

Article

Emerging Diseases in European Forest Ecosystems and Responses in Society

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Received: 18 January 2011; in revised form: 3 March 2011 / Accepted: 3 March 2011 /

Published: 4 April 2011

Abstract: New diseases in forest ecosystems have been reported at an increasing rate over the last century. Some reasons for this include the increased disturbance by humans to forest ecosystems, changed climatic conditions and intensified international trade. Although many of the contributing factors to the changed disease scenarios are anthropogenic, there has been a reluctance to control them by legislation, other forms of government authority or through public involvement. Some of the primary obstacles relate to problems in communicating biological understanding of concepts to the political sphere of society. Relevant response to new disease scenarios is very often associated with a proper understanding of intraspecific variation in the challenging pathogen. Other factors could be technical, based on a lack of understanding of possible countermeasures. There are also philosophical reasons, such as the view that forests are part of the natural ecosystems and should not be managed for natural disturbances such as disease outbreaks. Finally, some of the reasons are economic or political, such as a belief in free trade or reluctance to acknowledge supranational intervention control. Our possibilities to act in response to new disease threats are critically dependent on the timing of efforts. A common recognition of the nature of the problem and adapting vocabulary that describe relevant biological entities would help to facilitate timely and adequate responses in society to emerging diseases in forests.

Keywords: biosecurity; communicating biological concepts; forest health; global change; invasive pathogens; legislation; pathway analysis; species concepts

1. Introduction

New diseases in forest ecosystems have been reported at an increasing rate over the last century [1]. Some of the reasons for this are the increased disturbance by humans to forest ecosystems, as well as increased planting of forest monocultures and planting of exotic species [2]. Intensified international trade of plant material has facilitated the introduction of species to new areas [3]. Historically, the log export trade has been one of the recognized pathways for the spread of forest pathogens. For example, the Dutch elm disease pathogen, *Ophiostoma ulmi*, was thought to be introduced into North America on diseased elm logs from Europe [4]. Increasingly however, the nursery trade, particularly in ornamental plants, is thought to be responsible for the movement of pathogens [5,6]. *Phytophthora ramorum*, causing sudden oak death, has decimated the tanoak population in California, and it is thought to have been introduced through the import of ornamental plants from Europe, and spread through trade with nursery plants within the U.S. [7].

Climatic conditions, such as temperature and precipitation, can strongly influence the activity of forest pathogens and the severity of disease (e.g., [8,9]). The anticipated future changes in climate may affect the distribution of current forest pathogens by altering the balance between host, pathogen and environment [10,11]. Changing climatic conditions may also increase the introductions of new diseases by removing abiotic constraints that have previously limited the geographical distribution of pathogenic fungi [12]. The forestry sector provides society with products such as construction material, paper, bioenergy and recreation. Economic impacts of forest disease can include loss in value of forestry products, the cost of removing dead and dying amenity trees and the cost of control operations to limit or reduce disease. The fungus *Heterobasidion annosum* s. l. causing root rot, for example, has been estimated to cause annual losses to the European forestry sector of €790 million [13] and introduced pathogens are estimated to cost USD2.1 billion in the U.S. alone [14]. Forest diseases can also affect urban amenity trees, heritage trees and other trees of significant cultural value. As such, they can have severe ecological and social impacts on society, converting forest diseases into a threat to the ‘public good’ [15]. Due to fungal diseases the populations of both ash (*Fraxinus excelsior*) and elm (all three species; *Ulmus glabra*, *U. minor* and *U. laevis*) have decreased drastically in Sweden and since 2010 have been listed as ‘vulnerable’ on the Swedish red list [16]. Not only the tree species themselves, but also a range of other organisms associated with ash and elm, such as different lichens, fungi, insects and plants are also then threatened (e.g., [17]). Pathogens infecting tree species with important ecological roles may potentially alter the balance within whole ecosystems, leading to further ecological damage such as affecting carbon and nitrogen cycles [18,19]. Taken as a whole, emerging diseases may also influence the global carbon cycle by modifying carbon sequestration processes [20] and carbon sinks [21].

