the fact that (1) pests may adapt to new hosts within their invasive range and (2) pests that have already showed the ability to infest more than one genus of conifers are more likely to be able to adapt to new hosts. Additionally, the pest list was limited to those species associated with living or recently dead trees. Sources and databases used in the production of the pest list are detailed in Table 1. In addition to the sources listed in Table 1, an extensive number of published books in the areas of forest entomology and pathology were reviewed in the production of the pest list including Furniss and Carolin (1977), Ciesla (2011) and Reeb and Shaw (2015). Annotated country or regional checklists of taxa known to contain plant pests were also reviewed.

Data on distribution, host range, potential pathways of introduction and spread (e.g. wood fuel, plants for planting, seeds), pest status (primary, secondary or potential pest) and recorded impacts, vector status and history of invasiveness were recorded for each pest and will be used in the preparation of additional publications.

Results

The completed pest list contained 1378 pest species, over 1000 of which were known pests or potential pests of spruce. Based on data gathered concerning the pests' impacts, only key pests of Sitka spruce plantations are highlighted and reviewed here. Pest threats to Sitka spruce plantations are summarized in Table 2.

Pests of forest nurseries

Common disease problems in forest nurseries producing Sitka spruce include damping off and various root rots caused by numerous species from genera including *Fusarium* Link, *Phytophthora* de Bary and *Pythium* Pringsheim. Other common diseases include grey mould caused by *Botrytis cinerea* Persoon and blights caused by species of *Sirococcus* Preuss (Buxton et al.,1962; Sutherland et al., 1989). In Europe, *Sirococcus* blight of Sitka spruce is caused by *S. conigenus* (de Candolle) P. Cannon & Minter, while an additional species, *S. piceicola* Rossman, Castlebury, D.F. Farr & Stanosz, has been described from parts of Canada and Switzerland (Rossman et al., 2007). Outbreaks of violet root rot caused by *Helicobasidium purpureum* (Desmazières) Donk have also been recorded in nurseries (Gregory and Redfern, 1987).

Springtails, insects of the order Collembola, usually feed on decaying material. However, in large numbers springtails will feed on the cotyledons of recently emerged seedlings which, if not killed, will go on to develop into multi-stemmed plants with no commercial value (Alford, 2012). Species of *Lygus* Hahn can also be highly damaging, as feeding by *Lygus* species causes growth distortion and the formation of multiple leaders (Sutherland et al., 1991). Various weevil species can cause damage to the root collar in nurseries, girdling trees and killing

Table 1 Sources searched in the production of the pest list. In addition to the sources listed below, extensive reviews were made of published texts in the area of forest entomology and forest pathology.

Source	Link	Notes
Bark and ambrosia beetles	http://www.barkbeetles.info/index.php	Used to review the host records of species within genera known to infest coniferous species.
CABI crop protection compendium	https://www.cabi.org/cpc/	The advanced database search was used to generate a list of pests of *Picea* within the CABI crop protection compendium.
EPPO Global Database	https://gd.eppo.int/search	Searches were performed to identify all pests of *Picea* species within the database.
Fungal Databases, US National Fungus Collections	https://nt.ars-grin.gov/fungaldatabases/	The advanced database search could not provide an output for all records on *Picea* due to the sheer volume. The advanced database search was used to gain records of fungi on *P. sitchensis*. A further advanced database search was then performed for genus of pathogenic fungi identified on *P. sitchensis* in the first search and for any other genera of pathogenic fungi identified during the literature search.
Google Scholar	https://scholar.google.com/	Literature searches were made using the key terms spruce AND pest, spruce AND disease, *Picea* AND pest, *Picea* AND disease.
HOSTS	http://www.nhm.ac.uk/our-science/data/hostplants/search/index.dsml	The advanced search function was used to identify Lepidopteran species recorded on *Picea*.
ScaleNet	http://scalenet.info/	The ecological associations search function was used to identify those scales associated with *Picea*.

Table 2 Endemic, new and emerging pest threats to Sitka spruce plantations covered by this review, listed in alphabetical order and their global distribution.

Scientific name	Disease name	Principle hosts	Status in Ireland	Global distribution
Pathogens				
Armillaria spp. (Fries) Staude	Honey fungus	Broadleaved and conifers	Present: *Armillaria cepistipes* Velenovský, *A. mellea* (Vahl) Kummer, *A ostoyae* (Romagn.) Herink Not recorded: *A. borealis* Marxmüller & Korhonen	Cosmopolitan
Chrysomyxa spp. Unger	Rust fungus	*Picea* Miller	Absent	Circumboreal
Gemmamyces piceae Borthwick	Spruce bud blight	*Picea* Miller	Present	Europe, Alaska
Heterobasidion annosum sensu stricto (Fries) Brefeld	Root and butt rot	Various conifers	Present	Eurasia
Heterobasidion irregulare Garbelotto & Otrosina	Root and butt rot	*Calocedrus decurrens* (Torrey) Florin, *Juniperus* Linnaeus, *Pinus* Linnaeus	Absent	North America and introduced to Italy
Heterobasidion occidentale Otrosina & Garbelotto	Root and butt rot	Various conifers	Absent	Western North America
Heterobasidion parviporum Niemelä & Korhonen	Root and butt rot	*Picea* Miller	Absent	Eurasia
Lirula macrospora (R. Hartig) Rehm	Needle cast fungi	*Picea* Miller	Absent	Circumboreal
Lophodermium piceae (Fuckel) von Höhnel		*Picea* Miller	Present	Eurasia
Neonectria fuckeliana (C. Booth) Castlebury & Rossman	Stem canker of spruce	*Abies* Miller, *Picea* Miller, *Pinus radiata* D. Don	Present	Asia, Europe, New Zealand, North America
Phaeolus schweinitzii (Fries) Patouillard	Brown cubical rot	Various conifers	Present	Temperature northern hemisphere, New Zealand, South Africa
Porodaedalea pini sensu lato (Brotero) Murrill	Red ring rot	Various conifers	Present	Eurasia, North America
Rhizina undulata Fries	"Group dying"	Various conifers	Present	Europe, North America, South Africa
Rhizosphaera kalkhoffii Bubák	Needle cast fungi	Various conifers	Present	Europe, North America, Asia
Rhizosphaera pini (Corda) Maublanc		*Abies* Miller, *Pinus* Linnaeus, *Picea* Miller, *Tsuga* Carrière	Absent	Asia, Europe, New Zealand, North America
Invertebrate pests				
Scientific name	Common name	Principle hosts	Status in Ireland	Global distribution
Acleris gloverana (Walsingham)	Western blackheaded budworm	*Abies* Miller, *Picea* Miller, *Pseudotsuga* Carrière	Absent	Western North America
Choristoneura freemani Razowski	Western spruce budworm	*Picea* Miller	Absent	Western North America

