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Tree Disease and Pest Epidemics in the Anthropocene: A review of the drivers, impacts and policy responses in the UK

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Abstract

The growing incidence of new tree pest and disease epidemics, many of them with the potential to radically reshape our native woodlands and forests, is closely linked to a significant upsurge in global trade and transportation in recent decades. At the same time, interventions designed to actually manage any pest and disease outbreaks that occur can reshape forest landscapes in a variety of ways. In this review-based paper we argue that disease-driven interactions between biology, public policy and human agency along pathways of introduction and at outbreak sites will become increasingly common in the Anthropocene, where the latter is understood as an era in which human influence over non-human nature is ever more pervasive. We discuss the nature of these interactions in terms of the increased risk of disease introduction via various trade pathways and through the subsequent policy and behavioural responses to two disease outbreaks made by policymakers and stakeholders in the UK (*Phytophthora ramorum* and ash dieback (*Hymenoscyphus fraxineus*)). Human influence is evident both in terms of the underlying risk drivers and in the subsequent course and management of these and other outbreaks.

Keywords: Anthropocene, global trade, tree pests and diseases.

Highlights

- Tree pests and disease outbreaks are symptomatic of Anthropocenic environmental change.
- New outbreaks have potential to radically reshape native woods and forests.
- Interventions to manage disease may also reconfigure the forest landscape.
- Analysis in this paper shows human influence is entangled with biological processes.

1. Introduction

If it is true, as advocates of the Anthropocene contend, that humans have become the dominant force influencing natural systems, then the introduction and spread of invasive pests and diseases via commercial trade and transportation since the Industrial Revolution must be one of its most troubling features. Indeed as Anderson et al. (2004) argue, the introduction of alien pathogens has until recently been one of the most underestimated causes of global anthropogenic environmental change. The growing incidence of new disease outbreaks and epidemics, many of them with the potential to reshape our native and commercial woodlands and forests at a landscape scale, is closely linked to a significant upsurge in the global movement of plants and plant products and the use of infected or infested wood for the packing of other goods in trade in recent decades (Brasier 2008; Eyre et al. 2013). As Evans (2014) observes, the resulting unprecedented mixing of species across continents and ecosystems is surely one of the most profound manifestations of the Anthropocene. Insects that previously had been constrained by native predators that limited their population growth are being introduced into new environments in which natural predation is much less or even absent altogether; newly introduced pathogens, meanwhile, are presented with potential new host species and microbial and biotic opportunities to exploit. Human mediated climate change, meanwhile, by creating opportunities for spread for organisms previously constrained by low temperatures, further exacerbates the problem. Alongside increased temperatures, more frequent severe weather events such as storm, drought and fire are likely to provide further opportunities for both alien and native pests to flourish (Evans 2014).

The resulting tally of new pest and disease outbreaks, many of them unknown to science a decade or two ago, now pose a significant threat to the world's trees, woods and forests. For example, the spread of *Hymenoschyphus fraxineus* (Chalara ash dieback) throughout north-western Europe, and its arrival in the UK in 2012, is just the latest in a series of pest and disease outbreaks that have swept through Europe's forests over the last 10 years (Boyd et al. 2013). Well documented outbreaks include those due to oak processionary moth (*Thaumetopoea processionea*), an insect pest now widespread throughout Belgium, the Netherlands and Germany, chestnut blight *(Cryphonectria parasitica)*, a fungal pathogen that had a devastating impact on the American chestnut (*Castanea dentata*) in the eastern United States in the early 1900s and pine tree lappet moth (*Dendrolimus pini*), a native of continental Europe, Russia and Asia, where it has long caused periodic and large-scale damage to pine plantations (*Pinus* sp.).

The cumulative impact of these and various other pests and diseases is often dramatic and widespread. Globally, the damage caused by invasive forest pests and diseases can significantly impact on a range of ecosystem services, reducing biodiversity and wildlife habitats, altering natural landscapes and their recreational or cultural value, as well as affecting the ability of forests to sequester carbon, protect watersheds or combat desertification (Boyd et al. 2013; FAO 2009). In addition, there are impacts on the productivity of forests in terms of timber, fuel wood and non-wood forest products that have economic and livelihood implications (FAO 2009). For instance, the mountain pine beetle epidemic described above has had serious consequences for local economies in North America, as well as having significant effects on the ability of these forests to sequester carbon. In the UK, the loss of almost 30 million elms (*Ulmus* sp.) between 1970 and 1990 due to an outbreak of

Dutch elm disease (DED) was a very significant environmental event by any standards, impoverishing many upland woodland communities in Scotland and Wales but also removing the culturally highly valued ‘elmscapes’ of lowland England (Tomlinson and Potter, 2010). The European outbreak of ash dieback in Poland and Lithuania since the early 1990s and Denmark since 2002 has been similarly damaging, with extensive loss of woodland areas traditionally dominated by ash (*Fraxinus* sp.) and serious impacts on commercial forestry operations. In some locations, dieback has been so severe that up to 90% of standing trees have been lost (Kowalski, 2006). Other less pathogenic outbreaks can have equally serious long-term consequences. Fungal-like pathogens such as *Phytophthora alni* have been identified as a significant cause of long-term decline in native alder (*Alnus glutinosa*) communities across Europe, for instance, while a number of weaker invasive diseases are thought to be contributing to acute oak decline syndrome across much of Europe (Boyd et al. 2013).