The society has not been able to respond in a constructive way to stop these new and invasive challenges [15]. Part of the problem is the lack of a common understanding of the nature of the threat,

and part is the lack of proper tools to approach these challenges (Table 1). Introduced species do not share a common co-evolution with their host populations thus new diseases impose complex or new patterns of interaction with host trees that may not carry the appropriate resistance to the disease. In order to identify and respond to new disease outbreaks, we propose a number of concepts which need to be made accessible to a wider community, such as the intrinsic complexity of the invasive and emerging pathogens, the importance of pathways for pathogen introduction and how introduced and emerging diseases require re-defining basic terms such as ‘species’ concept. We evaluate the typical responses normally adopted by society to emerging disease such as quarantine, eradication or mitigation measures. Furthermore, we identify a number of unresolved issues related to societal responses to these new challenges.

2. Understanding Biological Concepts in Forest Pathology

2.1. Complexity of Invasive and Emerging Pathogens

Responses to future disease outbreaks require a comprehensive theoretical framework in which to formulate our predictions. Being able to identify species more likely to become invasive or turn into emerging diseases would greatly facilitate prevention tasks [22]. Understanding the reasons for the success of an invasive species is often possible in retrospect, however problems arise when we try to predict which species will have a higher likelihood of establishment and spread in the future [23,24]. Several traits can discriminate between invasive and non-invasive species [25], and this applies to some emergent pathogens that share common features such as a broad host range [24]. Unfortunately, trying to predict which species will become invasive based on climate matching and geographical range is often unsatisfactory. In addition, the small proportion of cases in which a species becomes invasive poses a fundamental problem when making predictions [23].

The complexity of the process leading to an emergent disease or to an invasion also represents a difficulty when trying to formulate theories. As an example, the process of invasion can be understood in three steps: (1) introduction into a new habitat; (2) initial colonization of and successful establishment in the habitat; (3) followed by subsequent dispersal and secondary spread into additional habitats. Host jumps have been identified as a major driver for new pathogens to cause damage [24] and, in the case of plant pathogens, they are frequently initiated by humans [26,27]. Anthropogenic activities can also facilitate introduction and colonization for example, due to increased niche opportunities after disturbing native communities [28]. While arrival into a new habitat is typically the direct or indirect result of human activities, final establishment may result from more complex relationships, and the characteristics needed in one of the steps above may be different from the characteristics needed for another [29,30].

Table 1. A summary of the main concepts preventing more societal engagement in the prevention of emerging diseases in Europe.

CONCEPTS	ISSUES	EXPLANATIONS	REPRESENTATIVE EXAMPLES
Understanding biological concepts in forest pathology			
(1) Complexity of invasive and emerging pathogens	It is difficult to predict what pathogens will become invasive and cause epidemics	• Pathogens and hosts co-evolved under specific environmental conditions and are in equilibrium—changes in this equilibrium (such as when a pathogen introduced to a new host or environment) result in changes in disease levels that are difficult to predict • Pathogens can have ‘novel weapons’ allowing them to become invasive • The activity of vectors that can carry pathogens to new locations may affect the epidemic	e.g., Susceptibility of <i>Pinus contorta</i> to sweet fern rust [39] e.g., The epidemic of <i>Phytophthora ramorum</i> on Japanese larch in the UK [65]
	The invasive capacity of pathogens sometimes relies on other external factors		e.g., Efficient dispersal, high reproduction capacity [36]
(2) Pathways of pathogen dispersal	It is important to understand the role of anthropogenic activities in the global dispersal of pathogens	• Long-distance dispersal is primarily mediated by humans • Dispersal methods include: 1) Vegetative imports e.g., seeds, 2) Wood and wood packaging, and 3) Nurseries/live plants	e.g., Trade in live plants, seeds or movement of wood [3,5]
(3) Species concepts for pathogen dispersal	It is critical to define accessible terminology for the broader society to be able to describe and communicate species concepts	• Differences between species are not always morphologically visible • Differences within species are important—the introduction of new mating types or genotypes may change the behavior of a pathogen	e.g., Difference between two species causing Dutch elm disease [4]
	New species can also be created	• Species can sometimes hybridize to create new pathogens	e.g., The emergence of <i>Phytophthora alni</i> causing alder decline [64]

Table 1. Cont.