Continued

Table 2 *Continued*

Scientific name	Disease name	Principle hosts	Status in Ireland	Global distribution
Choristoneura fumiferana (Clemens)	Eastern spruce budworm	*Picea* Miller	Absent	North America
Cydia pactolana (Zeller)	Spruce bark tortrix	*Abies alba* Miller, *Larix* Miller, *Picea abies* (L.) H. Karst., *Pseudotsuga menziesii* (Mirb.) Franco	Absent	Eurasia
Dendroctonus micans (Kugelann)	Great European spruce bark beetle	*Picea* Miller	Absent	Eurasia
Dendroctonus rufipennis (Kirby)	Spruce bark beetle	*Picea* Miller	Absent	North America
Dendrolimus sibiricus Chetverikov	Siberian silk worm	Polyphagous on conifers	Absent	China, European Russia, Korean Peninsula, Mongolia, Siberia
Elatobium abietinum (Walker)	Green spruce aphid	*Picea* Miller	Present	Widespread
Gilpinia hercyniae (Hartig)	European spruce sawfly	*Picea* Miller	Absent	Eurasia, introduced to North America
Hylobius abietis (Linnaeus)	Large pine weevil	Polyphagous on conifers	Present	Eurasia
Ips typographus (Linnaeus)	European spruce bark beetle	*Picea* Miller	Absent	Eurasia
Lambdina fiscellaria (Guenée)	Hemlock looper	Polyphagous on conifers and broadleaved trees	Absent	North America
Lymantria monacha (Linnaeus)	Nun moth	Polyphagous on conifers and broadleaved trees	Absent	Eurasia
Nalepella haarlovi Boczek	A mite	*Picea* Miller	Absent	Great Britain, Denmark, Finland
Oligonychus ununguis (Jacobi)	Spruce spider mite	Polyphagous on conifers	Absent	Widespread
Polygraphus jezoensis Niijima	A bark beetle	*Picea* Miller	Absent	Far East, introduced to European Russia
Polygraphus proximus Blandford	Sakhalin fir bark beetle	*Abies* Miller and occasionally other conifers	Absent	Far East, introduced to Siberia and European Russia
Physokermes hemicryphus (Dalman)	Small spruce bud scale	*Abies* Miller, *Picea* Miller	Uncertain	Europe and North America
Physokermes inopinatus Danzig & Kozár	Hungarian spruce bud scale	*Abies cephalonica* Loudon, *Picea* Miller	Absent	Europe
Physokermes piceae (Schrank)	Spruce bud scale	*Picea* Miller	Uncertain	Continental Europe, status in North America uncertain
Pissodes strobi (Peck)	White pine weevil	*Picea* Miller, *Pinus* Linnaeus, *Pseudotsuga menziesii* (Mirbel) Franco	Absent	North America

them, such as root weevils of the genus *Otiorhynchus* Germar (Sutherland et al., 1989). Mite species such as *Nalepella haarlovi* Boczek and *Oligonychus ununguis* (Jacobi) can also cause damage to young spruce plants in nurseries, including Sitka spruce. Mite feeding causes needles to turn yellow, dry up and die (Löyttyniemi, 1969; Alford, 2012). Impacts of these pests tend to be greatest during hot, dry growing seasons (Poteri et al., 2005).

Pathogens of Sitka spruce plantations in Ireland and Europe

Heterobasidion annosum (Fr.: Fr.) Bref. is the causal agent of a heart rot of the wood and is the most commercially important fungal disease in Ireland (Joyce and OCarroll, 2002). Fruiting bodies release basidiospores that land and germinate on freshly cut stumps. Stumps are then colonized by the fungus, which spreads to nearby standing trees via root to root contacts. From there, the fungus will grow necrophytically through sapwood and heartwood, reducing timber value and killing trees (Asiegbu et al., 2005). *Heterobasidion annosum sensu lato* (*s.l.*) is a species complex of five distinct species, varying in distribution and host preference (Otrosina and Garbelotto, 2010). *Heterobasidion annosum sensu stricto* (*s.s.*) is the only species in the complex which has been recorded in Ireland and Great Britain. In continental Europe, *Heterobasidion parviporum* Niemelä & Korhonen is widespread and considered a specialist on Norway spruce (*Picea abies* (L.) H.Karst.). *Heterobasidion abietinum* Niemelä & Korhonen is limited to Central, Southern and Eastern Europe on fir species (*Abies* Miller). Two species of *Heterobasidion* Brefeld are present in North America: *H. irregulare* Garbelotto & Otrosina, which is transcontinental and largely associated with infection of pines (*Pinus* Linnaeus) and *H. occidentale* Otrosina & Garbelotto, limited to Western North America and capable of infecting a wide range of coniferous species. If *H. parviporum* was to be introduced to Ireland and the UK, the threat to Sitka spruce is uncertain. There is no evidence that *H. parviporum* is more aggressive on Sitka spruce compared with *H. annosum s.s.*, but it remains uncertain if introduction of this species to Ireland or Great Britain could lead to increased impacts as Sitka is not as widely grown in Europe outside of these islands (Tuffen, 2016). Introduction of the North American *H. irregulare* to Italy circa World War II has led to pockets of dead stone pine (*Pinus pinea* Linnaeus), though overall spread of the pathogen has been slow (D'Amico et al., 2007).

Armillaria (Fries) Staude is a widely occurring fungal genus commonly referred to as honey fungus. Some species, such as *Armillaria mellea s. l.* (Vahl) Kummer, are cosmopolitan species, whilst others have a more limited distribution. These fungi cause root rot in a range of coniferous and broadleaved species, spreading via root to root contacts between trees or infecting via rhizomorphs that grow through the soil (Worrall, 2004). More serious damage is incurred by trees already weakened by other pests (de Brit and McAree ,1977; Reeb and Shaw, 2015). In Ireland, *A. mellea s.l.* is the species primarily recorded as causing root disease of Sitka spruce (Joyce and OCarroll, 2002). Other species of *Armillaria* recorded on Sitka spruce in Europe are *A. borealis* Marxmüller & Korhonen, *A. cepistipes* Velenovský and *A. ostoyae* (Romagnesi) Herink (Mulholland et al., 2012), the latter two have also been recorded on the island of Ireland.