In this review-based paper we argue that tree disease outbreaks and pest invasions are likely to become permanent features of the Anthropocene forest landscape – and that many of them are traceable, with varying degrees of directness, to commercial interests and human behaviour. Drawing insights from a still emerging literature on the connections between trade, biosecurity and disease transmission, we begin by discussing the drivers of tree disease risk in terms of some of the key trade and human movement pathways, pointing to the ways in which pests and pathogens continue to move along pathways despite international attempts to regulate and constrain them. Based on a review of the documented events surrounding current outbreaks in the UK, we go on to explore the ways in which governments, stakeholders and various publics are mobilised once outbreaks are confirmed. The paper points to a series of interactions between contingent policy responses and human behaviour on one hand and the biological and epidemiological properties of pests and pathogens on the other. Human influence is thus evident both in terms of the underlying risk drivers and in the entanglements of human and non-human nature that emerge during the course and management of outbreaks. In analysing this double movement, we begin by reflecting on how the globalisation of trade and human movement has enacted complex pathways through which tree pests and diseases are conveyed, considering briefly the four main pathways of ‘plants for planting’, movement of timber and wood products, wood packaging and human movement. Impacts and policy responses are then discussed by considering two contrasting disease outbreaks in the UK illustrative of the risks associated with the plants for planting pathway: *Phytophthora ramorum* and ash dieback (*Hymenoscyphus fraxineus*). A conclusion of the paper is that interactions between pests and pathogens, human actions and policy responses will help define the forests of the future. Improved biosecurity measures at ports of entry, changes to plant purchasing and sourcing practices and further changes to forestry policy and practice to enhance resilience will all be needed in response.

2. Trade and human movement pathways as disease and pest conveyors

There is growing evidence that the rate at which new tree pests and diseases are being introduced is increasing (Bridges 1995; Freer-Smith & Webber 2015). One of the main explanations for this is the growth in trade and the human-mediated movement of huge consignments of plants, timber and wood products that now takes place around the world every day. The upsurge has been particularly strong since the early 1990s following the rapid export growth enjoyed by newly industrializing countries such as China, Brazil and India and while there are plenty of examples in the history of epidemics that can be linked to movements of diseased timber or infected plants (see below), the number of such cases has increased significantly since the early 2000s and there are positive correlations between the amount of trade imports and invasive species in Europe (Maxwell et al. 2014). The main pathways of pest and disease introduction are already well known and documented (see, for instance, MacLeod, et al, 2010), the most important being the timber, wood products, wood packaging and (ever more significant) 'plants for planting' pathways, though other disease conveyors such as the transportation of large volumes of biomass for power generation have the potential to become more significant. Alongside this, global tourism and the movement of people provide opportunities for the unintentional transportation of organisms into new environments.

2.1 The timber, wood product and wood packaging pathway

Of these pathways, the movement of timber and wood products is the longest established and was implicated in the introduction of pathogens such as DED into the UK in the 1960s. Carried on the bodies of scolytid bark beetles, the outbreak has been traced to a single consignment of infected elm logs imported in the UK from Canada in the early 1960s (Brasier 1973). Historically, the unintended use of infected wood in the packaging of goods for export has given rise to some of the most damaging tree disease outbreaks in recent times. In the United States, the highly invasive insect pest, emerald ash borer (EAB) (*Agrilus planipennis)*, is thought to have arrived on wood packaging, probably in the form of dunnage from cargo ships (Haack et al. 1997). The US Forest Service has calculated that up to 50% of maritime shipments and 9% of air freight use solid wood as a packing material, and this can play host to insect pests such as the Asian longhorn beetle (*Anoplophora glabripennis*) and the pine wood nematode (*Bursaphelenchus xylophilus*). Asian longhorn beetle was probably introduced into the US in the early 1980s on the wood used to pack and transport the pipework manufactured in China for the refurbishment of New York's sewage system (Haack et al. 1997).