CONCEPTS	ISSUES	EXPLANATIONS	REPRESENTATIVE EXAMPLES
Responses in society (1) Quarantine and monitoring—preventing introduction	Not enough measures have been taken to limit pathogen dispersal	• Accurate knowledge about the distribution of pathogens is needed • Faster response is needed from the government to legislate against pathogens	e.g., The distribution of <i>Fusarium circinatum</i> needs to be clarified in Europe [66]
	Detection of forest pathogens in trade material can be difficult	• Some organisms that may cause disease in the future are undescribed or not yet pathogens and are therefore unregulated • Some pathogens have a latency period prior to causing disease and are thereby difficult to detect	e.g., It took seven years for the cause of sudden oak death to be identified [67] e.g., Molecular state of the art detection methods can improve identification
(2) Control and management—preventing establishment and further spread	Managing pathogens once they are established in an area can be difficult	• The timing and size of control efforts is critical to success • Developing an inclusive approach, incorporating many elements of society is important	e.g., The control of Dutch elm disease in Gotland and Malmö, Sweden [68] E.g., The management of <i>Phytophthora cinnamomi</i> in Australia [69]
Reluctance in society	Legislating for stricter phytosanitary measures is complicated by the drive for global trade There may be philosophical objections to managing disease in forests	• Identifying risk activities and confronting those responsible with the full cost of their actions. • When dealing with introduced pathogens forests can no longer be viewed as natural systems with disease as a natural component	
	It is difficult to quantify the true cost of forest diseases	• Cost can include both direct loss of trees or timber and indirect losses such as the effect on the surrounding environment, society or carbon cycle	e.g., The broader cost of Dutch elm disease to society in Sweden [70]

Once established in a new region, the transmission potential of the pathogen within the host population will determine the size of the outbreak. In theory, there is a non-linear association between transmission and size of epidemics: small changes in the transmission potential may result in large differences in the dynamics of the epidemic [24]. Changes in the transmission potential can be due to a wide variety of reasons such as changes in host ecology and environment, changes in host distribution, changes in host phenotype, changes in host genetics and changes in pathogen genetics [24]. Again, when trying to predict emergence or invasion, all these different theoretical causes may result in a broad range of possible outcomes. An efficient dispersal, such as spores spread via wind or water, seems to be a common feature amongst some invasive species. The fact that the entire population of trees of widespread genera such as *Castanea*, *Ulmus*, and *Fraxinus* quickly became infected over large areas in the last century reveals the importance of the pathogens' spread capacity for invasiveness (e.g., [31,32]). Besides the dispersal capacity of a pathogen, vectors can play a crucial role on the emergence of infectious diseases [33]. For example, the causal agents of beech bark disease, *Neonectria* spp., have a low capacity to spread and cause damage on their own, but became invasive due to vectoring by the native beech scale insect, *Cryptococcus fagisuga* [34]. Similarly, in the case of the Dutch elm disease, the level of damage is strictly dependent on the activity of the bark beetle vectors, although in this case the fungus is highly pathogenic. By carrying *Ophiostoma novo-ulmi* to new elm trees causing disease and tree mortality, the bark beetles also create a suitable substrate for further breeding creating a positive feed-back loop increasing the speed of the epidemic.

Invaders with large impacts may exhibit small but critical differences to native species previously occupying the invaded niches, providing them with a higher competitive ability to exploit local resources [35,36]. The emergence of 'novel weapons' is a useful concept in order to explain how a pathogen can become invasive [37]. Mirroring what has been observed for invasive plants, fungal pathogens with 'novel weapons' may allocate resources normally used for defense or competition into reproduction therefore increasing their spread [36]. Plant and forest pathology disciplines assume that pathogens co-evolved with their hosts under specific environmental conditions leading to equilibrium between host, pathogen and environment [38]. When a pathogen with 'novel weapons' is interacting with a host lacking an appropriate defense system, the resulting level of disease will be more severe than expected from a native pathosystem. For example, *Pinus contorta* provenances originating from regions outside the natural distribution of sweet fern rust (*Cronartium comptoniae*) were much more susceptible to the disease than provenances originating from within the region when tested in a common garden experiment [39]. Moreover, pathogens invading a new environment may experience a lower competitive pressure from the microbial community compared with that experienced within their native range and this allows the introduced pathogens to more readily reach their pathogenic potential [37].