'Group dying' was previously a health issue in Sitka stands in Ireland. Investigations into why groups of Sitka spruce were being killed in Ireland and Great Britain revealed an association of the phenomenon with the fungus *Rhizina undulata* Fr.: Fr. This pest infects via the roots, rotting them and eventually causing tree mortality. 'Group dying' is no longer a significant economic disease in Ireland. The fungal fruiting bodies commonly occur at the site of fires and discouragement of campfires in plantations has successfully managed the disease (Hibberd, 1991).

In Europe, there are no needle cast diseases of Sitka spruce that are of particular importance, though cases may occur that cause damage on a local level. On the island of Ireland, only *Lophodermium piceae* (Fuckel) Höhn. seems to be associated with needle cast of spruce (Annemarie Hamilton, *personal communication*). Elsewhere in Europe, *Rhizosphaera pini* (Corda) Maubl., *R. kalkhoffii* Bubák and *Lirula macrospora* (R. Hartig) Darker may also cause needle cast symptoms on Sitka spruce (Holsten, 2001; Reeb and Shaw, 2015).

Insect pests of Sitka spruce plantations in Ireland and Europe

Hylobius abietis (Linnaeus), large pine weevil, is a major hindrance to forest regeneration in Ireland and beyond. Sitka spruce is particularly susceptible to damage compared with other commercially grown conifers in Europe (Nordenhem and Nordlander, 2014). Larvae develop within the stumps of trees and, after emergence, adult weevils feed on the root collars of seedlings and recent transplants, killing the young trees by girdling them (Dillon and Griffin, 2008). Between 1980 and 2000, *H. abietis* caused serious damage to 88 000 ha of conifers across the five European nations studied: Germany, Hungary, Lithuania, Romania and Slovakia (Grégoire and Evans, 2007). The principal method of protecting conifer transplants is application of pesticide sprays or dips before shipping from the nursery, but considerable research has gone into biological control options including the use of entopathogenic nematodes (Dillon and Griffin, 2008). Additional spruce feeding *Hylobius* Germar species are present in Continental Europe, though are generally of minor economic importance (Viiri and Miettinen, 2013).

Elatobium abietinum (Walker) (green spruce aphid) is a widespread pest of *Picea* spp. which, on the island of Ireland, affects productivity of Sitka spruce when populations are high by causing defoliation (Day, 2002). Experimental work has been carried out to investigate the losses caused by *E. abietinum* defoliation. In Ireland, one year's complete defoliation can result in a reduction in leader growth of 50 per cent (de Brit and McAree, 1977). Plots of young Sitka spruce (4–6 years) in Wales exposed to 3 years of high aphid populations suffered a reduction in height of 8 per cent and stem volume reduced by 6 per cent compared with trees treated to keep aphid populations low (Straw et al., 2005). In experimental plots of mid-rotation Sitka spruce (23–28 years old), those with high aphid populations had a reduced mean volume increase of 6 per cent per year compared with treated plots (Straw et al., 2011). Impacts of *E. abietinum* are expected to increase under climate change scenarios. Milder winters are associated with a higher winter survival of

E. abietinum (Day, 2002), and drought conditions have also been shown to significantly increase needle loss due to *E. abietinum* feeding (Banfield-Zanin and Leather, 2014).

Another defoliator of spruce in Britain and Europe is *Gilpinia hercyniae* (Hartig), the European spruce sawfly. An outbreak occurred in Wales between 1968 and 1974, leading to significant reduction in growth of trees (Williams et al., 2003). The outbreak came to an end after an epidemic of a baculovirus caused a population crash of the pest (Evans, 1987). *Gilpinia hercyniae* was also accidently introduced to Canada in the 1920s, with an outbreak occurring in spruce stands throughout north-eastern North America in the 1930s (Natural Resources Canada, 2015). The baculovirus that ended the epidemic in Wales was accidentally introduced to Canada when natural parasitoids from Scandinavia were released in an effort to control the pest. The combination of the virus and parasitoids successfully reduced the outbreak populations, with no serious impacts having occurred since the introduction of the virus (Moreau and Lucarotti, 2007). This virus has also been successful at controlling the pest in Wales. This pest is absent from the island of Ireland, which has a Protected Zone and measures in place to prevent introduction. Plants of spruce (*Picea* spp.) exported to the island of Ireland from the range of *G. hercyniae* must originate from nurseries that are official pest-free places of production.

The great European spruce bark beetle, *Dendroctonus micans* (Kugelann), is present across much of Continental Europe except for the Iberian Peninsula (Jerger et al., 2017). It is also absent from the island of Ireland but has been established in Great Britain since the 1970s (Bevan and King, 1983). The range of the pest in Britain continues to expand, and it has recently been found in Southern Scotland (Forestry Commission, 2018). *Dendroctonus micans* is a damaging pest on a range of spruces. The beetle colonizes the phloem of trees, where it feeds. Death of trees occurs when feeding damage leads to girdling, and the most damaging outbreaks in Europe have been associated with the geographical expansion of the pest westwards (Grégoire, 1988). Timber from infested trees can usually be salvaged as long as the tree is felled before death. This is due to *D. micans*, unlike many other bark beetle species, not vectoring pathogenic fungi that reduce timber quality (Jerger et al., 2017). Unlike Norway spruce, which is considered to have high risk of being attacked by *D. micans,* in Britain Sitka spruce is considered to have a low susceptibility to initial attack by the pest. However, there is a medium risk of tree mortality should an attack occur (Forestry Commission, 2012). *Rhizophagus grandis* Gyllenhal is a predatory beetle which only attacks *D. micans* and has been widely used as a biological control agent against the pest, including breeding and release programmes in Great Britain (King et al., 1991).