2.2 The tourism and travel pathway

A significant increase in human movement across the globe, especially due to tourism, heightens the risk of unintentional human-mediated introduction of pests and pathogens, either through bringing back plants or wood products or in contaminated soil on footwear, vehicles and bicycles. Although this pathway poses a smaller risk to tree health than other trade pathways, it is not insignificant and may also be a source of pathogen spread within countries as well as between countries. The British have a long history of plant collecting, from the early American explorers who brought back over 100 species of North American trees by the mid 1600s to, more recently, the Victorian obsession with collecting exotic plants from around the world, many of which ended up in botanical gardens or private garden collections. A large proportion of the ornamental plants and shrubs found in British gardens today are the legacy of those early plant hunters, including species such as *Rhododendron*, lupins (*Lupinus* sp.) and lilies (*Lilium* sp.). Today the practice of bringing back plants from different countries continues and while current UK legislation restricts the importation of plant material from outside the Eurozone, individuals are permitted to bring plants (with or without soil), seeds and bulbs into the country from another country in the European Union providing they are free from pests and diseases. Clearly, verifying a plant is pest- or disease-free is difficult as many diseases take a long time to show visible symptoms. This is in contrast with the strict biosecurity regime imposed by New Zealand border control that enacts severe penalties on those attempting to import banned goods, including on the spot fines, deportation and, in some cases, imprisonment.

2.3 The biomass pathway

The expansion of renewable energy generation in many EU member states has led to estimates of huge increases in imports, largely from North America, if the potentially industrial-scale demand for wood chips is to be satisfied (EPPO 2011). The growth in movement of wood chips increases the risk of imported material being infested with various insect pests, including EAB mentioned above and other highly damaging bark- and wood-boring *Agrilus* beetles, amongst others (Flø, *et al.* 2014). The risk of new introductions can only increase proportionately and there are concerns that phytosanitary regulations and the ability to inspect the large volumes of imported biomass are inadequate. While the importation of coniferous wood chips into Europe is regulated in order to prevent the spread of the pinewood nematode, the import of deciduous wood chips to Europe from North America is largely unregulated.

2.4 The 'plants for planting' pathway

The escalating international trade in live plants is widely seen as posing some of the greatest risks to native plant communities, woodlands and landscapes (Brasier, 2008; Potter, et al, 2010). This is due to the pests and pathogens that may be carried on the root systems and other components of the huge volumes of trees and ornamental shrubs that are traded and moved around the world each year (Braiser, 2008). For instance, sweet chestnut blight (*Cryphonectria parasitica*) was brought into the US early in the twentieth century as nurserymen responded to public demand by importing large consignments of Japanese chestnuts (*Castanea crenata*) (Freinkel 2009). Once established, the outbreak spread rapidly throughout the eastern seaboard, killing an estimated 3.5 billion American chestnut (*Castanea dentata)* trees and effectively eliminating this native tree from the rural landscape. *Phytophthora ramorum (*known in the US as 'Sudden Oak Death' and one of a large number of *Phytophthora* species that pose threats to trees and plants*),* an equally virulent fungal-like pathogen, has been traced to Southeast Asia. It is thought to have entered international trade pathways on exotic horticultural plants of various kinds. Sudden Oak Death was first identified on the western seaboard of the US, where the resulting epidemic has infected millions of tanoaks (*Notholithocarpus densiflorus)* and seriously depleted the coastal forests of California and Oregon (Cobb et al. 2012). From an initial site of infection in South West England, the pathogen has spread throughout the UK and is currently regarded as a high risk outbreak by the UK's plant health authorities, threatening a range of tree species, including commercial timber species such as Japanese larch (*Larix kaempferi*) as well as core plant species making up lowland heathland (Defra, 2013a) (see further discussion below).

The globalisation of the live plant trade that is so heavily implicated in these and other outbreaks is arguably the most dramatic (and potentially damaging) change in trade flows to have occurred over the last twenty years (Dehnen-Schmutz et al. 2010). Long supply chains are increasingly complex and difficult to monitor, with many different actors taking key decisions at different points. Traditionally, the horticultural industry was made up of firms specializing in breeding and producing particular seed or vegetative plant groups. Following a period of rapid globalisation, these roles and distinctions between businesses in the increasingly complex supply chain are now less clear. Specialisation has increased efficiency and the potential to distribute ever-greater volumes and varieties of plant material and plants for planting more rapidly through (often unregulated) industry channels (Drew et al, 2010). Given extensive horizontal and vertical integration, the horticultural industry can be seen as a supply chain with multiple layers of firms, each with a unique set of functions. In terms of governance, this proliferation makes it difficult to identify the most suitable moment at which to intervene to stop or reduce the transmission of pests and disease. Traditionally this happens at ports of entry and the International Plant Protection Convention (IPCC) was established to ensure that inspection and quarantining practices applied at national borders meet a common standard. However, such efforts are in constant tension with the desire to liberalise trade and safeguard market opening (Maye, et al, 2013). Under the terms of the World Trade Organisation's Sanitary and Phytosanitary (SPS) Agreement, all new biosecurity measures must be scrutinised for their trade distorting effects. The practical effect is that any WTO member must allow the importation of plant material unless it is able to demonstrate a meaningful risk. Risk assessment tools consequently dominate international biosecurity practice, with an emphasis on procedures such as Pest Risk Analysis (PRA) being used to make an evidence-based case for any restrictions on trade.