When trying to predict the probability of an ecosystem to be invaded, we might encounter a similar sort of complexity as when trying to predict which pathogens will become invasive. General concepts such as lower diversity, host continuity, or unfavorable climatic conditions, normally associated with a higher vulnerability may or may not relate to a higher invasiveness. Theoretical models suggest that a pathogen entering into a new community is less likely when the latter has a higher species diversity [28]. High infection rates are often observed when tree species are planted in dense monocultures whether in their native environment or as exotics [2,37]. In contrast, when invaders are

better competitors or use different resources to native species the effect of diversity becomes weaker [35]. Unfortunately, a higher diversity does not always protect against pathogen invasion and could potentially increase the odds of having an invasion promoter *i.e.*, a species that could facilitate the expansion of the invader [35]. An invasion promoter, for example, is essential for macrocyclic rust species such as *Cronartium ribicola*, the causal agent of white pine blister rust, where the presence of the alternate host is a prerequisite for the survival of the pathogen (see also [40]). In order to address the complexity of managing emerging diseases, general management recommendations need to be backed up by a thorough understanding of the underlying mechanisms in each pathosystem [41].

Understanding past and present drivers for emergence may not necessarily increase our potential to anticipate future disease outbreaks when new factors may arise and be more influential. Future drivers of emerging plant diseases are hypothesized to be introductions of new pathogens, climate change, and intensification of management [27]. At present, introductions have been the result of human activities, while in future, it is hypothesized that climate change may act as a major driver for emerging diseases [12,27]. Moreover, there is a discrepancy between the scale of understanding climate processes (landscape, county) and the scale in which plant pathology operates (forest, field). In this sense, monitoring epidemiologically relevant variables may strengthen our capacity to make predictions [42].

2.2. Pathways of Pathogen Dispersal

The relatively low frequency of long distance spore/insect spread minimizes the risk of intercontinental infections occurring naturally. This is partly because of the low probability of spore/insect survival and partly due to the low probability of exposure of susceptible plants to such long distance spread. Instead, most new diseases are associated with infected plants or plant material that have been transported across borders for planting or packaging [5]. For example, the most common pathway for plant pathogens introduced into Great Britain between 1970–2004 was vegetative imports such as seedlings, tubers and scions [43]. Seeds can also vector pathogens; the outbreak of pine pitch canker (caused by *Fusarium circinatum*) in South Africa is thought to be the result of importing contaminated seed from Mexico [44].

Nurseries are not only a frequent source of vegetative imports but could also be an ideal site for the creation of new species of pathogens. New species of pathogens can develop as the result of hybridization between closely related ancestors [45]. It is very likely that nurseries provide a venue for allowing pathogens from different hosts to meet in a common place. Should hybridization occur between species resulting in novel pathogenicity patterns, tree nurseries provide a multitude of new potential host species. Nurseries also offer a venue for pathogens from different hosts to meet in a common place. This can facilitate host jumps leading to the development of new diseases. In addition, by being centers of trade for plant material, nurseries provide dissemination routes for any diseased plants [46,47]. Since symptoms of new diseases are normally not well described and latent or cryptic disease phases may go undetected for prolonged periods, plants may be disseminated without any disease problems being recognized.

Commercial tree species that are planted worldwide, such as *Eucalyptus* spp. or *Pinus radiata*, have not only suffered from extensive damage due to introduced species, but have also been responsible for

the movement of several exotic pathogens into native hosts [48,49]. *Fusarium circinatum*, a typical pathogen of *Pinus radiata* has been observed on native *Pinus pinaster* plantations in Spain [50]. The canker pathogen *Neofusicoccum eucalyptorum* was regarded to be specialized in *Eucalyptus*, until it jumped onto three native tree species after introduction in Uruguay [51]. Host-jumps from native species into commercial species have also been observed [26], for example guava rust caused by *Puccinia psidii* jumped from native Myrtaceae in South America onto introduced *Eucalyptus* and now threatens eucalypts in Australia [52]. Another example comes from boreal forests in Sweden, where the introduced *Pinus contorta* became infected by the local canker fungus *Gremmeniella abietina* [53]. Such host jumps may also threaten the new hosts at their native origin, should the pathogen unintentionally be carried back there. International legislation has put very little emphasis on minimizing this type of risk.

