Forestry An International Journal of Forest Research

Institute of Chartered Foresters

Forestry 2016; 89, 456–472, doi:10.1093/forestry/cpw029

Application of a wood pathway model to assess the effectiveness of options for reducing risk of entry of oak wilt into Europe†

Christelle Robinet[1]*, Jacob C. Douma[2], Dominique Piou[3,4] and Wopke van der Werf[2]

[1]*INRA, UR633 Zoologie Forestière, F-45075 Orléans, France*
[2]*Centre for Crop Systems Analysis, Wageningen University, Wageningen, The Netherlands*
[3]*INRA, UMR BIOGECO, F-33610 Cestas, France*
[4]*Ministère de l'Agriculture, de l'Agroalimentaire et de la Forêt, DGAL-SDQPV, Département de la Santé des Forêts, 252 rue de Vaugirard, F-75732 Paris, France*

*Corresponding author. Telephone: +33 238418038; Fax: +33 238417879; E-mail: Christelle.Robinet@orleans.inra.fr
†This paper is an additional contribution to the Special Issue 'Forest Health in a Changing World'.

Received 9 June 2016

The oak wilt fungus, *Ceratocystis fagacearum,* is native to North America, and is a threat to oaks in Europe. Therefore, the European Union has regulated the importation of oak wood from the US into Europe. We developed a pathway model to calculate the exposure of oak trees in Europe to the fungus under different regulatory scenarios and thus evaluate the effectiveness of the measures. The model describes the import, inspection and treatments of wood, as well as the trade among European countries and processing to sawn wood, final product and residues. The model quantifies the frequency of escape of the fungus from wood with a vector, and the transfer to host trees. Existing regulations reduce exposure by a factor >30 000 compared with a scenario without regulation. Exposure is highest around European ports and during transportation of wood across Europe. Wood treatments and shipment to a restricted set of ports are effective measures, each reducing exposure by more than 90%. Pathway modelling is a promising tool to study entry pathways of alien tree pests and evaluate risk reduction options: it provides a systematic and transparent approach but is limited by availability of biological data.

Introduction

Biological invasions are increasing in frequency and importance across the world, especially of insects (Liebhold *et al.*, 1995; Vitousek *et al.*, 1996; Mack *et al.*, 2000; Roques, 2007; Roques *et al.*, 2009) and plant pathogens (Desprez-Loustau *et al.*, 2010; Pyšek *et al.*, 2010; Santini *et al.*, 2013; Roy *et al.*, 2014). This increase is due to the worldwide increase in volume and frequency of product movements (Levine and D'Antonio, 2003; Westphal *et al.*, 2008; Hulme, 2009; Eschen *et al.*, 2014) and to the higher speed of movement, which supports high survival of pests during transport over long distances (Roques, 2010).

According to the international treaty on Sanitary and PhytoSanitary measures (hereafter SPS agreement) (adopted by the World Trade Organization in 1997; FAO, 2011), national and supra-national policy makers may reduce the probability of pest entry by imposing regulations, but these should not create unnecessary trade barriers. According to the SPS agreement, regulations should be science-based, to avoid arbitrary decisions of importing countries or, worse, internal market protection in the guise of phytosanitary measures. However, pest risk assessments are usually made using decision trees and other pragmatic qualitative approaches, and a quantitative scientific underpinning is usually lacking. Given the increasing importance of invasive alien plant pests, and the existing agreements on world trade, it is critical to build a better quantitative understanding of the role of trade and transport in biological invasions (Hulme, 2009; Banks *et al.*, 2015).

Over the last decade, researchers and pest risk assessors have begun analyzing entry quantitatively, using the so-called pathway models (Fowler *et al.*, 2006; Yemshanov *et al.*, 2012; EFSA, 2014). Pathway models describe quantitatively the entry process of a pest into an area of concern, up to the point(s) of contact with the susceptible host or receiving host habitat. They quantitatively describe product flows, e.g. by trade and processing, and take account of pest survival or multiplication at successive points in the pathway and calculate the exposure of hosts or host habitat to the pest. Pathway models add rigour to pest risk analysis by quantifying risks of pest entry and the effect of risk reduction options and by making explicit the assumptions that are made in these quantifications. There is as yet little experience with the application of pathway models in regulatory plant health and the benefits and limitations of this tool need to be further explored.

The oak wilt fungus, *Ceratocystis fagacearum* (Bretz) Hunt, is native to North America (Eastern US; Liebhold *et al.*, 1995). It causes rapid wilt and death of oaks in its native range (Appel, 1995; Liebhold *et al.*, 1995; Wilson, 2005; Juzwik *et al.*, 2008; Koch *et al.*, 2010; Harrington, 2013). It can be transmitted to oaks by root connections between diseased and healthy trees and by insect vectors (e.g. sap beetles and bark beetles) (Gibbs and French, 1980; Rexrode and Brown, 1983; Juzwik *et al.*, 2011). The insect vector gets contaminated when it feeds on mycelium mats of the fungus that grow between the bark and the cambium of affected trees. Healthy trees may become infected with the fungus when contaminated insect vectors feed on sap draining from fresh wounds. The fungus can then spread rapidly through the vascular system of the tree, causing a vascular wilt disease that may kill the tree, similar to the Dutch elm disease (caused by the fungus *Ophiostoma ulmi*) and the pine wilt disease (caused by the nematode *Bursaphelenchus xylophilus*).

North American red oaks (*Quercus* spp. subgenus *Erythrobalanus*) naturally or experimentally infected by *C. fagacearum* rapidly decline and die. In contrast, infected North American white oaks (*Quercus* spp. subgenus *Lepidobalanus*) generally display some declining branches but do not die of the disease (EPPO, 2011; Juzwik *et al.*, 2011). Although most oaks in Europe are white oaks (*Quercus robur*, *Quercus petraea*, *Quercus pubescens*), experiments in North America have shown that European white oaks infected with *C. fagacearum* die rapidly (Pinon *et al.*, 1997, 2003). There are many European insect species that have the potential to act as vectors of *C. fagacearum* (Yates, 1981; Yates, 1984; Anonymous, n.d.) and among them, the oak bark beetle, *Scolytus intricatus* (Ratzeburg), could be an effective vector (Haack, 2001; Juzwik *et al.*, 2011). This bark beetle is present in almost all European countries (de Jong *et al.*, 2014; http://www.fauna-eu.org). *Ceratocystis fagacearum* poses a major threat to European oaks, as European oaks are susceptible while a suitable vector is present in Europe. *Ceratocystis fagacearum* has not established in Europe yet. This pest has therefore been recommended for regulation by the European and Mediterranean Plant Protection Organization (EPPO) (http://www.eppo.int/QUARANTINE/listA1.htm).

Since 2000, the European Commission has issued several regulations for oak logs coming from the US (Council Directive 2000/29/EC, Commission Decisions 2005/359/EC, 2006/750/EC and 2010/723/EU). These regulations offer three options for importing oak logs from the USA into Europe: (1) imports of logs of red or white oak with or without bark, whereby the logs are fumigated (hereafter referred as option BF; with Bark Fumigated), (2) imports of logs of white oak with or without bark that are not fumigated (option BNF; with Bark Non-Fumigated), red oaks being excluded from this import option and (3) imports of red or white oak logs without bark (option DB; DeBarked). While the regulations have so far been successful in keeping Europe free from *C. fagacearum*, the comparative effectiveness of these three options has not been scientifically studied, and the contribution of different elements in each import option is unknown.

We developed and parameterized a pathway model to assess the exposure of oak trees in the European territory to *C. fagacearum* due to importation of oak logs from the US under different risk mitigation scenarios. The model keeps track of the volume of wood infested with the oak wilt fungus along the pathway, accounting for both the wood trade (from the US to Europe and then within Europe) and the wood processing chain within Europe, until the final use of the wood product and the disposal of waste. Post-entry transformations are considered because derived products may also carry the pathogen. The model is used to calculate exposure (i.e. the amount of propagules of *C. fagacearum* that are transferred to a host tree), taking into account regulatory measures required under each import option.

The first objective of this study was to determine the effectiveness of the current EU regulation by estimating exposure to *C. fagacearum* under these three import options and to compare these estimates to exposure with a benchmark scenario without regulatory measures. We identified the parts of the pathway that have the greatest contribution to exposure in each case. The second objective was to determine the effectiveness of each component (i.e. each individual risk reduction measure) of the current import options. Thirdly, we determined vulnerability of European countries, irrespective of the difference between their import volumes, by determining exposure resulting from a standard import volume per country. Finally, we quantified uncertainty in the calculations. Using this case study, we explored the feasibility and benefits of developing a pathway model, as well as the data needs and major hurdles when pursuing this goal.

Methods

Model structure

The model for oak wilt is built on a generic pathway model for wood pests (Douma *et al.*, 2015) and describes the movement of oak wood from the US to regions in Europe including wood processing to products and waste, as well as the escape of the vector from the wood in different parts of the pathway, and its transfer to hosts. The model follows the infested wood product from its origin to its final destination, including treatments, inspection, processing and transportation.

The model is spatially explicit. It partitions the wood flow from the US over the 93 ports in Europe that are known to import wood from the US (Figure 1). It further partitions the trade flow over countries in Europe and within each country to NUTS2 regions for wood processing. The model distinguishes a total of 266 NUTS2 regions (European Nomenclature of Territorial Units for Statistics; http://ec.europa.eu/eurostat/web/nuts/overview). The average size of a NUTS2 region is 18 159 km^2 (standard deviation: 22 739 km^2). At successive steps in the pathway, the wood flow and the escape and transfer of the pathogen to host trees are calculated. These points at which the flow is measured, and at which it may branch, and at which escape and transfer of the pathogen may happen, are called 'nodes' in pathway modelling (e.g. Douma *et al.*, 2015). The pathway ends when all wood has been processed into final product (FP) and waste, and transfer to hosts for all nodes in the pathway has been calculated. The pathway considers the volumes of the flows and accounts for probabilities (which are treated as proportions in the calculations) to calculate the partitioning and branching of the flows (Figure 1).