For a country such as the UK, embedded as it is within the European Union's Single Market, the plant health authorities find themselves treading a difficult path between the exercise of precaution needed to reduce the risk of new disease introductions and the requirement to ensure free and unrestricted movement of plants and plant materials between member states. Following the formation of the Single Market, all member states have been subject to a Europe-wide system of standards and plant passports which permits the free movement of any plant material coming from outside the EU once a certificate of plant health (the passport) has been granted at the first point of entry. Differences between member states' inspection regimes and weak enforcement of penalties at some ports of entry mean that there have been a significant number of biosecurity breaches over the years. The decision to treat the EU as a single regulatory zone as far as imports from outside the EU is concerned has been widely criticised, with McLeod, et al (2010) pointing to the, often, inconsistent manner in which new and established trade pathways are treated. A significant increase in the volumes of live plants shipped into the EU from China and South East Asia is thought to have significantly raised the risk of new disease introductions, for instance (McLeod, et al, 2010). While some of these importations might be from certified sources, the growing throughput of material enhances the risk that known and unknown pathogens will be introduced into environments in which there are native trees with no co-evolved resistance to disease or pest predators. Driving this trade are changes in the way we use and deploy plants. A growing preference for 'instant woody landscapes', for instance, means that semi-mature or even mature trees with large root balls more likely to carry disease are transported around the world. The discovery of oak processionary moth (*Thaumetopoea processionea*) on a 10-metre oak planted in 2013 adjacent to the Olympic Park in Stratford is a good illustration of this trend (FC 2014). In this high profile case, the tree, imported from a nursery in Belgium, had a plant passport certifying it free from pests and diseases, yet was later found to be harbouring a small egg plaque. This example highlights the difficulty of identifying infestations at the border, especially on large semi-mature trees. Scale this up to the huge volume of consignments of plant material arriving at ports daily and it is clear that intercepting new pest and disease incursions at the border is a real challenge.

While human agency is clearly implicated in the introduction and global spread of new invasive pests and diseases, the subsequent trajectory of an outbreak in a given territory is also often heavily influenced by how far those affected (governments, stakeholders and wider publics) choose to respond to manage the risks and limit impacts. There are a range of interventions that plant health authorities can take but the eventual course of any outbreak depends on interactions between the biological and epidemiological properties of the pest or pathogen, the speed and effectiveness with which containment and control measures can be put in place and the susceptibility of the pest or pathogen to any control measures that may actually be implemented. Sometimes biology supersedes policy, to the extent that a pathogen is able to spread so rapidly that all efforts to slow an outbreak fail. This was the case with the DED outbreak in the UK during the 1970s, when a new strain of the fungal pathogen proved so virulent that interventions had little effect on its eventual spread (Tomlinson and Potter, 2013). More typical is a less biologically determined, but more policy and behaviourally influenced, relationship between the timing and effectiveness of containment and control measures and the course of a disease outbreak. We, therefore, now turn to a closer discussion of how two such outbreaks have been managed and responded to in the UK within different landscapes and institutional settings in order to explore the nature of these complex interactions between human agency and disease processes. The first example, *Phytophthora ramorum,* demonstrates the difficulties associated with attempts to control the spread of a fungal pathogen that has been present in the UK for over 10 years, but has a changing risk trajectory and uncertainty around its epidemiology, geographical range, susceptible host species and, therefore, the resulting set of environmental and economic impacts. *P. ramorum* involves a complex and large range of institutional, industry and private stakeholders, including forestry, horticultural and private garden interests and there is evidence of how the plant health authorities struggled to bring these together in their efforts to formulate a coherent response. In contrast, ash dieback was only identified in the UK in recent years, and while there are uncertainties around its potential geographical range in the UK and the extent of tolerance in UK ash populations, it was known early on that the disease would have a significant impact on both ash woodlands and ash in the wider landscape. Interestingly, ash dieback prompted intense media and public debate when it was first identified in the UK and these, together with a by then heightened sensitivity to tree health issues amongst expert stakeholders, helped shape a much more strategic, if ultimately somewhat performative, response from government to what was seen as an impending national crisis.

3. Ramorum: responding to an outbreak with a shifting risk profile

The current outbreak of *Phytophthora ramorum* in the UK shares many of the features of DED described above, not least in terms of the difficulty of dealing with changing outbreak characteristics and a rapidly shifting risk profile. However this more recent experience suggests that anticipating risk and taking precautionary action in the way that would have been required to prevent the DED epidemic is still just as difficult in a world of genetic mutation, expanding markets and the existence of powerful vested interests committed to the promotion of free trade (Maye et al. 2012; Potter, 2013). In terms of the pathways presented above, the disease is thought to have arrived in the UK as a single introduction, probably on infected nursery stock originating from within the European Single Market via the plants for planting pathway. Almost certainly originating in South East Asia, the highly damaging disease owes its common name, Sudden Oak Death, to outbreaks in the United States in 2001, where it has killed millions of oaks (*Quercus* sp.) and tanoaks along the coastal flanks of California and Oregon (Cobb et al. 2012).