Wood and wood packaging can also be a common pathway. *Heterobasidion irregulare* was introduced with wood into the Italian Peninsula during World War II [54] and *Ceratocystis platani*, causal agent of canker stain of plane (*Platanus orientalis*), was introduced into Europe on packaging material in the 1940s [55]. The importance of this pathway has been recognized through international regulations governing the treatment of wood packaging material to reduce pest and pathogen movement (as the International Standard for Phytosanitary Measures No.15 [56]). There is an increased recognition of the need for handling problems in a generic manner through pathway analysis where the means of spread with the highest risk are recognized and threats can be handled efficiently without the need for identification on a case by case basis [5]. However, regulations based on pathway analysis may be regarded as being too generic, thus not meeting the requirement of minimal impact for trade within the International Plant Protection Convention (IPPC) of 1951 [57].

2.3. Species Concepts for Fungal Pathogens

Responses in the society to threats posed by pathogens are dependent on a proper awareness of the types of problems that we encounter. Yet there are several obstacles to the perception of emerging diseases. Organisms are generally assumed to be relatively homogenous and genetically stable and the complication of intraspecific variation is not fully recognized [37,58]. Improvements in molecular techniques have increased our knowledge of the complex breeding systems and taxonomy of pathogens. Cryptic species with minimal or no morphological differentiation have been identified in a multitude of fungal taxa [37,59,60]. They can be associated with different host ranges and pathogenicity patterns. To handle these issues in a legislative context represents a major challenge. Without proper naming of the threats, it is also hard to define the countermeasures that need to be taken. One example of how these issues have been treated by taxonomists is provided by the root rot pathogen *Heterobasidion* spp. Studying mating incompatibility and host range, the *Heterobasidion annosum* species complex was found to include several taxa with varying host preference and pathogenicity during late 1970s and 1980s. The species present in Australasia was not the pathogenic *H. annosum* and highlighted the need, from a plant quarantine perspective, to quickly differentiate the saprotrophic Australasian species from its pathogenic relative. Thus, the southern hemisphere species was renamed as *H. araucariae* and *H. annosum* was declared a quarantine threat in Australasia [61].

Another problem arises from our lack of appropriate common language to describe intraspecific variation in fungal populations. A fundamental problem lies in the way we build concepts, *i.e.*, we frequently categorize observations based on visual similarity. However, pathogens evolve from common ancestors into populations with pathogenic traits that affect the dominant local tree species. Such traits may not have an obvious external phenotype, and are therefore hard to recognize without knowledge of the evolutionary history or performing pathogenicity tests. In terms of legislation there are few examples where subspecific naming has been used to identify particular severe tree pathogens. One example is provided by Dutch elm disease (DED) that was epidemic in Europe after the First World War [4]. The pathogen and vectors were exported to North America in the thirties and there the causal fungal partner of the disease complex (*Ophiostoma ulmi*) was altered or even replaced with a closely related fungal species that remained unrecognized. This new species was later reintroduced into Europe and it became obvious that the newly introduced American variant was much more aggressive. It was later described as a new species, *Ophiostoma novo-ulmi*. Today this new species is spread all over Europe. Had the biological distinction between the two species of *Ophiostoma* been recognized and named prior to the unfortunate re-entry into Europe, we would potentially have had the appropriate concepts and words available that could have helped to ban the import of infested plant material and saved elms from facing eradication.

As well as recognizing species differences, variation in genotypes may also be important. Introduction of another genotype may significantly increase the risk in an area if the new genotype is another mating type, which then enables sexual reproduction [29,62]. The ability to reproduce sexually allows pathogens to adapt to changing environmental conditions [62]. So, even though the species is already present in a location it may be important to limit further introductions. Introduction of closely related pathogens may also give rise to interspecific hybridization potentially causing new diseases. The alder phytophthora, *Phytophthora alni*, which was first discovered in U.K. in the early 1990s, is thought to be a hybrid between two other *Phytophthora* species [63], which are individually much less aggressive on alder [64]. In this case, the species dynamics was not understood until sufficient research resources was allocated to the disease; this only happened after substantial damage had already been caused to alders throughout most of Europe.