Another highly damaging bark beetle pest that is absent from both Britain and Ireland is the European spruce bark beetle *I. typographus*. The main host of *I. typographus* is Norway spruce, but Flø et al. (2018) demonstrated that the pest can breed successfully in Sitka spruce and is likely to be able to colonize Sitka spruce in European plantations. Data from 10 countries in Europe found that, between 1990 and 2001, over 2 800 000 ha of spruce were attacked, leading to the loss of 31 643 000 m^3 of timber (Grégoire and Evans, 2007). Damage from *I. typographus* increases after severe storms, as windthrown trees provide new breeding grounds and allow populations to build to levels where mass attack of healthy trees is possible (Komonen et al., 2011). Protected Zone measures are in place to prevent introduction of both *I. typographus* and *D. micans* to the island of Ireland. Wood of conifers imported from Europe must be either bark free, kiln-dried or originate from an area known to be free of the pests. However, cases of non-compliance occur, and in March 2017 retailers in Northern Ireland were found to be selling firewood that did not meet current plant health requirements (Forest Service Agency, 2017). *Ips typographus* is also occasionally intercepted in British ports but has yet to establish (Poulson, 2015). This may be related to the biology of the species, which can only successfully colonize live trees when large numbers of adult beetles attack *en masse* (Liebhold and Tobin, 2008). Though non-compliant timber and wood packaging material may occasionally be intercepted, the current measures have so far kept the numbers of *I. typographus* entering low enough to prevent establishment.

Continued exclusion of *I. typographus* and *D. micans* is particularly important in light of climate change. Average Irish summer temperatures are predicted to rise by as much as 2.5°C (Sweeney et al., 2003). Both *I. typographus* and *D. micans* begin their summer flight when temperatures are above 20°C (Poulson, 2015; Forestry Commission, 2018). If summer temperatures rise in Ireland under climate change, this will lead to an increased flight period for these bark beetles with a greater number of years being conducive to the build up of damaging populations.

The risk of other pests of Sitka spruce in Europe may also increase in light of climate change. *Lymantria monacha* (Linnaeus), nun moth, is a widespread Eurasian species that is highly polyphagous on broadleaved trees and conifers but shows a preference for conifers (Molet, 2012). The current climate of the island of Ireland is marginal for establishment, but modelling under various climate change scenarios indicates that as summers warm the whole of the island of Ireland may be suitable for pest establishment, with the range of the pest expected to expand north in Europe by 500–700 km (Vanhanen et al., 2007). Outbreaks of the pest, which typically last 5–7 years, can cause severe defoliation that can kill host trees (FAO, 2007). *Lymantria monacha* is a known pest of Sitka spruce and has been recorded attacking and defoliating this host in Denmark (Secher Jensen, 1991).

Pathogens of Sitka spruce in North America

In the old growth Sitka spruce forests of the Pacific Northwest, many species of fungi cause damaging root, heart and stem rots; those considered most economically important are summarized here, but numerous fungi cause decay rots worldwide. In North America, the primary *Heterobasidion* species found on Sitka spruce is *H. occidentale* (Otrosina and Garbelotto, 2010). Significant impacts on Sitka spruce from *Heterbasidion* root and butt rot are not reported in North America and in Alaska it is considered most important on western hemlock (*Tsuga heterophylla* (Rafinesque) Sargent), with losses primarily due to bole breakage and uprooting due to the wood decay (Holsten, 2001). In Oregon, it is stated that there is little knowledge concerning impacts on Sitka spruce due to 'lack of any plantation management' (Reeb and Shaw, 2015).

Red ring rot caused by *Porodaedalea pini s.l.* (Brotero) Murrill will cause heart rot of mature trees and is considered to be the most damaging of the heart rots in Western North America (Scharpf, 1993). *Porodaedalea pini s.l.* has a complicated taxonomy, being a species complex, and the type species *P. pini s.s.* is limited to Europe (Fischer, 1996; Brazee and Linder, 2013). Further research is required to classify the species of *P. pini s.l.*, which has been recorded damaging to Sitka spruce in the Pacific Northwest (Bier et al., 1946; Zabel and Morrell, 1992; Dubois, 2017). It is likely this species is absent from the island of Ireland and the rest of Europe, and further analysis is required to ascertain potential impacts should the pest be introduced.

Brown cubical rot caused by *Phaeolus schweinitzii* (Fries) Patouillard is a serious disease of Sitka spruce in the Pacific Northwest. Though present on the island of Ireland, incidence is rare (de Brit and McAree, 1977); Coillte has recorded 14 trees infected by this pest between 1979 and 2017 (Annmarie Hamilton, personal communication). This may be related to the fact that it is primarily a disease of old growth forests (Reeb and Shaw, 2015). Decay can cause significant losses and infected trees are predisposed to wind throw and breakage.

Sitka spruce is host to a number of species of the rust genus *Chrysomyxa* (Wallr.) Unger in both North America and Europe. Many of the rusts in this genus are dioecious: alternating between conifers, mostly in the genus *Picea*, and members of the plant family Ericaceae, which include heathers and rhododendrons (Crane, 2001). Some species infect and produce spore masses on needles, whereas others such as *C. monesis* Ziller infect spruce cones and prevent normal seed development, which can significantly impact seed orchards (Ziller, 1954). *Chrysomyxa ledicola* Lagerh sporulates on foliage but is not particularly damaging to Sitka spruce and the application of control measures is not usually necessary under forest conditions (Shaw and Harris, 1960). This is despite the vast number of spores that can be produced on infected needles. So many spores were produced in Alaska in 2012 that ‘orange goo’ covered the shoreline of the village of Kivalina, alarming residents (NCCOS, 2012). It is also common in Sitka spruce stands along the Oregon coast (Reeb and Shaw, 2015). *Chrysomyxa arctostaphyli* Dietel (spruce broom rust) infection of Sitka spruce and other *Picea* species causes formation of witches’ brooms, leading to stem deformations and over time mortality of trees (Natural Resources Canada, 2015). Plants of *Picea* are prohibited from being imported into the European Union from outside of Continental Europe, but there remains a risk of *Chrysomyxa* species entering on cones or seeds, which are not regulated, or on their alternative hosts such as *Rhododendron* Linnaeus. Though Western North American species of rust are not recorded as particularly damaging on Sitka spruce, two new species have recently been described from China on *Picea asperata* Masters (Cao et al., 2017) and the susceptibility of European and North American spruces to these and other Asian *Chrysomyxa* is unknown.