At different nodes in the pathway, and for each NUTS2 region, the model calculates the yearly exposure, *E*. This exposure is defined as the number of propagules that transfer to a host tree within a NUTS2 region in a year, in relation to a transfer from a given node (e.g. wood import in ports or wood storage at factories). This exposure is calculated as the product of the infested wood volume at a location, the density of propagules of the pest in the infested wood at this location, the probability that the pest escapes from the wood, the probability that it disperses in the environment, and the probability that it then encounters a host:

$$E_{P,j,r} = V_{P,j,r}\ n_P\ w_{e,P}\ w_{d,j,r}\ h_{j,r} \tag{1}$$

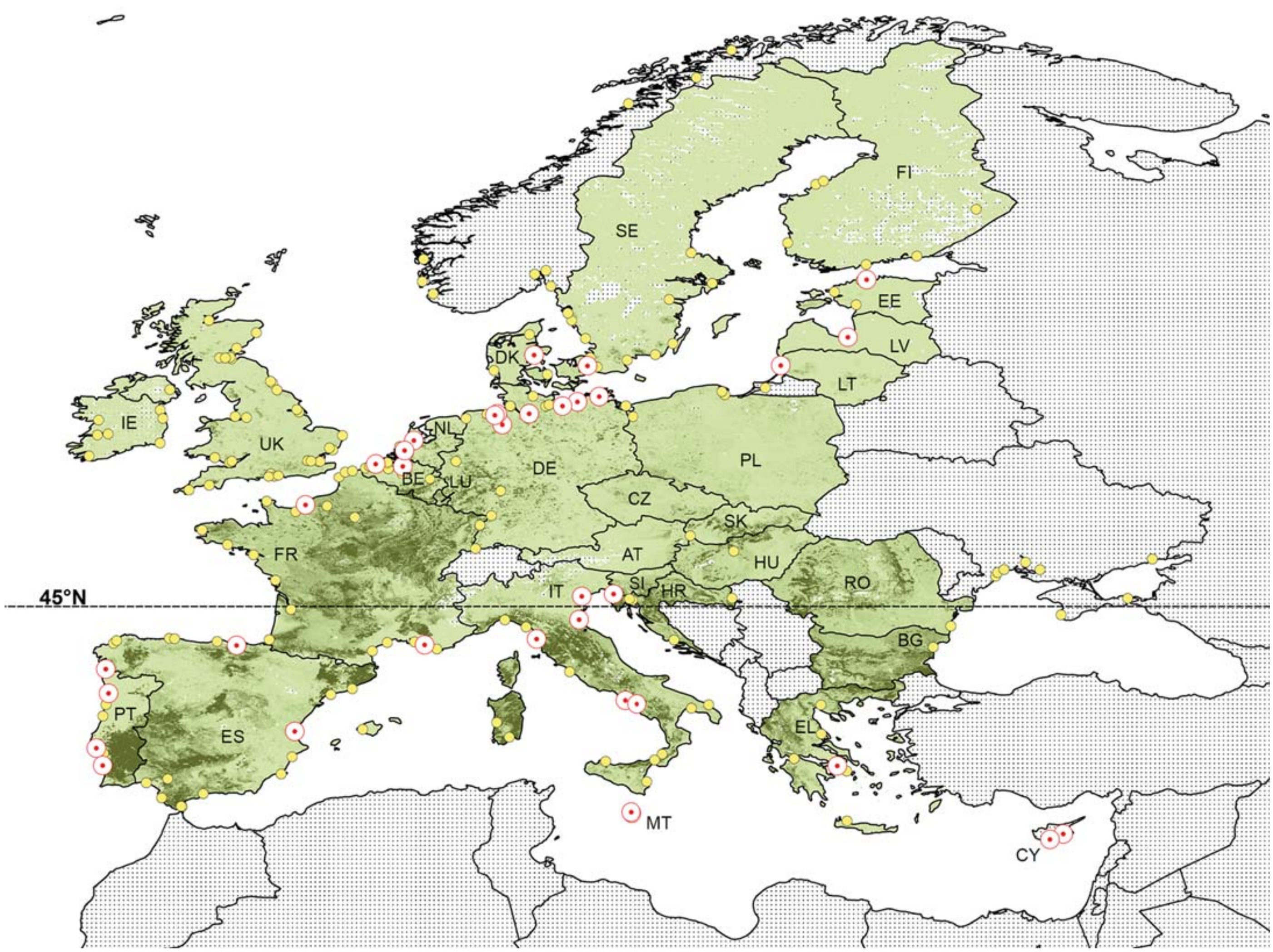

Figure 1 Spatial distribution of oak trees in Europe (background scale indicates the proportion of land covered by *Quercus* spp.), location of ports (small points) and location of the 35 ports where entry of wood with bark is allowed under the import options 'bark fumigated' (BF) and 'bark non-fumigated' (BNF) (big points with small dot inside). The dotted line indicates the latitude of 45°N which is the southern limit of the area allowed for wood transport under import option BNF. The map was generated with ArcMap™ Version 9.2.

where $E_{P,j,r}$ is the number of propagules that transfer to a suitable host from product P ('round wood' (RW), 'sawn wood' (SW), 'final product' (FP) or 'residues' (RES)) in country j in region r, $V_{P,j,r}$ is the infested volume of product P that arrives at a given node of the pathway in country j in region r, n_P is the number of propagules per m^3 of infested product P, $w_{e,P}$ is the probability that a propagule escapes from the infested product P, $w_{d,j,r}$ is the probability that an individual gets dispersed in country j in region r (given the flight period, which depends on climate), and $h_{j,r}$ is the proportion of land covered by host plants in country j in region r. The fungus may transfer to oak trees in Europe at seven nodes: during storage at ports, during storage at factories that transform RW to SW, during storage at factories that transform SW to FP, during transportation of RW and SW, and it can also transfer from FPs and wood residues (RES) (Table 1).

To calculate the volume of infested product at each node (Table 1), we first calculated the initial volume of oak RW that is exported each year from the US to Europe, V, from the reported tonnage and wood density. The infested volume was calculated by multiplying V with the infestation level of RW coming from the country of origin (the US) (w_{CO}), the probability that the pest survives treatments applied in the US (s_{TCO}), and the probability that the pest that is in the bark (as opposed to in the wood) (w_b) to account for the effects of removing the bark in option DB. The imported product was allocated to European countries and distributed over ports in each European country according to wood import statistics of the ports where unloading is allowed (35 ports under import options BF and BNF, and 93 ports otherwise; Table 3). While exporters and importers aim to meet the European regulations of pest freedom, the wood may nevertheless contain the pathogen. RW is therefore subjected to phytosanitary inspection in the ports and infested RW is not admitted if infestation is detected. The probability of detection is defined as p_d. Only the part of the infested volume that is not intercepted during inspection enters into Europe. If the fungus is present but not detected, it may disseminate around ports of entry or further down along the pathway.

A proportion of the oak logs that are imported to a country in Europe are transported to other European countries (intra-European trade) and the pest may transfer during transportation. Another proportion of RW is transformed to SW at wood factories within the country of importation. At factories, the pest may transfer from RW during storage in the open

Table 1 Overview of the model structure, non pest-specific parameters (related to the wood pathway) and pest-specific parameters. The model describes the pest pathway along the wood trade and wood chain from the country of origin (CO) until the FPs (anywhere in Europe). First, only 'RW' is considered, and then the derived products ('SW', 'RES' and 'FP'). Exposure (when the pest escapes from the wood, disperses and find a host tree) can happen at seven points in the pathway: from RW near the ports of entry, during transportation of the wood (RW and SW) across Europe, around wood factories (from RW, SW and RES) and at the end-use location (from FP). The column on the right provides equations used to calculate the infested volume of wood product (*V*) and exposure (*E*, number of propagules able to transfer to a host tree in Europe)

Location	Parameters for wood pathway	Parameters for pest pathway	Infested volume (*V*) and Exposure (*E*)
Country of origin (RW)	Tonnage of RW (M)	Infestation level (w_{CO})	
	Wood density (ρ) Proportion of wood with bark (w_{ba})	Survival to treatments (s_{TCO}) Probability to find pest in bark (w_b)	$V_{RW} = M \times (1/\rho) \times w_{CO} \times s_{TCO} \times (w_{ba} + (1 - w_{ba}) \times (1 - w_b))$ $V_{SW} = 0$
		↓	
Port of entry k in country j (RW)	Flow entering port k ($w_{k,j}$)	Detection probability at entry in Europe (p_d)	
		Probability of escape ($w_{e,p,RW}$), dispersal ($w_{d,p}$) and host encounter ($h_{z,k,j}$) given dispersal distance (z) Number of propagules in 1 m^3 (n_{RW})	$V_{RW,k,j} \leftarrow V_{RW}(j) \times (1 - p_d) \times w_{k,j}$ $E_{RW,k,j} = V_{RW,k,j} \times n_{RW} \times w_{e,p,RW} \times w_{d,p} \times h_{z,k,j}$
		↓	
Intra-EU trade (RW then also SW)	Proportion of wood going from any country i to any other country j ($w_{i,j}$) Distance travelled (l_j)	Probability of escape from RW ($w_{e,t,RW}$) and SW ($w_{e,t,SW}$), dispersal ($w_{d,p}$) and host encounter in country j (h_j)	$V_{RW,j} \leftarrow \sum_i V_{RW}(i) \times w_{i,j}$ $E_{RW,j} = V_{RW,j} \times n_{RW} \times w_{e,t,RW} \times T_{RW}(j) \times w_{d,j} \times h_j$
	Speed of transportation of RW (v_{RW}) and SW (v_{SW}) Number of working hours per day (t) Duration of the stay in each country (a) $T_{RW}(j) = l_j / (v_{RW} \times t)$ (b) $T_{SW}(j) = l_j / (v_{SW} \times t)$ Number of exchanges between countries (m)	Number of propagules in 1 m^3 of RW (n_{RW}) and SW (n_{SW})	$V_{SW,j} \leftarrow \sum_i V_{SW}(i) \times w_{i,j}$ $E_{SW,j} = V_{SW,j} \times n_{SW} \times w_{e,t,SW} \times T_{SW}(j) \times w_{d,j} \times h_j$
		↓↑ Number of exchanges (m)	
Factories in Europe (RW, SW and RES)	Proportion of RW going for processing (w_α)	Survive rate to treatments (s_T)	$V_{RW,j,r} = V_{RW,j} \times w_f$ $E_{RW,j,r} = V_{RW,j,r} \times n_{RW} \times w_{e,F1} \times w_{d,r} \times h_{j,r}$
		Survive rate to processing into SW (s_{F1})	