3. Responses in Society

3.1. Quarantine and Monitoring-Preventing Introduction

Society has taken measures to limit dispersal through the most common pathways like trade to meet the perceived problems with introduced diseases. These measures may include sanitary actions such as heat treatment of any pathogens in imported wood products, or a sender-end inspection of potentially diseased plant materials. However, quarantine measures are not always effective and there are large problems in performing perfect control at borders. As an example, despite the international regulations governing the treatment of wood packaging material as the International Standard for Phytosanitary Measures No. 15 [56], not all countries have adopted these guidelines and this standard is not necessarily effective for all species of pathogens [71].

Within the EU, trade of plant material is allowed between member states and only a sanitary passport is needed as regulated in the Council Directive 2000/29 EC [72]. The member states not only issue sanitary passports to their products, but also to products imported from outside the EU which are then distributed further internally. Two independent organizations recommend to the European Commission which organisms may be listed as harmful: the European and Mediterranean Plant Protection Organization (EPPO) and the European Food Safety Authority (EFSA) [57]. Efficacy of quarantine policies within a region will only be as good as the weakest of the quarantine controls of its borders [15]. In addition, quarantine measures rely on the accuracy of existing knowledge of the global distribution of pathogens. A review of the records on the distribution of the quarantine organism *Fusarium circinatum* revealed several cases where observations needed confirmation, while other observations were not included [66]. The authors highlighted observations of the pathogen in nursery stocks in Northern Spain [73] which were not included in the official documentation, and of a record in Italy which needed further confirmation. It was not until the disease was officially reported almost 10 years later in both places [50,74] that the EU officially limited plant movement from the infected regions (2007/433/EC) [75].

Current risk assessment and regulation of new pathogens in international plant health protocols is based on lists of identified organisms recognized as a potential threat [5]. The process of adding species to the list is often too slow since once a species is recognized as a threat it is usually already a problem. Ash decline, for example, was allowed to spread from Poland and Lithuania through northern Europe for at least 10 years [32] before the causal pathogen was identified in 2006 [76], and its sexual stage in 2009 [77,78]. *Phytophthora ramorum* was identified as the causal agent of sudden oak death disease seven years after the first outbreaks were observed on tanoaks (*Lithocarpus densiflorus*) in California, U.S. [67]. This means that unknown harmful organisms are not on the list and thereby are unregulated. In addition, as mentioned earlier, pathogens frequently do not cause disease on their original host or within their native range, so may not be recognized as threats until they are already introduced to a new host or into a new area. A pest risk analysis based solely on identified species is also associated with other problems related to the complex nature of pathogen speciation mentioned earlier.

Import of regulated plant material into Europe is allowed if examined and found to be free of regulated fungi and other pests and pathogens [72]. There might, however, be problems in identifying a diseased plant. Following infection there usually is a latency period where the plant remains free of symptoms and this latency period can occur for a relatively long time period. Symptoms might also be restricted to belowground parts of plants that are difficult to examine in an efficient manner. Molecular analysis applied on routinely collected samples may enable identification of otherwise undetected pathogens, however this process may be costly and time consuming, and the problem of relying on lists of already identified threats still persists. Other detection methods can include a global network of sentinel plantings which can provide early warnings for the transfer of unknown pathogens between countries. Currently, several initiatives from the EU, New Zealand, CABI and the U.S. are on-going [79]. Monitoring within countries is also important for the early detection of new pests/pathogens. High throughput sequencing tools (e.g., 454 pyrosequencing, Solexa, SOLiD) can provide an efficient tool for screening high numbers of samples [80], which can complement current monitoring schemes based on symptoms (defoliation, chlorosis).