Insect pests of Sitka spruce in North America

Many insect pests are highly damaging to Sitka spruce plantations in North America. *Pissodes strobi* (Peck) (white pine weevil) is the most destructive pest of Sitka spruce in its native range. In early spring, females lay eggs in the leaders of spruce trees; when larvae hatch they mine downwards girdling leaders and killing them. The feeding activity can both reduce yield and quality of timber and damage can lead to stem defects such as forking (Reeb and Shaw, 2015). In a 26-year study in the Pacific Northwest, on average trees were attacked 4–6 times and most of the trees ended with multiple stems and severe crooks (Mitchell et al., 1990). Its susceptibility to damage by *P. strobi* meant Sitka spruce was not a favoured species for forestry in its native range, despite the high value of its timber, though recent breeding programmes for resistance may now make Sitka spruce plantations economically viable again (King and Alfaro, 2009).

Spruce bark beetle, *Dendroctonus rufipennis* (Kirby), can cause high levels of mortality of mature spruce trees during outbreaks, including Sitka spruce (Reeb and Shaw, 2015). A damaging epidemic occurred over a 30-year period on the Kenai peninsula of Alaska, affecting Sitka, white and Lutz (*P x lutzii* Little) spruce, but populations have now decreased (van Hees, 2005). Huge outbreaks of *D. rufipennis* on other spruce species are ongoing. In 2017, aerial surveys showed 500 000 ha of forest in British Columbia to be affected by the pest, and it is the largest outbreak ever recorded in the Omineca Region, located in the northern interior of British Columbia (Ministry of Forests, lands, Natural Resources Operations and Rural Development, 2018).

The spruce budworms (*Choristoneura* Lederer) are very well-known defoliators of *Picea* in North America. However, Sitka spruce is not widely reported as damaged by these species. *Choristoneura freemani* Razowski (synonym: *Choristoneura occidentalis* Freeman), the western spruce budworm, is largely recorded as an economic defoliator of Douglas fir during regular outbreak periods (Woods et al., 2010; Alfaro et al., 2014). *Choristoneura fumiferana* (Clemens), the eastern spruce budworm whose range actually extends across North America, primarily defoliates white spruce (*P. glauca* (Mönch) Voss), red spruce (*P. rubens* Sargent), black spruce (*P. mariana* (Miller) Britton, Sterns & Poggenburg) and the balsam fir (*Abies balsamea* (Linnaeus) Miller) in British Columbia (Burleigh et al., 2002). Though the *Choristoneura* spp. do not widely damage Sitka spruce in their native range, budworms should still be considered to pose a threat to Sitka spruce as pests can adapt when they find themselves in an environment without their preferred host species.

The western blackheaded budworm, *Acleris gloverana* (Walsingham), is reported as occasionally causing defoliation damage to Sitka spruce. An outbreak in Alaska between 1948 and 1955 defoliated most stands of Sitka spruce in the Tongass National Forest, Alaska, leaving 75 per cent of trees with top kill (McCambridge, 1955).

The hemlock looper, *Lambdina fiscellaria* Guenée, is widespread in Canada and has a more restricted distribution in the US. It has three subspecies, *L. f. fiscellaria*, *L. f. lugubrosa* and *L. f. somniarai*, which have been described on the basis of differences in larval hosts or adult pheromones—but no clear morphological differences. Studies on mitochondrial DNA of these three subspecies did not indicate clear sub-specific divisions between *L. f. lugubrosa* and *L. f. somniarai* (Sperling et al., 1999). In Canada, this species is a serious defoliator which has destroyed several million hectares of coniferous forests in the east over the years. Between 1910 and 1975, the pest caused timber losses estimated at 12 million m^3 in Newfoundland and 24 million m^3 in Quebec (Natural Resources Canada, 2015). Sitka spruce is only usually used as a host of *L. fiscellaria* in British Columbia during outbreak years (Alfaro et al., 1999). In August of 1965, the pest caused severe defoliation of about 146 ha of Sitka spruce on the north-west coast of Wrangell Island, Alaska, and the authors state that in this instance Sitka spruce was the preferred host over western hemlock (Torgersen and Baker, 1967). It remains unclear if this pest could adapt to Sitka spruce stands as a principal host in the absence of its preferred hosts. Alternatively, *L. fiscellaria* may initially infest other tree species grown on the island of Ireland such as western hemlock and then move onto Sitka spruce during outbreak years.

Emerging and potential threats to Sitka spruce

A number of new and emerging pests of spruce were identified in Europe and North America. Since around 2012, resinous bark lesions and mortality of large Sitka spruce trees have been noted in Northern Ireland. In many cases, the fungus *Neonectria fuckeliana* (C. Booth) Castl. & Rossman was found to be associated with these dead and dying trees. Investigations are underway to discover the factors that may have led to this disease developing in the stands (Richard O'Hanlon, AFBI, personal communication). On Norway spruce in Norway, infection of *N. fuckeliana* has been occurring in conjunction with infestation by the spruce bark tortrix, *Cydia pactolana* (Zeller) leading to extensive accumulative impacts (Uimari et al., 2018). *Cydia pactolana* has not been recorded on the island of Ireland. It is uncertain if *C. pactolana* can utilize Sitka spruce as a host, but if Sitka spruce is a suitable host this pest has potential to increase the impacts of the current *N. fuckeliana* outbreak in Northern Ireland.

Recently, the European spruce bud blight pathogen, *Gemmamyces piceae* Borthwick, has been found in Alaska for the first time infecting Sitka spruce (Winton, 2017). This pathogen is relatively widespread in Europe, and in 2009 a massive outbreak occurred on Colorado blue spruce (*Picea pungens* Engelmann) in the Czech Republic, leading to mortality of trees after several years of repeated infection (Černy et al., 2016). *Gemmamyces piceae* has been previously recorded in Ireland on Norway and Colorado blue spruce, but there are no records to date on Sitka spruce (Annemarie Hamiliton, Coillte, personal communication). Infection by *G. piceae* causes misshapen black buds, which are frequently killed prior to bud break. In the Alaskan outbreak, most of the surveyed trees had only a few infected buds (<5 per cent), but some heavily infested trees had up to 100 per cent of buds dead or damaged. The distribution of the pest indicates it is not a recent introduction to Alaska, and a study on the population genetics of *G. piceae* has been initiated to address this question (Winton, 2017).