Continued

Table 1 *Continued*

Location	Parameters for wood pathway	Parameters for pest pathway	Infested volume (V) and Exposure (E)
	Proportion of SW used or going for processing (w_β)		
	Proportion within w_β going for processing and not used directly (w_γ)	Survive rate to processing into FP (s_{F2})	$V_{SW,j,r} \leftarrow V_{SW,j} \times w_f + (1 - w_{F1,RES}) \times w_\alpha \times s_T \times s_{F1} \times V_{RW,j} \times w_f$
	Proportion of wood ending in residues at 1st processing ($w_{F1,RES}$) and second processing ($w_{F2,RES}$)	Survive rate into residues (s_{RES})	$E_{SW,j,r} = V_{SW,j,r} \times n_{SW} \times w_{e,F2} \times w_{d,r} \times h_{j,r}$
	Relative number of factories in each region r (w_f)	Probability of escape from RW ($w_{e,F1}$), SW ($w_{e,F2}$) and RES ($w_{e,RES}$), dispersal ($w_{d,r}$) and host encounter in region r of country j ($h_{j,r}$)	$V_{RES,j,r} \leftarrow w_{F1,RES} \times w_\alpha \times V_{RW,j,r} \times s_{RES} + w_{F2,RES} \times w_\beta \times w_\gamma \times V_{SW,j,r} \times s_{RES}$
		Number of propagules in 1 m^3 of RW (n_{RW}), SW (n_{SW}) and RES (n_{RES})	$E_{RES,j,r} = V_{RES,j,r} \times n_{RES} \times w_{e,RES} \times w_{d,r} \times h_{j,r}$
		↓	
Anywhere in Europe (SW and FP)	Relative human population density in each region (w_{hp})	Probability of escape from FP ($w_{e,FP}$), dispersal ($w_{d,r}$) and host encounter in region r of country j ($h_{j,r}$)	$V_{FP,j,r} = w_\beta \times V_{SW,j} \times ((1 - w_{F2,RES}) \times w_\gamma \times s_T \times s_{F2} + (1 - w_\gamma)) \times w_{hp}$
		Number of propagules in 1 m^3 of FP (n_{FP})	$E_{FP,j,r} = V_{FP,j,r} \times n_{FP} \times w_{e,FP} \times w_{d,r} \times h_{j,r}$

air at these factories. The RW is distributed over regions in a country in proportion to the number of factories in each region. The produced sawn wood has three different destinations. A first proportion of the sawn wood is transported to other countries in Europe (intra-European trade). During transport the pest can transfer to a host. A second proportion is for direct final use and is considered as a FP. A third proportion of sawn wood is transported to factories where it undergoes a second transformation into FPs. The pest can transfer from sawn wood around these factories, provided that it survives the preceding transformation and treatment, with probabilities s_{F1} and s_T, respectively. The pest can also transfer from wood residues produced in these factories during the first and second transformation, provided it survives processing, with probability s_{RES}. The pest can finally transfer to a host from the FPs. This requires survival of the second transformation and treatment, with probabilities s_{F2} and s_T. These FPs are distributed among NUTS2 regions within the country according to human population density in these regions.

Three sequential processes are considered in the calculation of the transfer to the host. These are escape of the fungal propagules from the infested wood, the dispersal of the infested vector from the wood into the environment, and finally the encounter with hosts. Escape requires a vector, either an exotic vector coming with the wood from the US or a European vector (potential European vectors being widespread; see SM1). The escape probability $w_{e,P}$ (Eq. 1) is expressed per m^3 of infested wood. The calculation of dispersal takes into account that vector activity is required for dispersal. The dispersal probability is therefore calculated as the proportion of the year ($w_{d,j,r}$ in Eq. 1) during which vectors are active. The probability of encountering a host ($h_{j,r}$ in Eq. 1) is determined by the proportion of the area of a NUTS2 region that is covered by host trees. When calculating exposure during storage at ports, the spatial coordinates of the port are taken into account, and the probability of host encounter ($h_{z,k,j}$ for port k in country j) is calculated as the proportion of land covered by host trees within a radius from the port corresponding to the flight capability of the vector, z (see SM2).

The pathway model takes spatial information into account at three levels: (1) national, (2) NUTS2 (i.e. regional within countries) and (3) finer resolution data. Country level datasets were used to calculate the pest transfer during transportation across Europe (since data about intra-European trade was available only at country level from Eurostat, http://ec.europa.eu/eurostat). We used datasets at NUTS2 level resolution to distribute wood over regions according to the number of factories in each of the regions (the number of factories was available only at this spatial scale over Europe). NUTS2 level databases on human population were used to distribute the FPs over regions according to the number of inhabitants. Finally, precise georeferenced datasets of forest and tree cover were used to calculate pest transfer around ports.

Parameter estimation

The model has 21 parameters characterizing the wood, the wood processing and the wood trade, and 24 pest-specific parameters (Tables 1–2; see details in SM1 and SM2). Parameters of the first category are, for instance, wood density (to convert imported tonnage into a volume), wood flow among European countries, proportion of wood imported with bark, proportion of RW going to first transformation, proportion of sawn wood going to second transformation and host cover (Table 1, SM2). Other parameters characterizing the wood and processing flow are the number of processing facilities in each NUTS2 region, human population density in each NUTS2 region, average transportation distances among EU countries and duration of transportation. The imported quantities and the intra-European trade flows were retrieved from Eurostat, a harmonized trade-database of members of the European Union (http://ec.europa.eu/eurostat). The spatial distribution of oaks in Europe was obtained from the Joint Research Centre (Köble and Seufert, 2001; Figure 1).

Table 2 List of pest specific parameters, their estimates and their uncertainty levels. Values in italics represent the minimum most likely, the most likely and the maximum most likely values. Some parameters (*) were log10-transformed for the beta-PERT distribution. Other parameters (**) were randomly sampled from a set of predefined values

Parameters	Definition	Import options and scenario				Uncertainty
		No reg.	BF	BNF	DB	
w_{CO}	Proportion of infected oaks in the USA (between 0 and 1)	0.35 *0.1–0.35–0.5*	0.35 *0.1–0.35–0.5*	0.17 *0.1–0.17–0.4*	0.35 *0.1–0.35–0.5*	Medium
s_{TCO} (*)	Survival rate to the treatments done in the USA between tree felling and export of oak RW (between 0 and 1)	1 *0.9–1–1*	0.001 *0.0001–0.001–0.01*	1 *0.9–1–1*	0.001 *0.0001–0.001–0.01*	Medium
w_b	Probability that the pest is in the bark (compared with other parts of the wood) (between 0 and 1). If 1 then the pest is only in bark and debarked products cannot carry the pest. If 0 then the pest is not in bark, therefore importing wood with or without bark does not affect the infestation level of the wood.	0.01 *0.005–0.01–0.05*	0.01 *0.005–0.01–0.05*	0.01 *0.005–0.01–0.05*	0.01 *0.005–0.01–0.05*	Low
p_d	Probability of an infested consignment of RW to be detected at entry in Europe (between 0 and 1).	0.0884 *0.01–0.0884–0.1*	0.0002 *0.0001–0.0002–0.001*	0.3031 *0.1–0.3031–0.5*	0.0002 *0.0001–0.0002–0.001*	High
$w_{e,p,RW}$ (*)	Probability of pest escape from 1 m^3 of infested RW around ports (between 0 and 1). It can account for: whether the European vector is present (if required for the pest at this step) and whether the imported products are stored outdoors and confined in a room during the storage in the port.	0.001 /m^3 *0.0001–0.001–0.01*	0.001 /m^3 *0.0001–0.001–0.01*	0.0001 /m^3 *0.00001–0.0001–0.001*	0.00001 /m^3 *0.000001–0.00001–0.0001*	High
$w_{e,t,RW}$(*)	Probability to escape from 1 m^3 of infested RW per day when transported within Europe (between 0 and 1). Same description as $w_{e,p,RW}$ but during transportation within Europe and not during storage in the port. These probabilities are multiplied with the time spent in each country, which depends on the transportation duration there (distance to travel and speed).	0.001 /m^3/day *0.0001–0.001–0.01*	0.001 /m^3/day *0.0001–0.001–0.01*	0.00001 /m^3/day *0.000001–0.00001–0.0001*	0.00001 /m^3/day *0.000001–0.00001–0.0001*	High
$w_{e,t,SW}$ (*)	Probability of escape from 1 m^3 of infested sawn wood per day when transported within Europe (between 0 and 1). Same description as $w_{e,t,RW}$.	0.00001 /m^3/day *0.000001–0.00001–0.0001*	0.00001 /m^3/day *0.000001–0.00001–0.0001*	0.000001 /m^3/day *1×10^{-7}–0.000001–0.00001*	0.000001 /m^3/day *1×10^{-7}–0.000001–0.00001*	High
$w_{e,F1}$(*)	Probability of escape from 1 m^3 of infested RW when stored in wood factories before transformation from RW to sawn wood (time implicit) (between 0 and 1). Same description as $w_{e,p,RW}$ but during storage at factory and not during storage in the port.	0.0001 /m^3 *0.00001–0.0001–0.001*	0.00001 /m^3 *0.000001–0.00001–0.0001*	0.00001 /m^3 *0.000001–0.00001–0.0001*	0.0001 /m^3 *0.00001–0.0001–0.001*	High
$w_{e,F2}$(*)	Probability of escape from 1 m^3 of infested sawn wood when stored in wood factories before transformation from sawn wood to FPs (time implicit) (between 0 and 1). Same description as $w_{e,p,RW}$ but during storage at factory and not during storage in the port.	0.0001 /m^3 *0.00001–0.0001–0.001*	0.00001 /m^3 *0.000001–0.00001–0.0001*	0.00001 /m^3 *0.000001–0.00001–0.0001*	0.0001 /m^3 *0.00001–0.0001–0.001*	High
$w_{e,RES}$(*)	Probability of escape from 1 m^3 of infested residues resulting from the transformation of RW into the sawn wood and then into the FP (time implicit) (between 0 and 1).	0.0001 /m^3 *0.00001–0.0001–0.001*	0 /m^3	0 /m^3	0.0001 /m^3 *0.00001–0.0001–0.001*	High