3.2. Control and Management—Preventing Establishment and Further Spread

When a new pathogen has been introduced, actions are frequently taken in order to limit further spread and prevent establishment. Preventing establishment is, however, extremely difficult as can be exemplified by the introduction of the pine wood nematode, *Bursaphelenchus xylophilus*, in Europe [81]. The pine wood nematode originates from North America and has been found to kill pines and larch of susceptible species outside its native range. When the pine wood nematode was first discovered in Portugal in 1999 [82], the EU adopted large scale control measures in order to prevent its establishment and further spread [83]. Trees showing symptoms in the infested area as well as within a buffer zone of 20 km were felled and removed. It has, however, been found subsequently in various areas of Portugal and a 20 km demarcation zone was established along the Spanish border, in order to stop further spread into Europe. Despite this, the pine wood nematode has been discovered and eradicated in Spain in 2008 and 2010 [84].

Even when a pathogen is already established in an area, further countermeasures may still be worth taking. Control strategies need integrated efforts at different spatial and temporal scales: tree, landscape (or forest stand) and at a regional or international scale [85]. A good example of taking a broad, inclusive approach to controlling forest disease can be found in the management of Dutch elm disease on the isolated island of Gotland in Sweden. Since there is little possibility of natural reintroduction of the pathogen from the mainland, the governing body of the county has worked with local interest groups to preserve the elm population. A critical part of the control strategy is to involve the public by disseminating information about the disease and its control [68], as seen in other schemes elsewhere e.g., *Phytophthora ramorum* in the U.S. [85] or *P. cinnamomi* in Australia [69]. The removal of infected elms seems to successfully decrease the advance of the disease in Gotland (R. Vasaitis pers. com. 2010). This can be compared to a similar strategy of removing infected hosts made in the city of Malmö on mainland Sweden, where the eradication may have failed because the control program did not incorporate a sufficiently large geographical area. Time is also a crucial factor that needs to be considered since this will determine both the size of the potential damage and the size of the actual damage. In particular cases large scale control operations can be implemented. In Sweden for example, large numbers of trees were removed after the devastating storm in 2005, to reduce potential *Ips typographus* outbreaks [86]. This was possible as a result of collaborative efforts across all levels of the forest sector including private forest owners, companies and local administrators. At later stages of an epidemic, control can be difficult as well as costly and a strategy towards protecting remaining uninfected areas is normally adopted e.g., [87].

4. Reluctance in Society

Although many of the contributing factors to new diseases are anthropogenic there has been a reluctance to control them by legislation or other governmental control. In the European Union these issues are discussed in the standing committee of plant health and final decisions are taken by the European Commission [72]. The potential for individual countries to have stricter phytosanitary regulations is also limited by the pressures of free trade from both within and outside the EU [57]. The reluctance of the society to control trade contrasts with the need to pay for the management of a

pathogen when it is already established; sometimes the beneficiaries of such payments are the ones who took higher environmental risks initially. In other words, specific trade pathways may allow the introduction of new pathogens but the cost of the resultant disease is paid for by forest owners or by the society at large. Confronting those responsible for the problem with the full cost of their action may act as an effective incentive to reduce new introductions [15].

The reluctance to establish stronger barriers for new disease introductions could also be explained by the ideological view that forests are part of the natural ecosystem and forestry is perceived as utilizing a self-regulated resource in which humans should not interfere. Pests and pathogens are commonly regarded as natural disturbances and as part of the natural ecosystem and thus not something that should be managed [88]. In contrast, in agricultural ecosystems which are seen as artificial, pests and diseases are regarded both as something that has been caused by the management practices used and as something that should be controlled. Most forests are actually not as natural as we may perceive but are influenced and affected by different anthropogenic activities. In Fennoscandia, pristine forests without any traces of earlier land-use are extremely rare [89] and more than 80% of Swedish forests are used and viewed as productive forests [90]. Furthermore, the introduction of forest pathogens from other continents is usually human-mediated and the resulting pathosystem is not in coevolutionary balance as previously discussed. This can result in dramatic effects on forest ecosystems both in economic and ecological terms.