Scale insects damage plants both by sucking sap, which reduces plant vigour, and also through the production of honeydew which encourages the growth of sooty moulds that smother plant leaves or needles and reduces photosynthesis. The Hungarian spruce bud scale, *Physokermes inopinatus* Danzig & Kozár, is an emerging pest of spruce in Europe. It was first described from Hungary in 1973 and then later found in other European countries, including Greece where the host was Greek fir (*Abies cephalonica* Loudon) (Stathas and Kozár, 2010). In 2010, a severe outbreak occurred on Norway spruce in Southern Sweden. The outbreak covered approximately 1 000 ha and defoliation was caused by the vast amounts of honeydew and associated sooty moulds (Gertsson and Isacsson, 2014). Sitka spruce trees that were close to the outbreak were also infested (Gertsson and Isacsson, 2012) and in 2013 the pest was found infesting white spruce (*Picea glauca* var. *conica*) at a site 15 km away (Gertsson and Winde, 2014). Due to the level of infestation, many of the trees were felled in order to salvage the timber (Gertsson and Isacsson, 2014). Other species of *Physokermes* Targioni Tozzetti are also pests of spruce. A damaging outbreak of *P. piceae* (Schrank) occurred on Norway spruce in Lithuania in 2010, where over 7 000 ha were infested (Gedminas et al., 2015). It is currently not clear if spruce bud scales of the genus *Physokermes* are present on the island of Ireland. There are two old records of *Physokermes* sp on the island, from County Wicklow in 1908 and County Tyrone in 1912. Both records were on silver fir (*Abies alba* Miller) and so may refer to *P. hemicryphus* (Dalman), which has been recorded on this host in other European countries (O'Connor et al., 2013). If Ireland is free of *P. piceae* and *P. inopinatus*, action to prevent these scale insects entering on planting material from Continental Europe should be considered.

Dendrolimus sibiricus Chetverikov, the Siberian silk worm, is indigenous to China and south-eastern Siberia but has been introduced to European Russia, Mongolia and the Korean Peninsula (Gninenko and Orlinskii, 2002). Though there are records of the moth being caught in the Moscow region; results of a survey published in 2007 failed to find definitive evidence of the moth in Central European Russia, calling into question if the pest is spreading westwards as has been previously reported (Baranchikov et al., 2007). The range of the pest has expanded northwards in Siberian forests, with outbreaks occurring in regions where they have previously not been observed, thought to be related to the warming climate (Kharuk et al., 2017). *Dendrolimus sibiricus* infests a range of conifer species, including spruce, but does show a preference for Siberian fir (*Abies sibirica* Ledebour) and Siberian pine (*Pinus sibirica* du Tour). Laboratory investigations into the potential host range in Europe demonstrated that Sitka spruce was a suitable host for larvae (Kirichenko et al., 2008). Outbreaks of *D. sibiricus* can cause massive economic impacts. The 1995–1996 outbreak in Siberia reportedly caused 38–48 per cent mortality of trees (Mozolevskya *et al*., 2002) and the 2017 outbreak spanned 800 000 ha with conifer mortality within about 300 000 ha (Kharuk et al., 2017). If the pest does spread to Europe, either via natural spread or through trade in commodities such as plants for planting or coniferous wood where egg masses have been laid, impacts could be massive where the climate is suitable for the pest to reach outbreak levels (Möykkynen and Pukkala, 2014).

The Sakhalin fir bark beetle, *Polygraphus proximus* Blandford, is an East Asian bark beetle species. It is a secondary pest in its native range, infesting felled logs or trees weakened by fire or other factors, but has become invasive in the fir forests of Siberia and European Russia. Though the primary hosts are firs, it will also infest spruce (including Norway spruce), pine, larch and hemlock and, as it spreads, may be able to infest additional new hosts (EPPO, 2014). It has caused major impacts in its invasive range and is one of the main factors contributing to the degradation of Siberian fir forests due to the high level of mortality of infested trees (Krivets et al., 2015). A second East Asian *Polygraphus* species, *P. jezoensis* Niijima, was identified in European Russia for the first time in 2013 (Chilakhsaeva et al., 2013). *Polygraphus jezoensis* has a preference for spruce species, and in Japan it is considered one of the most destructive bark beetles on spruce (Nobuchi, 1979). It is not yet clear if *P. jezoensis* will be as destructive in its introduced range as the related *P. proximus*, and this emerging risk should be monitored.

Discussion

Protecting Sitka spruce in Ireland—the role of PRA

Forestry in Ireland contributes an estimated €2.3 billion to the economy each year and employs between 14 000 and 16 000 people (Coillte, 2014). Given that Sitka spruce makes up over 50 per cent of the forest plantations in Ireland, it is imperative that pest threats are identified early and action taken to exclude pests where possible to prevent economic losses. Horizon scanning through monitoring of scientific literature, trade journals, media and even social media can help to identify new threats early. Assessing risks to Sitka spruce does pose some challenges. The native range of Sitka spruce is the coastal Pacific Northwest of North America. Plantations of this species as an exotic conifer globally are limited. Within Europe, the majority of stands are found in the UK and Ireland, with lower levels of plantings in Denmark, France, Sweden and Norway (Houston Durrant et al., 2016a). Sitka spruce is not currently planted widely anywhere in Asia or Oceania, though specimen trees in some countries will exist. This is in contrast to some native European forest species such as Scot's pine (*Pinus sylvestris* Linnaeus)—the most widespread species of pine globally—whose native range extends from Spain to the Far East of Russia (Houston Durrant et al., 2016b), as well as being a widely planted exotic species. This means Sitka spruce has not been widely exposed to pests outside of its native range, and its susceptibility to them is unknown. A relatively minor pest of Norway spruce, or another spruce species, may be highly damaging to Sitka spruce if introduced to a new area as has been seen with other coniferous forestry pests. *Polygraphus proximus* is one such example, and another is *Dendroctonus valens* (Leconte)—the red turpentine beetle. The latter is a largely secondary pine pest in North America but has caused widespread mortality of Chinese red pine (*Pinus tabuliformis* Carrière) since its introduction to China. Impacts in China were exacerbated by the planting of monocultures of Chinese red pine, as well as drought- and cold-related damage, and over 10 million pines have been killed in the Chinese outbreak (Yan et al., 2005). In a similar way, the widespread planting of Sitka spruce in same-age monocultures in Ireland could also be conducive to the rapid spread of a newly introduced pest.