Continued

Table 2 *Continued*

Parameters	Definition	Import options and scenario				Uncertainty
		No reg.	BF	BNF	DB	
$w_{e,FP}$(*)	Probability of escape from 1 m^3 of infested FPs (time implicit) (between 0 and 1).	0.000001 /m^3 1×10^{-7} – *0.000001– 0.00001*	0.000001 /m^3 1×10^{-7}– *0.000001– 0.00001*	0.000001 /m^3 1×10^{-7}– *0.000001– 0.00001*	0.000001 /m^3 1×10^{-7}– *0.000001– 0.00001*	High
$w_{d,p}$	Probability of the vector dispersing around each port *p*. It can depend on climate conditions and season (between 0 and 1). Since the flight season is 5 months per year, this probability is 5/12.	5/12 *3/12 – 5/12– 7/12*	5/12 *3/12 – 5/12– 7/ 12*	5/12 *3/12 – 5/12– 7/ 12*	5/12 *3/12 – 5/12– 7/ 12*	High
$w_{d,r}$(*)	Probability of the vector dispersing in each region *r*. Same description as $w_{d,p}$ but per region (between 0 and 1).	5/12 *3/12 – 5/12– 7/12*	5/12 *3/12 – 5/12– 7/ 12*	0.0001 *0.00001– 0.0001–(1/ 12)*	5/12 *3/12 – 5/12– 7/ 12*	High
$w_{d,j}$(*)	Probability of the vector dispersing in each country *j*. Same description as $w_{d,p}$ but per country (between 0 and 1).	5/12 *3/12 – 5/12– 7/12*	5/12 *3/12 – 5/12– 7/ 12*	0.0001 *0.00001– 0.0001–(1/ 12)*	5/12 *3/12 – 5/12– 7/ 12*	High
z (**)	Mean dispersal distance of the pest or vector	1 km *1 – 2 – 5*	1 km *1 – 2 – 5*	1 km *1 – 2 – 5*	1 km *1 – 2 – 5*	High
z_{RES}(**)	Mean dispersal distance of the pest or vector escaping from residues	1 km *1 – 2 – 5*	1 km *1 – 2 – 5*	1 km *1 – 2 – 5*	1 km *1 – 2 – 5*	High
s_T (*)	Survival to treatments done in EU when producing the sawn wood and FPs (between 0 and 1).	0.00001 *0.000001– 0.00001– 0.0001*	0.00001 *0.000001– 0.00001– 0.0001*	0.00001 *0.000001– 0.00001– 0.0001*	0.00001 *0.000001– 0.00001– 0.0001*	Medium
s_{F1}	Survival rate to first transformation (from RW to sawn wood) (between 0 and 1).	1 *0.95–1–1*	1 *0.95–1–1*	1 *0.95–1–1*	1 *0.95–1–1*	Low
s_{F2}	Survival rate to second transformation (from sawn wood to FP) (between 0 and 1).	1 *0.95–1–1*	1 *0.95–1–1*	1 *0.95–1–1*	1 *0.95–1–1*	Low
s_{RES}	Survival in wood residues produced during first and second transformations (between 0 and 1).	1 *0.95–1–1*	1 *0.95–1–1*	1 *0.95–1–1*	1 *0.95–1–1*	Low
n_{RW}(*)	Number of propagules in 1 m^3 of infested RW	1 / m^3 *0.001 – 1 – 10000*	1/ m^3 *0.001 – 1– 10000*	1/ m^3 *0.001 – 1 – 10000*	1/ m^3 *0.001 – 1– 10000*	High
n_{SW}(*)	Number of propagules in 1 m^3 of infested sawn wood	1/ m^3 *0.001 – 1 – 10000*	1/ m^3 *0.001 – 1 – 10000*	1/ m^3 *0.001 – 1– 10000*	1/ m^3 *0.001 – 1 – 10000*	High
n_{FP}(*)	Number of propagules in 1 m^3 of infested FPs	1/ m^3 *0.001 – 1– 10000*	1/ m^3 *0.001 – 1– 10000*	1/ m^3 *0.001 – 1 – 10000*	1/ m^3 *0.001 – 1– 10000*	High
n_{RES}(*)	Number of propagules in 1 m^3 of infested wood residues	1/ m^3 *0.001 – 1 – 10000*	1/ m^3 *0.001 – 1 – 10000*	1/ m^3 *0.001 – 1– 10000*	1/ m^3 *0.001 – 1– 10000*	High

The pest-specific parameters were parameterized for the fungus *C. fagacearum* and for its North American or European vector, based on published data and expert knowledge. The uncertainty in parameter estimates was rated as low, medium or high based on available data to support the estimate (the guideline to rate uncertainty is shown in SM3, from EFSA PLH, 2013). Some parameters were parameterized without further supporting evidence, leading to high uncertainty in the absolute value of the parameter. In some cases, comparative differences in parameter values between import options could be estimated with greater confidence than the absolute values of the parameters.

Estimation of pest-specific parameters

Parameter w_{CO}: The proportion of oak wood infested with *C. facagearum* was estimated by multiplying the proportion of the geographic range of American oaks in which the fungus is present with the proportion of trees within the geographic range of oak wilt that is infested with the fungus (SM1). Since logs imported into Europe under the option BNF are necessarily white oaks and these species are generally less susceptible to oak wilt, the proportion of infected oaks was estimated to be lower in option BNF than in options BF and DB (Tables 2, 3).

Parameter s_{TCO}: The chance of the fungus surviving treatments of the wood in the US depends foremost on whether or not the wood is fumigated and was therefore specific to each import option (Table 2; SM1).

Parameter w_b: Mats of the fungus are found underneath the bark but not in the bark itself (SM1). Therefore, the probability that *C. fagacearum* is in the bark (compared with other parts of wood) was set to a low value.

Parameter p_d: The probability of detecting an infested log at entry in Europe was estimated by taking into account the proportion of incoming consignments which are inspected, the probability that an infested log is sampled within this consignment, and the probability of detecting the pest from an infested sample (SM1 and SM4).

Parameter w_e: The probability of escape of propagules from wood depends on the node along the chain. Seven parameter values related to this probability were defined. The pest can escape from RW around ports ($w_{e,p,\mathrm{RW}}$), from RW or sawn wood (SW) during transportation ($w_{e,t,\mathrm{RW}}$ and $w_{e,t,\mathrm{SW}}$), from RW or sawn wood around factories ($w_{e,F1}$ and $w_{e,F2}$), from residues around factories ($w_{e,\mathrm{RES}}$) and from FPs ($w_{e,\mathrm{FP}}$) (details in SM1). These probabilities are expressed as the probability that propagules escape from 1 m^3 of infested wood product, except during transportation, where it is given per m3 and per day transport in a country. Since wood containing bark (options BF and BNF) is sent to certified factories contrary to wood without bark (option DB) (Table 3), the escape probability from this wood ($w_{e,f,\mathrm{RW}}$) was considered lower in options BF and BNF than in option DB. The probability of escape during transportation across Europe ($w_{e,t,\mathrm{RW}}$) was considered higher in option BF since (1) in option BNF, some restrictions apply when transporting wood (season and area; Table 3) and (2) in option DB, wood without bark cannot carry

Table 3 Description of the three import options. Regulation is different for logs with bark that have been fumigated (option BF), logs with bark that have not been fumigated (option BNF) and logs without bark (option DB) (see Commission Decisions 2005/359/CE, 2006/750/CE). Several model parameters differ among these three options. These parameters are given in the last column called 'Associated parameters' (see Tables 2–3 for their definition). When assessing the effect of individual regulation measure (on wood, bark, treatment, inspection, ports of entry, storage, seasons of export, areas of export and processing), we used the value given in brackets in the last column

Regulated part	Import option 'BF'	Import option 'BNF'[a]	Import option 'DB'	Parameters used for individual risk reduction measures
Wood	Any oaks	White oaks only[b]	Any oaks	w_{CO} (0.17)
Bark	With or without	With or without	Without	w_{ba} (0) $w_{e,p,\mathrm{RW}}$ (0.00001) $w_{e,t,\mathrm{RW}}$ (0.00001) $w_{e,t,\mathrm{SW}}$ (0.000001)
Treatment	Fumigation	None	(1) Squaring , or (2) kiln drying (< 20% moisture), or 3) disinfected (hot air/water)	s_{TCO} (0.001)
Inspection	Fumigation test on samples	Identification test of the oak colour on at least 10% of logs in each lot		p_d (0.3031)
Ports of entry	List of 35 ports[c]	List of 35 ports[c]	Any ports	$w_{k,j}$ (35 ports)
Storage conditions in ports		In continuous wet conditions at certified locations as soon as the local oaks start to flush		$w_{e,p,\mathrm{RW}}$ (0.0001)
Season of exports from ports		15 Oct–30 April		$w_{e,t,\mathrm{RW}}$ (0.00001) $w_{e,t,\mathrm{SW}}$ (0.000001) $w_{d,r}$ (0.0001)
Export and transportation areas		only to areas >45°N[d]		$w_{i,j}$ l_j (0 below 45°N for both)
Processing	Only in certified locations and residues are destroyed	Only in certified locations and residues are destroyed		$w_{e,F1}$ (0.00001) $w_{e,F2}$ (0.00001) $w_{e,\mathrm{RES}}$ (0)