The first reported case of the disease in the UK was on viburnum in a garden centre in Sussex in February 2002. However, over the following weeks a number of infected trees were identified in historic woodland gardens in South West England, typically where its principal UK host species, *Rhododendron ponticum*, was present as an understorey and there were fears of further spread into surrounding semi-natural woodland (Tracy, 2009, Tomlinson et al., 2009). Certainly there was evidence of subsequent infection of nearby susceptible trees such as beech (*Fagus sylvatica)*, ash (*Fraxinus excelsior*), sweet chestnut (*Castanea sativa*) and evergreen oaks (*Quercus ilex)*. This presented a problem for the authorities in deciding how to frame the disease. Traditionally, the governance framework for dealing with plant health in the UK had been divided along inherited institutional lines. Responsibility for plant health and the regulation of the nursery trade lay with Defra and its executive agency, initially the Central Science Laboratory (CSL) but then more recently Fera. The Forestry Commission, by comparison, had lead responsibility for tree health and pests and diseases affecting the commercial forestry sector. *P. ramorum* cut across this neat administrative divide, impacting on both the nursery trade and some aspects of woodlands and forestry. Initially the emphasis was firmly on measures designed to monitor and destroy any infected nursery stock and much of the early focus of outbreak management was directed to raising awareness among nursery owners of this new threat to their commercial interests. Defra instituted an Emergency Programme in South West England soon after the disease was confirmed in 2002, with powers given to plant health inspectors to enter and inspect nurseries and woodland gardens in the region and to destroy any infected material found. Annual surveys of nursery stock were initiated, with a policy of destroying all infected plants found within 2 km where an infection had been found. Matters became more complicated in 2003, however, following the discovery that the pathogen was infecting established trees in Cornwall close to infected *Rhododendron ponticum*, a host species for *P. ramorum*. This broadened the scope of the outbreak and the campaign, bringing owners of public gardens and woodland into the frame and posing a public good, cross-habitat challenge for the authorities in controlling a disease that now appeared to be being transmitted beyond the nursery trade. Working to their more horticulturally-focussed brief, plant health inspectors were now required to serve Statutory Plant Health Notices (SPHNs) on some public woodland garden owners, a procedure which met with some resistance from owners not used to being required to destroy significant holdings of long established plants in historic garden settings and the associated economic impacts on their business. FC inspectors, meanwhile, became involved for the first time in the serving and enforcement of equivalent SPNHs requiring woodland clearance of rhododendron.

An administrative line had been crossed and the subsequent control effort would necessarily involve inter-agency working in order to slow the spread of the disease. In recognition of this, an Interdepartmental Programme Board was set up in 2003 in order to oversee surveillance and control under the Phytophthora Disease Management Programme (PDMP). By 2009 there was evidence that the outbreak had nevertheless continued to spread, with reports of resistance from some owners of public gardens to adopting the control measures that health inspectors were requesting (Tomlinson, et al, 2009). The government's response was to commission a science and policy review in order to compare what was described as 'the business case' for investing additional public money in an expanded programme. A new *Phythophthora* Disease Management Programme (PDMP) was put in place with the goal of containing the spread of the disease. This included money for an extensive programme of clearance of rhododendron understorey in private woodland throughout the country in an attempt to remove one of the disease's main sporulating host species. It was at this point, in autumn 2009, that the outbreak entered a new and more critical phase following the discovery of the disease infecting a large number of Japanese larch (*Larix kaempferi*) trees in South West England, an important forestry tree which accounts for almost 10% of the conifer growing area of Britain (Brasier & Webber 2010; Webber et al. 2010). For the first time, the disease had been found killing a commercially important conifer species anywhere in the world and by July 2010 an estimated 1,900 ha of larch plantations (about half a million trees) were showing signs of infection (Brasier & Webber 2010). In 2010 it was found on Japanese larch in Wales, Northern Ireland and the Republic of Ireland. This required government to reframe the way it dealt with a disease that was now having a significant impact on a small but well represented sector of the economy (in the form of the Forestry Commission and via stakeholder organisations such as the Confederation of Forest Industries (Confor)). Stakeholder workshops held that autumn and over the following months brought affected parties together to develop a new and much more interventionist approach to disease control that would entail widespread felling of affected forests. The level of sporulation on larch was greater than that on rhododendron increasing the risk of the disease spreading to other host plants, especially heathland species (Fera 2013) and a new programme of sanitation felling was agreed on this basis. To date thousands of hectares of plantation larch has been cleared in the UK in South West England, South Wales and West Scotland, where large scale commercial forestry operations means that the incidence of the disease is greatest in these regions (see Figure 1).