In order to regulate a pest or pathway at EU level, a PRA is required, due to international trade laws. The World Trade Organization (WTO) Agreement on the Application of Sanitary and Phytosanitary Measures, known more commonly as the SPS agreements, requires that phytosanitary measures placed on trades are technically justified. PRA is the accepted method to technically justify new regulations and is defined by the International Plant Protection Convention (IPPC) (the body recognized by the WTO as the standard setting authority) as 'The process of evaluating biological or other scientific and economic evidence to determine whether an organism is a pest, whether it should be regulated, and the strength of any phytosanitary measures to be taken against it' (IPPC, 2007).

PRA can be carried out on both pests and pathways. In pest-focused PRA, the risk of entry, establishment, spread and potential impacts of a specific pest is analysed, and if the risk is unacceptable then risk mitigation measures are identified. Table 3 outlines in more detail how the different sections are analysed. All PRAs must follow the general guidelines as laid down in the IPPC's international standard, ISPM 11 (IPPC, 2017), but PRA schemes vary between countries. Many countries are utilizing a rapid or express PRA format, where the process of PRA as outlined in ISPM 11 is simplified to allow for a more rapid assessment of pest risks. For example, the European and Mediterranean Plant Protection Organization (EPPO) developed an Express Pest Risk Analysis scheme for use by its members (EPPO, 2012). As a part of the FORM project, the first rapid PRA scheme for Ireland has been developed. Like the majority of PRA schemes, the Irish scheme rates the probability of entry and establishment, the potential rate of spread and the potential impacts on a qualitative scale, as outlined in Table 3. A six-point scale for rating risks was developed, with an associated guidance document for use by stakeholders and policymakers which broadly defines the qualitative ratings used. For example, the various likelihood ratings for entry are equated to how often it would be expected for a pest with that rating to enter the PRA area over a 10-year period—from no entry for pests with a negligible risk up to multiple times per year for a pest considered very likely to enter.

As a part of the FORM project, pests identified from the proceeding literature review have been prioritized for PRA on the basis of the expertise of a pest risk analyst, and the results of a hierarchical clustering (HC) analysis (work in progress). HC has previously been used to examine the likelihood of establishment of tree pests and diseases for the EU (Eschen et al., 2014). In this context, HC was used to examine the pest assemblages of various countries and identify those with the greatest similarity to Ireland, and pests were then ranked according to the frequency metric proposed by Watts and Worner (2009). The spruce infesting *Physokermes* species, *Lymantria monacha* (the nun moth) and *L. fiscellaria* (hemlock looper) were selected for PRA as pests with potential to cause significant damage. Their risks are summarized in Table 4. The identification of appropriate risk management measures will be made by the Department of Agriculture, Food and the Marine (DAFM) and so are not included within the table.

Globalization has led to dramatically increased movements of plants and plant products, and to an increase in the introduction of invasive species, including plant pests, to new regions (Hulme, 2009; Roques, 2010). The risks posed by trades in a specific commodity can be addressed via pathway-focused PRA. In the pathway PRA process, a list of pests that can be associated with the pathway or commodity is compiled and then subjected to risk analysis. A rapid pathway PRA scheme has also been developed for Ireland. In the Irish scheme, the pest list is first prioritized, with pests known to already be present on the island of Ireland and those species which are not recorded as causing

Table 3 Details on how likelihood of entry, establishment, spread and impacts are rated in the Irish PRA schemes.

Area of Analysis	Definition	Scale	Example factors taken into account in the assessment
Probability of entry	The probability of the pest entering the PRA area on a specific pathway, and transferring from that pathway onto a suitable host plant	Negligible Very unlikely Unlikely Moderately likely Likely Very likely	• Likelihood of the pest being associated with the pathway • Current regulations • Ease of detection during inspections
Probability of establishment	Likelihood of the pest being able to perpetuate in the PRA area after entry for the foreseeable future	Negligible Very unlikely Unlikely Moderately likely Likely Very likely	• Climate suitability • Host availability • Probability of current agricultural practises eradicating the pest
Rate of spread	The rate at which the pest would be expected to expand its geographical distribution within the PRA area, both by natural spread and spread of the pest in trade	Negligible Very slow Slow Moderate pace Quick Very quick	• Natural spread: approximate number of kilometres per year • Spread with trade: volume of trade and likelihood of the pest being associated with the pathway
Potential economic impacts	Market and non-market impacts of the pest in the PRA area	Negligible Very small Small Moderate Large Very large	• Yield or quality losses • Effectiveness of current agricultural practises at controlling the pest • Suitability of the climate for build up of damaging populations • Potential loss in trade due to the presence of the pest
Potential environmental impacts	Potential impacts on biodiversity and ecosystems	Negligible Very small Small Moderate Large Very large	• Impacts on biodiversity associated with the host plant(s) • Impacts on ecosystems e.g. where host plants are 'keystone species' in a particular ecosystem
Potential social impacts	Impacts of the pest on human activities	Negligible Very small Small Moderate Large Very large	• Reduction in the aesthetic value of hosts • Potential impacts on human activities • Potential impacts on human or animal health

Table 4 Overview of the Irish pest-focused PRAs being carried out for Physokermes spp. (*P. hemicryphus*, *P. inopinatus* and *P. piceae*), *Lymantria monacha* and *Lambdina fiscellaria.*