[a]This import option is not applicable to Greece, Spain, Italy, Cyprus, Malta and Portugal as fumigation (option BF) is required for these countries.
[b]The logs shall not be introduced into or through areas south of 45° latitude. Wood can be unloaded in the port of Marseilles, even if below 45°N, provided that the wood is immediately moved to areas above 45°N.
[c]List of the 35 ports where unloading oak logs with bark is allowed (Commission Decision 2006/750/CE): (1) Amsterdam, (2) Antwerp, (3) Århus, (4) Bilbao, (5) Bremen, (6) Bremerhaven, (7) Copenhagen, (8) Hamburg, (9) Klaipeda, (10) Koper, (11) Larnaca, (12) Leghorn, (13) Le Havre, (14) Lemesos, (15) Lisbon, (16) Marseilles, (17) Marsaxlokk, (18) Muuga, (19) Naples, (20) Nordenham, (21) Oporto, (22) Piraeus, (23) Ravenna, (24) Riga, (25) Rostock, (26) Rotterdam, (27) Salerno, (28) Sines, (29) Stralsund, (30) Valencia, (31) Valletta, (32) Venice, (33) Vigo, (34) Wismar, (35) Zeebrugge'. In option BNF, only ports in this list located above 45°N and Marseilles can effectively receive oak logs.
[d]List of countries considered in our simulations as above 45°N: Austria, Belgium, Bulgaria, Switzerland, Czech Republic, Germany, Danemark, Estonia, Finland, France, Croatia, Hungary, Ireland, Iceland, Liechtenstein, Lithuania, Luxembourg, Latvia, Montenegro, Macedonia, Netherlands, Norway, Poland, Romania, Sweden, Slovenia, Slovakia, UK.

a native vector and there is little chance that a European vector would feed on the wood and assist the fungus in escaping.

Parameter w_d: Three parameters related to dispersal from wood were derived: probability of dispersal around the ports, $w_{d,p}$, probability of dispersal in each region r, $w_{d,r}$, and probability of dispersal in each European country j, $w_{d,j}$ (see more details in SM1). Except in option BNF, under which transportation is allowed only during the period of non-activity of the vector, this probability was given by the proportion of the year during which the vector is active. This probability was assumed to be uniform across Europe.

Parameters z and z_{RES}: The mean dispersal distance of the vector was used to calculate the probability that propagules of *C. fagacearum* encounter a host around ports. The rate of disease spread observed in the US (3.5 m/yr; Haight *et al.*, 2011) and the maximal flight capability of *S. intricatus* (100 m at most; Anonymous, n.d.) were below the spatial resolution of the host tree distribution dataset (1 km). Consequently, we considered that the vector could disperse at 1 km, allowing it to reach oaks when they were located in an adjacent grid cell. Since the fungus cannot be transmitted directly (without a vector) from wood residues to trees, we assumed that the dispersal distance related to wood residues (z_{RES}) was the same as the dispersal distance related to other wood products (RW, SW and FP) (z).

Parameters s_{F1}, s_{F2}, s_{RES}: These parameters represent the probability that the fungus survives the first and second transformations and survives the generation of wood residues. These probabilities were set at high values since wood processing has negligible effects on fungus survival. Wood processing can however affect the vector if carried by imported wood but this impacts the probability of escape (w_e).

Parameter s_T: The probability that the fungus survives treatments applied in wood processing factories (s_T) was assumed to be low because the wood is dried, killing the fungus.

Parameters n_{RW}, n_{SW}, n_{FP}, n_{RES} express the number of propagules per m^3 of wood (RW, SW, FP and RES). We define a propagule as the mean number of spores carried by an insect vector visiting a host tree. Thus, one propagule is the average spore load of a single vector. Then, exposure is the number of propagules that can transfer to host trees in Europe.

Three import options under regulation and a scenario without regulation

We tested the three possible import options that are offered for import of oak wood from the US by the European Union (Table 3): option BF 'bark fumigated', option BNF 'bark non-fumigated', and option DB 'DeBarked' (Commission Decision 2006/750/EC; Table 3, Figure 1).

The option BF 'barked, fumigated' may be used for wood of white and red oaks. Fumigation of the wood is required, and a fumigation colour reaction test must be carried out on wood samples. Wood may be imported under this option to only 35 ports (Figure 1; Table 3), and processing is allowed only in certified locations in Europe. Residues must be destroyed.

The option BNF 'barked, non-fumigated' may only be used for white oak wood. No treatments are required in this option. However, at least 10% of the wood must be checked to confirm that the wood belongs to the white oak group by using another specific colour test. Furthermore, wood may only be imported under this option to 35 ports, and further transport from these ports is allowed only during the cold season (15 October–30 April) and to locations above the 45^{th} degree Northern latitude. Storage at the port must be under continuous wet conditions at certified locations as soon as the local oaks start to flush. Processing is allowed only in certified locations and residues must be destroyed.

The option DB 'debarked' requires debarking and both white and red oak wood may be imported under this option. Wood should be treated by: (1) squaring, or (2) kiln drying (<20% moisture) or (3) disinfection with hot air or hot water. No further restrictions apply.

In addition, a reference scenario was tested simulating no regulation.

To simulate option DB, values of pest-specific parameters were adjusted to reflect the import conditions. To simulate option BF, in addition to changes in the parameter values, the ports of entry were restricted to the list of 35 allowed ports (Figure 1; Table 3). In option BNF, in addition to this restriction and the changes in the parameter values (including a lower probability of escape and dispersal because transportation is restricted to the period of non-activity the vectors), we restricted the countries to which transportation is allowed (only above latitude 45°N) (Table 3; Figure 1). In the scenario without regulation, we considered absence of restrictions on the ports of entry, storage conditions, the season of transportation, the countries where transportation is allowed and the factories where processing is allowed. For all other parameters we took the worst case of the three options.

Simulations

Estimating the exposure for three import options and the no-regulation scenario

To compare import options and identify the nodes where exposure is highest, we simulated the exposure resulting from the tonnage of oak RW imported from the US to 28 countries in Europe between 2001 and 2009 (the latest year available when data were retrieved). We considered the 28 Member States of the European Union only (listed in SM3) as they are required to comply with the EU regulation. We assumed that a country did not import oak logs if no import data were reported in Eurostat. In this study, except when explicitly stated otherwise, the exposure was calculated for each country, each node along the pathway and each year. Then it was averaged over 2001–2009 for each country and each node, after which exposure was summed over the nodes for each country to calculate exposure per country and over all countries to calculate total exposure at the EU level. Simulations were done with trade data for individual years as available in Eurostat, to determine the variability in total exposure (sum of exposure over the nodes and countries). The proportion of wood that is imported under each import option is not known. For this reason, we calculated exposure for each option assuming that the entire tonnage of oak RW imported into Europe, as reported by Eurostat, was imported according to this option.

Estimating the effectiveness of individual risk reduction measures

Each import option prescribed by the European Union consists of a number of measures (Table 3). To get insight into which measures contribute most to a reduction in exposure, individual risk reduction measures were tested. We tested the following nine risk reduction measures: (1) effects of restricting imports to white oaks ('wood' option), (2) restricting imports to debarked wood ('bark' option), (3) restricting imports to fumigated wood only ('treatment' option), (4) increasing the detection efficiency ('inspection' option), (5) restricting imports to a limited set of ports ('ports' option), (6) adopting continuous wet conditions when appropriate during storage ('storage' option), (7) restricting transportation to the season when the vector is inactive ('season' option), (8) restricting transport to areas above 45°N ('areas' option) and (9) restricting processing of wood to certified locations only, including destruction of wood residues ('processing' option). The effects of these individual risk reduction measures were simulated, using the parameterization of the no-regulation scenario (Table 2) for the other parameters. The values associated with each risk reduction measure are reported in Table 3. The reduction in exposure was compared with the 'no regulation' scenario. Trade data from 2001 to 2009 were used to do these simulations.

Testing the vulnerability of the receptor countries

To compare vulnerability among countries for entry of oak wilt from imported oak wood, we calculated for each country exposure resulting from an imported quantity of 1000 tons of oak logs for each import option and the 'no regulation' scenario. The differences in exposure among countries are the result of differences in host cover, the distribution of wood processing factories among regions and the intra-EU trade patterns.

Uncertainty analysis

Uncertainty in exposure due to parameter uncertainty was assessed by running 500 simulations for random parameter sets drawn from beta-Program Evaluation and Review Technique (PERT) distributions for each parameter (Morgan and Henrion, 1990; Vose, 2008). A minimum, most likely and maximum value for each parameter were used as input to the beta-PERT distribution. In the PERT distribution, the scale parameter was set to four by default, to have a normal like distribution (Vose, 2008; see SM5, parameter values given Table 2). After the calculation of total exposure in Europe between 2001 and 2009 for the 500 replicate simulations, we determined the 95% enclosure interval, defined as the interval that contains 95% of the exposure values. Parameters for which uncertainty ranges over at least two orders of magnitude for at least one import option (e.g. min = 0.1, mode = 1 and max = 10) were drawn from a PERT distribution on a logarithmic scale of the parameter (i.e. min = −1, mode = 0 and max = 1) and then back-transformed to the original scale. For the probability to encounter a host around ports ($h_{z,k,j}$), we drew from three predefined dispersal distances (1, 2 or 5 km; Table 2) for which the host cover was calculated beforehand.

Programming code

The model was implemented in the programming language R (R Development Core Team, 2014) and the R code is given in Supplementary Material (SM5). Datasets used to make the simulations are available at: http://www.efsa.europa.eu/en/supporting/pub/809e.

Results

Comparing import options and the scenario without regulation and their uncertainties

Exposure was more than 30 000 times higher in the no-regulation scenario (3.63×10^{-1} propagules per year) than under current regulation (1.09×10^{-5} for option DB, 9.66×10^{-6} for option BF and 1.37×10^{-7} for option BNF) (Figure 2a). Note that the predictions are in units of vector loads and one vector load may represent a large number of spores of the pathogen. Exposure varied only slightly over the years (Figure 2b). Importing non fumigated wood with bark (option BNF) gave the lowest exposure (Table 3). This is mainly because only white oaks may be imported under this option and they are far less susceptible to oak wilt than red oaks.