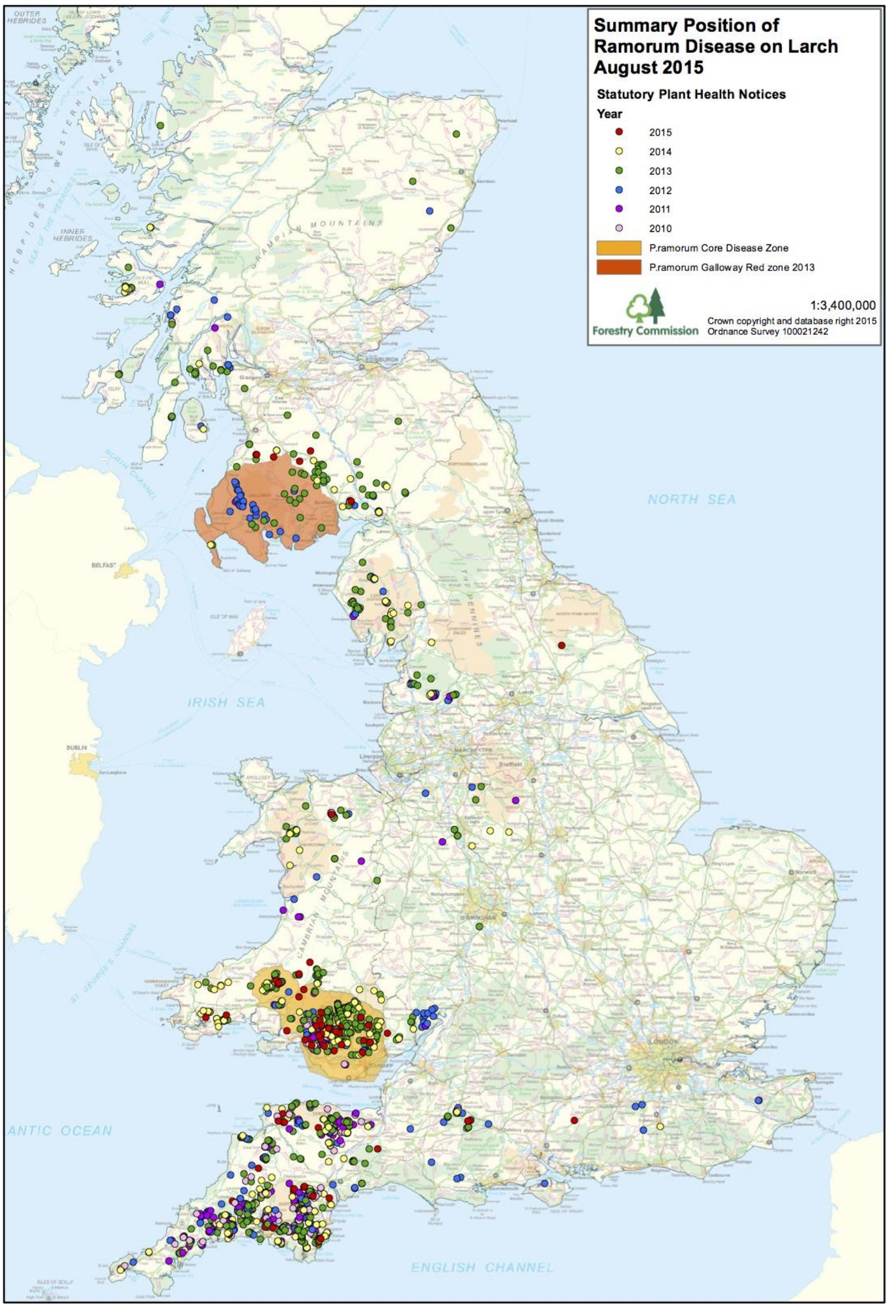

Figure 1: Extent of *Phytophthora ramorum* infection larch in the UK (source: FC 2015).

In summer 2013 the FC announced that eradication of the pathogen in the UK was no longer achievable, though efforts continue to slow its spread and contain its impact within the designated risk zones of South West England, South Wales and South West Scotland. It seems likely that, while the disease may be spreading more slowly than DED, its eventual, cumulative impact on landscapes, commercial forestry and horticultural heritage may be just as significant. Indeed, modelling work suggests that the area now affected by *P. ramorum* is already so great that, even were effective management solutions available for all the landscapes at risk, they would be prohibitively expensive to implement (Harwood et al. 2010). Forest pathologists agree that *P. ramorum* is one of the most complex disease systems now in circulation, difficulties in diagnosis being compacted by its tendency to be present for long periods without the host plants showing symptoms. Meanwhile, large numbers of spores are produced by infected plants. Although the authorities in the UK have implemented measures designed to prevent further importation of infected material, port inspections based on purely visual evidence may be ineffective because of the lack of outward symptoms of infection on host material. Control in the field has also proved difficult due to a reluctance to report early signs of disease in some private gardens and woodlands during the early stages of the outbreak. Management of the outbreak has also been stymied by an initial lack of clarity regarding who will bear the costs of clearance, the potential for continued spread on the footwear of garden visitors and walkers and the special epidemiological features of *P. ramorum* as a disease system. *P. ramorum* is unpredictable in its behaviour, as evidenced in its jump from rhododendron to larch (Brasier & Webber 2010). Indeed, a review of the PDMP highlighted the difficulty in proactively addressing needs for a 'moving target' pathogen and suggested the development of funding mechanisms that can be accessed rapidly and targeted at ongoing or future control programmes (Fera 2013).