Area of Analysis	*Physokermes* spp.	*Lymantria monacha*	*Lambdina fiscellaria*
Potential pathways of entry	• All life stages on plants for planting of *Picea* Miller and *Abies* Miller	• Larvae and egg masses on plants for planting • Larvae on cut foliage • Egg masses on timber • Egg masses on manmade objects	• All life stages on plants for planting • Larvae on cut foliage • Eggs and pupae on timber • Eggs and pupae in fresh mosses and lichens imported for ornamental purposes
Climatic Suitability	All three *Physokermes* species considered are found in areas of Europe with a similar climate to Ireland e.g. Southern Sweden, Netherlands. Climate is very likely to be suitable for establishment	Current climate is marginal for establishment, but the pest could be more significant under a climate change scenario	The pest is present in the Pacific Northwest of North America, where climate is very similar to Ireland
Host Availability	Sitka spruce is a known host of all three *Physokermes* species considered, and other spruce and fir hosts are present in the PRA area	*Lymantria monacha* is polyphagous on coniferous and broadleaved trees and hosts are widespread in the PRA area.	*Lambdina fiscellaria* subsp. *lugubrosa* is known to feed on Sitka spruce. Other subspecies of *L. fiscellaria* are likely to be able to adapt to European versions of their North American hosts (birch, fir, oaks and spruces)
Capacity for Spread	Limited natural spread capacity through passive dispersal of nymphs via wind. Pest is easily overlooked when infestations are light and could spread rapidly in trade	Males and females are capable of flight, though females are less active fliers unless they have laid their eggs	Males and females are capable of flight, but females are extremely poor fliers and their capacity for spread is very limited
Impacts in current distribution	All three species are pests of ornamental spruce in urban areas. Production of honeydew encourages sooty mould growth and can lead to defoliation. Occasional outbreaks are seen in forestry monocultures, especially those stressed by other factors that can lead to tree mortality	Causes periodic outbreaks in Europe causing mass defoliation of conifers and occasionally broadleaved trees, causing losses to timber production	Periodic outbreaks which can lead to losses of millions of cubic metres of timber due to extensive tree mortality
Potential impacts in Ireland	*Physokermes* species could cause accumulative impacts in conjunction with *Elatobium abietinum*, which in outbreak years can cause complete defoliation of older needles. Honeydew production by *Physokermes* species in the summer months could then affect current year needles	Current climatic conditions are not conducive to the build up of outbreak populations Potential impacts under a climate change scenario are to be investigated	Large outbreaks could occur close to the site of introduction, but the slow spread capacity of the pest means containment is likely, reducing potential impacts.

Table 5 The Risk Matrix of the Irish Pathway PRA scheme. The likelihood of introduction of the pest along the pathway is combined with the potential impacts in the PRA area (usually the island of Ireland) in order to gain an overall risk score. Pests that score a 'small risk' or higher are considered for risk management.

Likelihood of introduction	Potential impacts					
	Negligible	Very small	Small	Moderate	Large	Very large
Very likely	Negligible risk	Very small risk	Small risk	Large risk	Very large risk	Very large risk
Likely	Negligible risk	Very small risk	Small risk	Moderate risk	Large risk	Very large risk
Moderately likely	Negligible risk	Negligible risk	Very small risk	Small risk	Moderate risk	Large risk
Unlikely	Negligible risk	Negligible risk	Negligible risk	Very small risk	Small risk	Moderate risk
Very unlikely	Negligible risk	Negligible risk	Negligible risk	Negligible risk	Very small risk	Small risk
Negligible	Negligible risk	Negligible risk	Negligible risk	Negligible risk	Negligible risk	Very small risk

any impacts (termed potential pests) not being subject to further analysis. For each pest, or groups of pests with highly similar biology, the likelihood of introduction is assessed. For a pest to be successfully introduced to a region, it must both enter and establish. The overall likelihood rating for introduction is the least likely of entry or establishment, which is also how introduction is rated on the UK Plant Health Risk Register (Baker et al. 2014). Potential impacts of the pest in the PRA area (combining economic, social and environmental impacts) are then rated. In order to prioritize which pests pose a great enough risk to justify consideration of risk management measures, the likelihood of introduction and magnitude of impacts are combined in a risk matrix (Table 5), based on the Australian Biosecurity Import Risk Analysis scheme (Department of Agriculture and Water Resources, 2016). Those pests that score a 'small risk' or higher are considered for risk mitigation.

Traditionally, the EU has taken a pest-focused approach to PRA, whilst nations such as the US, Australia and New Zealand take a pathway based approach—not allowing new trades to be initiated until they have been risk analysed. The new EU plant health regulation (Regulation 2016/2031), which will come into force in December 2019, will now require all new trades in plants and plant products to be risk assessed. Pathway-focused PRA has an advantage over pest-focused PRA in that by identifying measures for all known pests, it is likely that these measures may also help reduce the risk of unknown pest threats being associated with the commodity, in a process referred to as 'manage once remove many' (Evans, 2010). For example, the implementation of ISPM 15, the international standard in regard to the phytosanitary treatment of wood packaging material, has been estimated to deliver more than 11 billion USD in net benefits to the US by 2050, due to its use averting the introduction of new pests (Leung et al., 2014).

The outputs of the FORM project will include the first Irish-focused PRAs. Previously, a joint PRA between Ireland and the UK was carried out for *H. fraxineus* under the UK scheme (Sansford, 2013). This PRA was initiated after the pest had already been detected on the islands of Great Britain and Ireland and was too late to introduce measures to exclude the pest since it was already established. It would be wrong to assume that an earlier PRA would have prevented the entry of *H. fraxineus*, especially since it was an emerging pathogen subject to high uncertainty, including initially being misidentified as *H. albidus* (Queloz et al., 2011), a species that was already recorded in Ireland. That being said, it is likely that if the risk had been identified and analysed earlier, Ireland and the UK would have at least had more time to prepare for the introduction of the pest from a policy and management prospective, even if effective measures to exclude it could not be identified. By taking a PRA-focused approach to risks to Sitka spruce, Ireland will be able to introduce measures to exclude pests, where feasible, and prepare for the invasion of new pests when exclusion is unlikely.

Conclusion

The island of Ireland has enjoyed healthy and productive Sitka spruce stands for many decades, with many of the most economically important pests of Sitka spruce excluded via existing plant health regulations. New pests, however, continue to emerge and global trade in commodities, such as plants for planting, timber and wood packaging material, is aiding the long distance spread of pests and diseases.

Consideration needs to be given to building resilience into Irish forestry not only from the perspective of pest introductions but also in the face of a changing climate. Many of our commercial forestry sites are also valued recreational areas and, through citizen science, the general public could also play a valuable role in helping to monitor and report pests in our forests.

It is not possible to entirely eliminate future pest risks to Sitka spruce, but Ireland's island status gives it a considerable advantage in maintaining healthy forests. Identifying pest risks early and analysing them through PRA is a key step towards ensuring successful regulation to exclude pests, so that the valuable contribution that Irish forestry makes to the country can be maintained.

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