When considering uncertainty in the parameters, the comparisons of import options and no-regulation scenario gave broadly similar results. Despite large fluctuations between individual realizations, the no-regulation scenario provided the highest exposure (95% enclosure interval is 0.02–5.09), option BNF the lowest exposure (95% enclosure interval is 1.94×10^{-9}–3.05×10^{-5}), and options BF and DB intermediate exposure (95% enclosure interval is 1.64×10^{-7}–1.87×10^{-4} for BF and 9.86×10^{-7}–4.09×10^{-4} for DB) (Figure 2a).

At which locations can a high exposure be expected?

When importing wood under option BF, exposure mainly arose from escape during transportation of infested RW (Figure 3a). Exposure was the highest in the UK, Germany, the Netherlands and France.

Option BNF resulted in a 70-fold lower exposure than option BF. Exposure due to transport of RW was strongly reduced under option BNF because of the geographical and seasonal

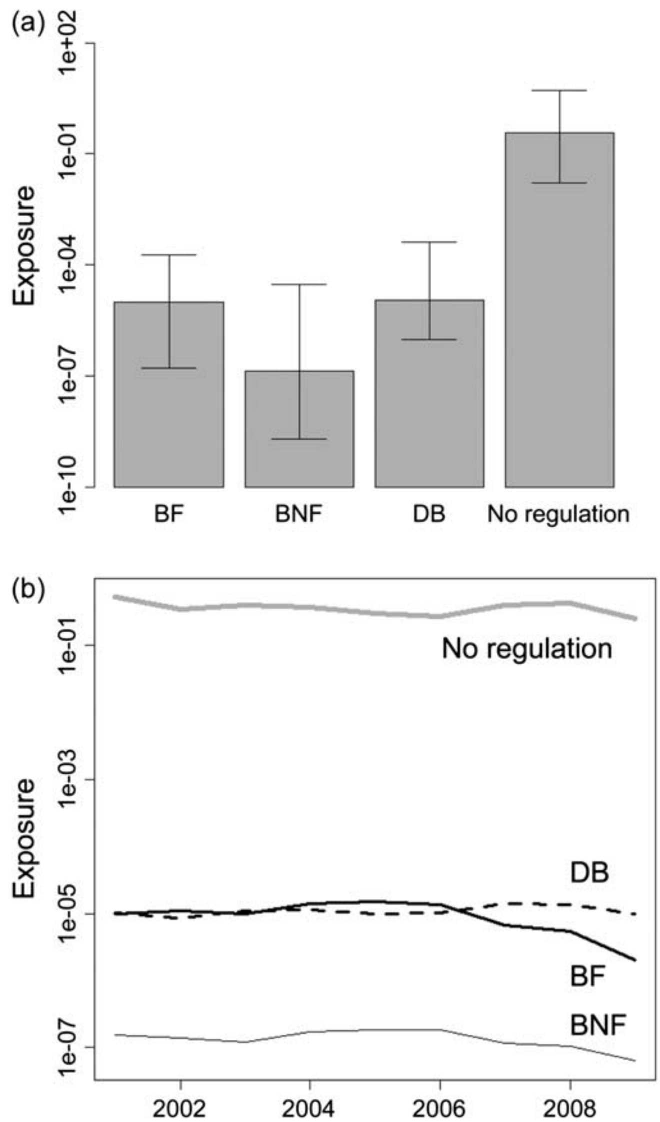

Figure 2 Exposure when considering three import options (BF: import of fumigated wood of red and white oaks, BNF: import of non-fumigated wood of white oaks, and DB: import of debarked wood of red and white oaks) and a scenario without regulation. For a more detailed description of the scenarios, see the text. Panel (a) describes the average exposure (propagules transferred to hosts per year) between 2001 and 2009, while panel (b) shows the variability of exposure over the years. The bar chart in panel (a) represents exposure for the most likely parameters' value and error bars represent the enclosure interval that contains 95% of exposure values when considering parameters' uncertainty. *Y*-axes are represented on a logarithmic scale.

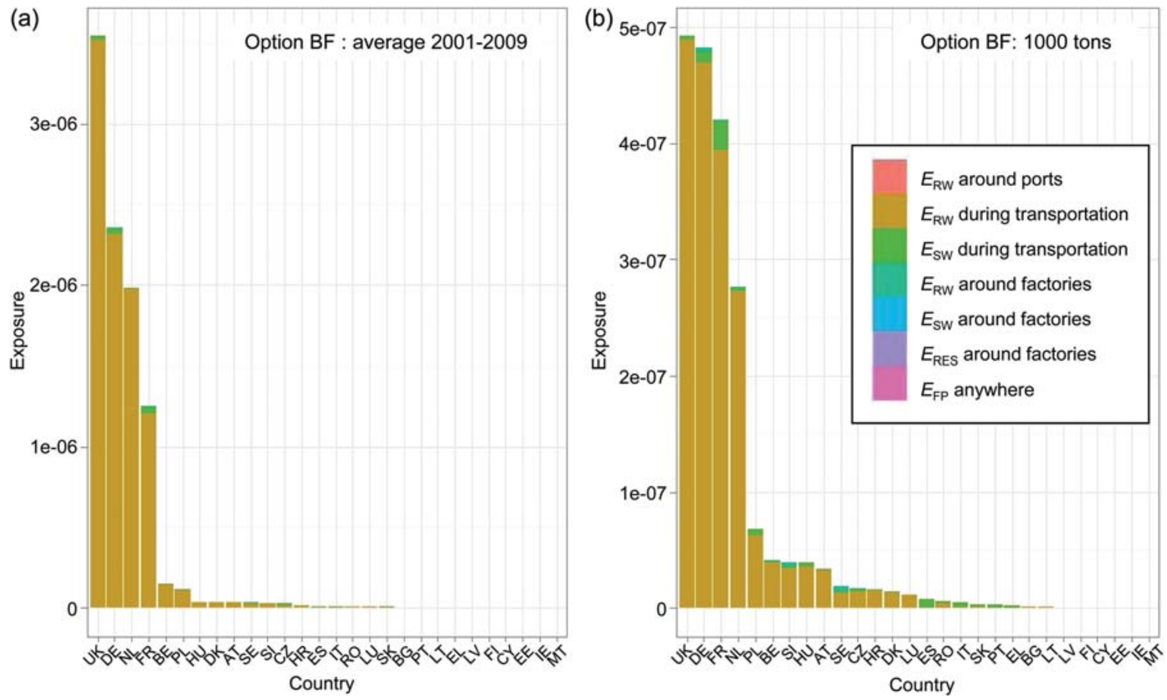

Figure 3 Exposure (*E*) at different points in the pathway and for each European country under import option BF (wood fumigated). Panel (a) shows the average exposure between 2001 and 2009 while panel (b) shows exposure resulting from importing 1000 tons of oak logs into every European country. Abbreviations for points of escape of the vector resulting in exposure: RW = round wood; SW = sawn wood; RES = wood residues and FP = final products. Full country names are given in SM3.

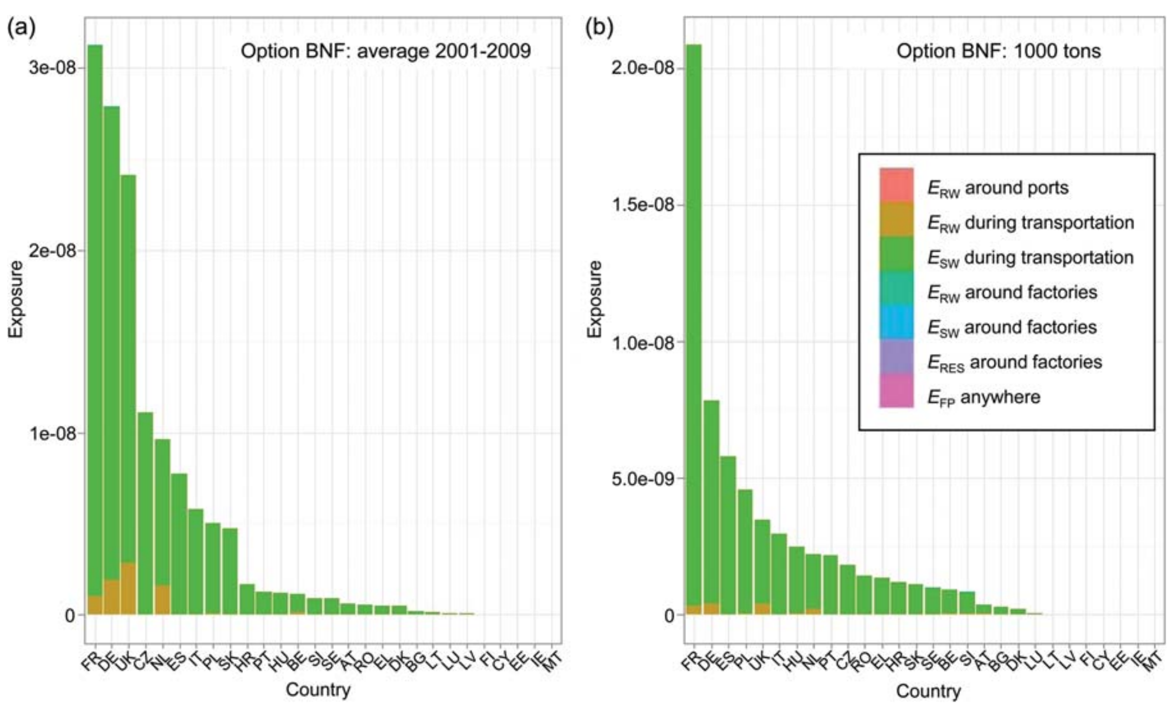

Figure 4 Exposure (*E*) at different points in the pathway and for each European country under import option BNF (wood of white oaks not fumigated). Panel (a) shows the average exposure between 2001 and 2009 while panel (b) shows exposure resulting from importing 1000 tons of oak logs into every European country. Abbreviations for points of escape of the vector resulting in exposure: RW = round wood; SW = sawn wood; RES = wood residues and FP = final products. Full country names are given in SM3.

restrictions on the transportation of RW from ports under this option (Figure 4a). The transportation of infested sawn wood made the most important contribution to the total exposure under this import option. France, Germany and UK had the highest exposure.