4. Chalara ash dieback: managing public expectations about disease control

If the *P. ramorum* experience in the UK demonstrates the *ad hoc* and even contingent manner in which disease epidemics tend to be responded to and managed under conditions of uncertainty, our second example confirms how difficult it is to contain a new introduction, even when there appears to be considerable political will and stakeholder support in doing so. *Hymenoscyphus fraxineus*, a fungal pathogen that causes dieback and extensive mortality of ash (*Fraxinus excelsior*) trees, was discovered for the first time in the UK in a nursery in Buckinghamshire in February 2012 on a consignment of 600 trees from the Netherlands. By August of the same year ash dieback had been confirmed at four nursery sites in England, two that imported plants from the Netherlands and two that supplemented local production with imported stock from Germany (Webber and Hendry, 2012). It was confirmed as being present in the wider environment when found in woodland in Norfolk in October that year. The disease had been spreading westwards from eastern European forests since the late 1990s and its impact on ash woodland in countries like Denmark and Norway is well documented in the scientific literature (Kowalski, 2006). While not listed on the UK's national risk register, ash dieback had long been seen by pathologists as a potential threat (Kowalski, 2006) but, until the time of its introduction, large consignments of potentially diseased young ash trees were being imported into the UK, largely to supply domestic forest nurseries. A failure to stop these imports when it was known that the risks were high has been seen by some commentators as a significant mistake, though confusion surrounding the taxonomic classification of the disease being observed on the continent and the extent of its pathogenicity did not help matters (Potter 2012). Experts now think that the disease has probably been present in the UK for at least 10 years prior to its official identification. It is possible that ash dieback would have reached the UK even with strict import controls according to meteorological modelling by the University of Cambridge that suggested that airborne incursion from the continent was likely (Defra 2013b). The heavy concentration of currently infected woodland in the South

East and in East Anglia, areas most exposed to spores drifting in from continental Europe, would seem to support this thesis. However, not all scientists agree that this is likely as the ascospores of *H. fraxineus* are sensitive to desiccation and do not remain viable for long periods of time (Gross et al*.* 2013; Chandelier et al. 2014) and the point of origin of the pathogen is still contested in expert circles.

Once identified as formally present in the UK, the official response to the pathogen was both immediate and dramatic. Unlike the DED and *P. ramorum* outbreaks, where the case for intervention was assembled slowly and in reaction to different phases of an unfolding outbreak, the government moved quickly to put various management measures in place. The Cabinet Office Crisis Committee (COBR) met in special session during the early days of the outbreak and this was followed by a decision by Defra to ban imports of (potentially infected) ash saplings. Emergency powers were invoked to prevent movements of infected ash around the country. On the ground, the relevant forestry agencies in England and in the devolved administrations undertook extensive ground survey and air surveillance work to identify infected trees in order to establish how far the disease had already spread. An interim Chalara Control Plan was put together and Ian Boyd, Defra's Chief Scientist, convened a Tree Health and Plant Biosecurity Expert Taskforce (Defra 2013a) to look more generally at the mounting threats to tree health from other invasive pests and diseases and to make recommendations for improving plant biosecurity (see further discussion below).

There are likely a number of reasons for the rapidity of this official response. Ash dieback followed a series of other new tree pest and disease introductions into the UK such as oak processionary moth and Asian longhorn beetle and the extent and depth of the governement's response has been attributed by some to the raised awareness of the threat to tree health in government circles generally (Pidgeon & Bartlett 2012). A Tree Health and Plant Biosecurity Action Plan had been published by Defra in 2011 and plant health was moving up the political agenda alongside the reform of the EU's Plant Health Regime (Defra 2012). Nevertheless, the intense media and public response to ash dieback took many by surprise and it was arguably this sudden politicisation of tree health as a policy issue, together with a heightened awareness of the risk to reputation and public perception of competence that the outbreak might entail, that prompted the speedy government response. Over a period of weeks, tree health was promoted from being an issue of largely expert concern to a major focus of public debate and media coverage, leading to questions being asked about institutional competence and broader critiques of biosecurity breaches in the live plant trade (Potter 2013). As Pidgeon and Barnett (2012) observe, by the end of 2012 ash dieback appeared to have joined a list of rapidly developing risk cases such as bovine spongiform encephalopathy (BSE) and the measles, mumps and rubella vaccination (MMR) affair, where what had changed was not the risk itself as the way it is perceived and interpreted by publics.