One of the critical barriers to managing forest diseases relates to the perceived cost. The positive effects of control measures against introduction have to be balanced with any costs in relation to restrictions to free world trade and the cost of not acting. Counter measures in forest ecosystems rapidly involve large areas, making them expensive and timely to implement. The uncertainty of predicting the potential damage is partly due to the lack of tools for quantifying direct impact on environmental services as well as other indirect effects. Estimated annual costs due to Dutch elm disease in Sweden range from €9 million to €232 million depending on the assumptions made [70]. In addition, the pathogen *Cryphonectria parasitica* causing Chestnut blight has not only produced direct losses in timber value in the local industry (easily quantifiable), but also reduced the presence of a culturally important tree in rural areas [91]. Quantification of the costs of invasion is possible but has rarely been undertaken (e.g., [14,92]). Control measures in order to protect threatened amenity trees such as elm, ash or alder can seldom be justified from an economic point of view, but must be preserved because of the societal and ecological values of such tree species. Including global issues such as effects on the carbon cycle in the cost-benefit equation may also elicit a greater response from society [93].

5. Improvement in Communicating Biology Is Needed

Biological knowledge is not always used as the basis for managing forest disease problems. An interesting obstacle to information flow relates to problems in communicating biological understanding to the political sphere of society (Table 2). Relevant response to new disease scenarios is very often associated with a proper understanding of the complex nature of new pathosystems such as cryptic species and intraspecific variation in the challenging pathogen or the host. Without a common language describing biological entities it is hard to communicate that a certain type of organism is

particularly dangerous. This might be the result of fundamental difficulties associated with the way we build concepts. As humans, we have a tendency to recognize categories based on color, shape or other macro characters while some of the traits important for pathogenicity have evolved without obvious morphological differences. This may not always be the case for pathogens. A similar sort of problem may favor the adoption of more visual solutions, such as increasing species diversity as opposed to more invisible alternatives such as maintaining intraspecific genetic diversity within hosts. Solutions have to be based on scientific evidence rather than relying on general formulae, thus improving communication does not necessarily have to imply excessive simplification of the problems.

Table 2. Factors that may help to improve societal understanding and appreciation of the importance of managing forest pathogens and diseases.

ACTIONS	EXAMPLES
(1) Improving communication of biological concepts to non-biologists	• Finding ways of clearly communicating disease concepts (e.g., co-evolution, latency, dispersal ecology) • Finding ways of clearly communicating species concepts for pathogens (e.g., cryptic species, hybridization, clonality)
(2) Improving collaboration with other fields or spheres of society	• Collaborating with social scientists or other disciplines to gain a more global perspective • Involving the broader society as part of the solution
(3) Identifying common areas of interest with the broader society	• Take a step further from explaining disease development by focusing on explaining the effects of forest disease and its management • Quantifying disease impact in economic terms • Invasive species as a threat for the ‘public good’

The lack of understanding between scientists and society may also be due to an inability to identify areas of common interest (Table 2). While scientists may be focused on understanding processes, politicians and managers may want more information on the effects of certain alternatives. Communicating the importance of emerging diseases in quantifiable economic terms may result in more supportive responses from the society; unfortunately, such an approach has rarely been adopted. Moreover, predictions of detrimental effects often come from different disciplines or from particular fields lacking a global perspective. Here, building a common view of the relevant aspects of forest diseases between biologists and social scientists might help in developing effective approaches to forest protection. Involving the society as part of the solution may be a better approach than focusing on its share of the problem.

The potential to act in response to new disease threats is critically dependent on the timing of efforts. As outlined above, common recognition of the nature of the problem and adapting vocabulary that describe relevant biological entities would help to facilitate adequate responses in society to emerging diseases in forests.

Acknowledgements

This research was funded through Future Forests, a multi-disciplinary research programme supported by the Foundation for Strategic Environmental Research (MISTRA), the Swedish Forestry Industry, the Swedish University of Agricultural Sciences (SLU), Umeå University, and the Forestry Research Institute of Sweden. Jonàs Oliva was funded by the post-doctoral grant 2008 BP A 00013 from the Agency for Administration of University and Research Grants (AGAUR) of the Autonomous Government of Catalonia. Anna Hopkins was funded by an Institutional Grant (IG2010-2009) from the Swedish Foundation for International Cooperation in Research and Higher Education (STINT) and by the EU project Increasing Sustainability of European Forests: Modeling for Security Against Invasive Pests and Pathogens under Climate Change (ISEFOR, EU FP7).

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