Option DB (Figure 5a) resulted in similar exposure as option BF. Under option DB, exposure resulted roughly equally from RW around factories, from RW around ports and from wood residues. Although there is only a small chance that the pest could escape from wood without bark, exposure was higher than in option BNF because conditions for importing wood are less restrictive (e.g. no restrictions for ports to which imports are allowed). Exposure was highest in Portugal, Spain and France (countries importing large quantities of oak logs directly from the US).

Without regulation (Figure 6a), the highest exposure was in Spain, Portugal and France, resulting mainly from transfer from infested RW near ports.

Effects of individual risk reduction measures on exposure

There was substantial variation in the effectiveness of individual risk reduction measures. Treatment (fumigation) applied in the country of origin ('treatment' measure) gave the highest reduction in exposure (Figure 7). Debarking ('bark' measure) before import was the second most effective measure. This measure affects not only the volume of infested wood imported in Europe but also, and more importantly, the probability of escape from wood by insect vectors. The third most effective single measure was restricting the ports to which import of oak logs is allowed ('ports' measure). Each of these three measures reduced exposure by more than 90%. The fourth most effective measure was restricting the storage conditions in the ports ('storage' measure). Restricting the imported wood to white oaks only ('wood' measure) had a moderate effect, reducing exposure by ~50%, and inspection reduced exposure by less than 30%. The other risk reduction measures had negligible effect.

Testing the vulnerability of the receptor countries across import options and the no-regulation scenario

The points along the pathway that were most important when considering the real historical import volumes were similar to the most important points identified when importing a standardized volume of imported wood across scenarios. However, the ranking of the countries differed for some scenarios (Figures 3–6).

In option BF, exposure mainly arose from transportation of infested RW among EU countries (Figure 3b). Since exposure at this node is not closely related to the volume of wood directly imported from the US but to the intra-EU trade, the ranking of EU countries did not differ considerably from the ranking for the historical import data, the top six countries differing by only one rank at most (UK, Germany, France, Netherlands, Poland and Belgium).

In option BNF, exposure arose mainly from transportation of infested sawn wood (Figure 4b). While the top two countries (France and Germany) remained the same as in the calculations with historical import data, the ranking of other EU countries slightly changed.

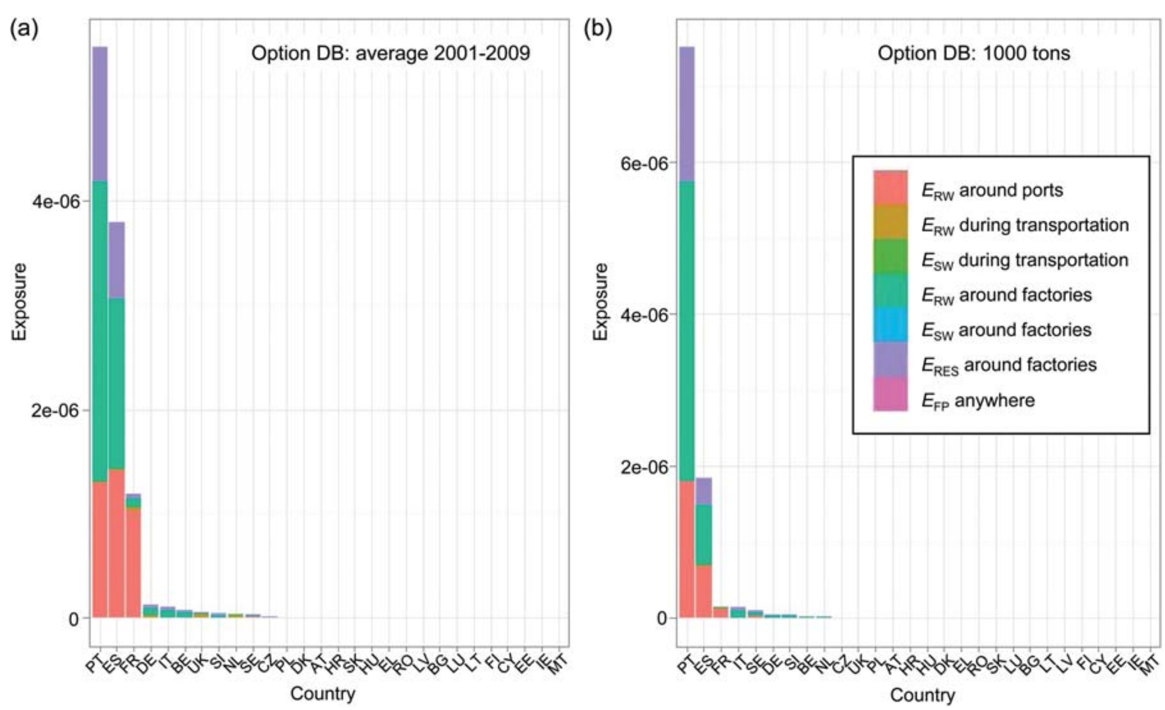

Figure 5 Exposure (*E*) at different points in the pathway and for each European country under import option DB (wood without bark). Panel (a) shows the average exposure between 2001 and 2009 while panel (b) shows exposure resulting from importing 1000 tons of oak logs into every European country. Abbreviations for points of escape of the vector resulting in exposure: RW = round wood; SW = sawn wood; RES = wood residues and FP = final products. Full country names are given in SM3.

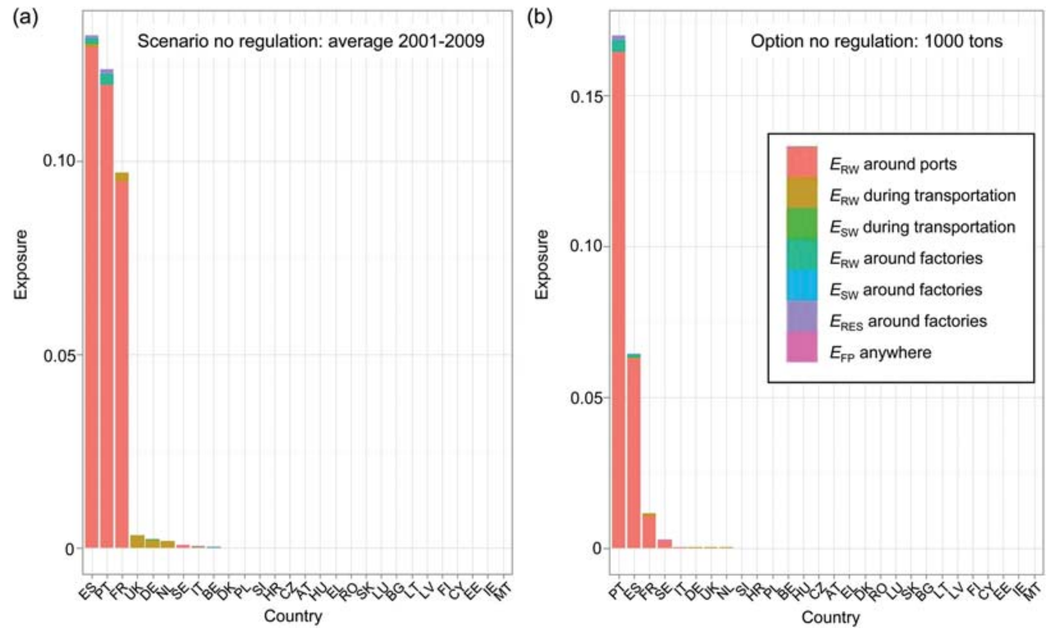

Figure 6 Exposure (*E*) at different points in the pathway and for each European country under the no-regulation scenario. Panel (a) shows the average exposure between 2001 and 2009 while panel (b) shows exposure resulting from importing 1000 tons of oak logs into every European country. Abbreviations for points of escape of the vector resulting in exposure: RW = round wood; SW = sawn wood; RES = wood residues and FP = final products. Full country names are given in SM3.

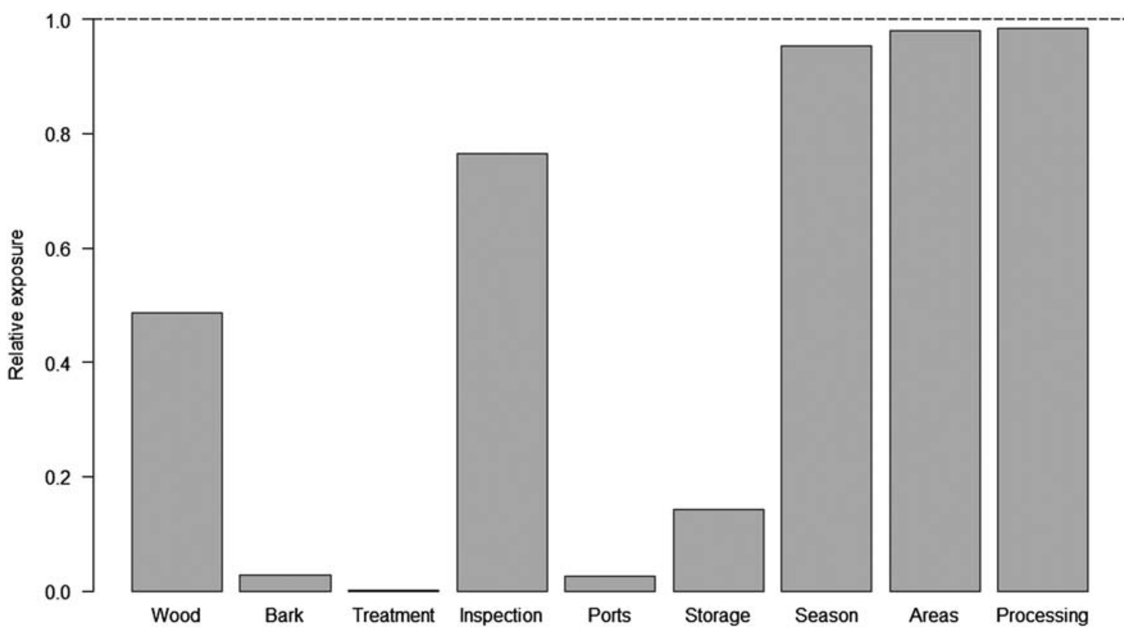

Figure 7 Relative exposure calculated for each individual risk reduction measure when implemented in the scenario without regulation: effects of restricting imports to only white oaks ('wood'), allowing imports of only debarked wood ('bark'), allowing imports of only fumigated wood ('treatment'), increasing the detection efficiency ('inspection'), restricting imports to only a set of ports ('ports'), adopting particular storage conditions at the port ('storage'), restricting transportation to the cold season ('season'), restricting areas where wood can be transported to above 45° latitude ('areas') and restricting wood processing to certified locations with destruction of wood residues ('processing'). Parameter values used for these simulations are given in Table 3. Default parameter values are taken from the no-regulation scenario (Table 2).