Nevertheless, the impact of all this activity on the course of the outbreak itself has been slight. Based on experience in Denmark, future years are expected to see very widespread tree mortality, albeit not quite as rapid or complete as in the case of DED. While the greater genetic variability of the ash genus means that not all trees will succumb, Danish experience suggests that the incidence of this natural tolerance will be low, probably in the range of 1-4% of all trees (McKinney et al. 2011; Kjær et al. 2011). Modelling work undertaken for Defra, meanwhile, suggests that the disease will be widespread by 2017 and that the resulting depletion of the UK's standing hardwood stock will be significant. The Chalara Management Plan (Defra 2013b), published in 2013, is effectively a strategy for adapting to loss. By putting the emphasis on the long-term development of tolerant strains of ash and the need to restock the landscape on this basis, the Plan implicitly accepts that large numbers of native trees will be lost in the meantime. New breeds of disease-tolerant ash trees will undoubtedly emerge from laboratories and field experiments in coming years, but while woodlands may be restocked, it is unlikely that there will be a replanting programme extensive enough to replace the widely scattered mature trees in open countryside that are such important (if often under-valued) landscape features in many parts of the country. The Management Plan makes some sensible suggestions for slowing the rate of spread in order to buy time (such as encouraging the removal of those recently planted stands of imported ash saplings most likely to be infected) but the strategy is the familiar one of adaptation to an outbreak and its consequences rather than control.

5. Conclusions

The increased incidence of tree pests and disease outbreaks around the world is arguably one of the clearest examples of anthropocentric impact on global natural systems in the Anthropocene (Boyd et al. 2014). In this paper we have argued that human influence can be see both in terms of the underlying drivers of disease risk and in the subsequent entanglements of human and non-human nature that arise as attempts are made to contain and manage outbreaks. To begin with, by focussing on the trade pathways along which pests and pathogens are being moved around the world, the paper illustrates how commitments to free trade and market opening carry with them an increased risk of disease transmission and introduction. As Brasier (2008, p. 803) puts it, pathogens are presented with "a novel opportunity for evolutionary exploitation" when introduced into environments without natural enemies and the result can be an uncontrolled experiment in co-evolution between the pathogens and a new set of host species. A pathways approach is useful, both in underlining the manner in which movements of timber, wood packaging and plants for planting can very effectively translate a pest or pathogen across bio-geographical zones but also in highlighting the range and diversity of human actors that are in play and who have a stake in continuing to trade. As way of framing the problem it underlines the challenges facing those attempting to manage the risks themselves. This tension is brought into particularly sharp focus in the case of the plants for planting pathway, a type of trade that has increased dramatically in recent years. In a European context, the free movement of plants and plant products has been facilitated by the creation of the European Single Market. Yet, as we show through reference to a series of introductions that can be attributed to this pathway, such market opening has also made it more difficult for individual member states (such as the UK) to adopt a precautionary stance in relation to the spread of tree pests and diseases. The paper suggests an unresolved (and still little debated) tension between the pursuit of free trade, effective biosecurity and the safeguarding of public goods like biodiversity and tree health.

The response from plant health authorities to new introductions brings into play a further series of interactions between disease processes and human agency, now more focussed on containment, management and mitigation. Our two examples of *P.ramorum* and ash dieback show how in the UK, despite policy commitments to taking a more proactive approach to regulating and managing outbreaks (for instance, as recommended in the UK's Tree Health and Plant Biosecurity Taskforce's report in 2013), there have been few outbreaks that have been successfully concluded. Forest pests and diseases often exhibit non-linear population dynamics and feedback effects that make future changes unpredictable, leaving science and policy reacting to the latest events. In the case of the *P. ramorum* outbreak in the UK, we show how an unpredicted (and unpredictable) change in the host range of the disease confronted the authorities with difficulties as a new set of stakeholders (commercial foresters) was brought into play. Ash dieback disease presented government with different challenges as Defra and the FC found themselves having to respond to a sudden surge in public concern and an implied challenge to their reputations. At a time of heightened public scrutiny of policy and science, the implication is that policy makers were required to manage 'perceived' risk and public expectations as well as respond to the biological and epidemiological risks that are being presented to them by scientists and biosecurity professionals through procedures such as the recently instituted plant health risk register. As Burns et al. (1993) observe, when an event is perceived as improperly managed, or that future risk is great, the public will react to reduce the threat. There are, therefore, reputational risks for government here if a more risk-aware and critical public perceive disease prevention efforts to be 'too little, too late'.

As pests and diseases become increasingly associated with trees, woods and forests in the Anthropocene, so it will become ever more important to understand and manage the drivers for pest and disease incursions and to develop nature conservation policies for novel ecosystems based on resilience. If the Anthropocene represents an unprecedented change in the nature of nature itself, then no environment can ever be considered truly 'natural' in the traditional sense and it is likely that novel ecosystems or 'neo-nature' will become more commonplace, where environments are shaped by both 'natural' and 'human' forces. This presents challenges for nature conservation policies that traditionally aim to 'preserve' nature in a certain, often pre-disturbance, state (Lennon 2015). What this paper demonstrates is that phenomena such as tree pest and disease outbreaks are likely to be highly complex interactions of both natural and biological processes, human action and policy responses. A clearer understanding of these dynamic entanglements is likely to be crucial for helping future forests to be resilient to the challenges of the Anthropocence.

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