In option DB, exposure mainly arose from RW around ports, from RW around factories and from wood residues (Figure 5b). As RW stored around ports were an important source of propagules in this option, the ranking of EU countries substantially differed from the ranking for the historical import data, though the top three countries (Portugal, Spain and France) remained the same.

In the scenario without regulation, the ranking between the standardized import and the historical import was very different. This result can be attributed to the exposure arising from the transfer of propagules from RW stored around ports (Figure 6b), which is in turn directly related to tonnages imported by each country.

Discussion

The oak wilt disease is one of the biggest threats for oak trees in Europe. Because of the possibility of entry with oak wood from the US, the EU has regulated this trade. This study is to our knowledge the first quantitative analysis of this pathway including an assessment of the efficiency of current import requirements. The current import regulation distinguishes three options for import of oak logs from the US, and each of these consists of a suite of measures, each varying in effectiveness. All three import options were found to be effective. This study illustrates how pathway modelling can be used to support pest risk analysis, even under high uncertainty.

Effectiveness of current European regulation on oak logs coming from the US

Each of the three import options described in the EU regulations (Table 3) reduced exposure by a factor of 30 000 (Figure 2). The import option with non-fumigated logs of white oaks with bark (BNF) resulted in the lowest exposure because white oaks have a much lower chance to contain the pest and because of restrictive and effective measures (Table 3; Figure 7). This result illustrates that a combination of several moderately effective measures: importing white oaks only, in a restricted set of ports and stored under continuous wet conditions when appropriate – imposed in the import option BNF - could perform better than applying a single highly effective measure, such as treatment in the country of origin (Figure 7).

Transportation of infested wood across Europe made a large contribution to exposure (Figures 3–4) but restrictions on transportation such as the season and areas where transportation is allowed had low efficacy (Figure 7). Consequently, exposure could be further reduced if more effective measures were developed to reduce exposure during transportation.

Where could the oak wilt fungus enter in Europe?

The highest exposure was predicted around ports of entry (scenario without regulation, Figure 5). Countries importing a high tonnage of oak logs (see SM3) and with high host cover near ports, such as Spain, Portugal and France (Figure 1), may expect relatively high exposure around the ports of entry. In contrast, even though Germany and Ireland import a high volume of oak logs (SM3), exposure is low because host trees are comparatively less abundant in the surroundings of their ports (Figure 1).

Another important pathway of introduction of oak wilt disease is wood transportation from one European country to another (options BF and BNF). The UK and the Netherlands are examples: these countries had high exposure (options BF and BNF) while they did not directly import a high amount of wood from the US (SM3).

Model validation

Policymakers need predictive tools for potential invasive species before these species actually invade new territories (Hulme, 2015). The validation of predictive pathway models is fundamentally problematic, first of all because such models describe events that have not yet occurred, and secondly, because they describe rare events, for which realizations do not happen enough to allow quantitative evaluation of predictions vs data, even if a model is used for 'back-casting'. Validation of pathway models for pest entry is thus difficult if not impossible. A weak form of validation can be achieved by assessing model consistency, applicability and accuracy. Following Dee (1995), we can distinguish four aspects of model testing: (1) correctness of the conceptual model formulation, (2) correctness of the mathematical model formulation, (3) correctness of the software code and (4) model accuracy (FAO, 2003). As mentioned, the evaluation of model accuracy against independent observations is difficult. However, regarding aspect (1), an earlier version of the pathway model was presented to seven European forestry experts in Brussels in September 2014. Most comments were related to assumptions made because of data limitations. For instance, it would be helpful to have data about inspection efficiency, more precise locations of wood factories throughout Europe, transportation distances, amount of RW used directly for final use, and distribution of host trees in urban areas, but also to include wood packaging materials as a pathway, and to consider time-explicit data on the wood trade and wood processing chain. Regarding aspects (2) and (3), mathematics and R code were cross-checked among co-authors and simulations were done in duplicate and then shared and compared via a shared folder in a Dropbox.

Pathway models: towards a quantitative assessment of the policy effectiveness?

Essl *et al.* (2015) listed key priorities to improve research and management of biological invasion pathways. The most important challenge is to gather complete information associated with the pathways, taking into account interactions with environmental, socio-economic and management factors. This study takes a step forward by considering real-world data on the wood trade and the wood processing chain, their complex network, their relationships and different risk reduction options.

Moreover, there is a growing need for quantitative assessments as they generally allow greater transparency and objectivity in the justification of plant health policy (Leung *et al*., 2012; Soliman *et al*., 2015). This case study is interesting because most of the measures defined in these import options were previously recommended by the EPPO according to the invasion risk of the pest (see EPPO data sheet related to *C. fagacearum*; http://www.eppo.int/QUARANTINE/listA1.htm), and have been implemented by the EU without – to our knowledge – the use of pathway modelling. This raises the question of what the benefits of a pathway model approach are for plant health compared with more qualitative approaches.

Building a pathway model forces the risk assessor to structure and formalize the wood pathway. Such a model may identify data and knowledge gaps and may quantify the uncertainty that arises from this lack of knowledge. The pathway model applied to oak wilt clarified that important parts of the pathway were not documented. For instance, detection efficiency in the ports and pest density in infested wood, but also biological uncertainties resulting from new species associations, are important knowledge gaps (see next paragraph). This study contributed to the identification of data gaps and showed the importance of collecting additional data. Furthermore, this lack of knowledge became apparent in the variation in exposure when including parameter uncertainty. Exposure varied up to two to four orders of magnitude when including parameter uncertainty (Table 2). While the predictions of the model are uncertain in an absolute sense, the analysis of effectiveness of risk reduction options is still useful, especially when comparing among different options and scenarios. This assessment was confirmed in interactions with stakeholders in the wood industry. It confirms the notion that risk assessments need not be completely parameterized to be informative (Leung *et al*., 2012).

Data gaps

This study identified a number of parameters that were estimated with high uncertainty. Data is needed about the probability of escape and the number of propagules per unit of infested wood. There is also high uncertainty about the probability of detection, related to a lack of harmonized protocols at the EU level and shortage of documentation (SM4). Further progress can be made if monitoring is set up to collect such data.

In addition to uncertainties about parameter estimates, there are also biological uncertainties with respect to the potential vector. Experiments should be done to confirm that the insect *S. intricatus* can carry the fungus and transmit the fungus to oaks. It is suspected that this species could spread the oak wilt disease in Europe and, if introduced in the US, contribute to spread of the disease in the native range. The species is thought to be a more efficient vector than American species, although confirmation is lacking (Haack, 2001; Juzwik *et al*., 2011). Since this insect was intercepted several times between 1985 and 2000 at ports of entry in the US (Haack, 2001), it is important not only for Europe but also for the US to study the relationship between this European insect and the oak wilt fungus to better anticipate the risk related to this potential new association.

Even if border controls constitute the first line of defense to prevent biological invasions, they have been proven to be highly inefficient in Europe (Bacon *et al*., 2012; Eschen *et al*., 2015) and in the US (Liebhold *et al*., 2012). Given a lack of harmonization and transparency among the pest detection procedures at the European border (beyond the general inspection rules defined in the European regulation), it was difficult to estimate the effectiveness of pest detection in ports. Despite this uncertainty at the border, this study illustrates that it is possible to act successfully on other levers before and after these border controls to reduce exposure (e.g. requesting pre-export treatments, restricting European ports where imports are allowed, storing the product in proper conditions).

Generic models in pest risk assessments

The pathway model presented here was conceptualized in a way to be generic and thus applicable to other wood pests (insects or pathogens). Its structure accounts for typical steps in the trade and processing chain of wood (Douma *et al*., 2015). Applying this model to pest species on quarantine lists (e.g. EPPO, 2014) or pest species identified as able to colonize European trees (e.g. Roques *et al*., 2015) would be useful to estimate the risk of entry given import tonnage and current regulation measures. New, pest-specific parameters should be estimated to apply the model to these species, together with wood-specific parameters when considering other wood products than oak logs. Other aspects of structure and parameterization of the model may not need to be adapted.

More generally, a wood product could contain not only the targeted pest species but also other possible harmful species. There is now growing need to consider commodity-specific policy instead of individual pest-specific policies (Hulme *et al*., 2008; Essl *et al*., 2015). The wood pathway model presented here can be used to estimate exposure of host trees to any wood pests arriving with imported wood products, as it considers general patterns of the wood trade and wood processing chain. In this sense, this model could be useful to support commodity-specific policies.

The current model only accounts for imports of infested RW from a country of origin to Europe. To assess more generally the risk of introduction of forest pests, it is necessary to consider other possible commodities, especially imports of sawn wood and wood packaging material. Then, to complement this approach in the context of pest risk assessments, it is necessary to consider not only the probability of entry but also the potential establishment and spread, taking into account climate suitability and habitat distribution, and ultimately the economic impact of the pest species (e.g. Soliman *et al*., 2015; Venette, 2015). Some generic models to describe potential establishment (e.g. CLIMEX, Sutherst *et al*., 2007; NAPPFAST, Magarey *et al*., 2007), potential spread (e.g. generic spread module, Robinet *et al*., 2012) and economic impact (e.g. Waage *et al*., 2005; Soliman *et al*., 2015) are already available and could effectively be combined in the future.

Conclusions

This generic pathway model is useful to assess the probability of entry of forest pests with imported wood in Europe in the context of plant protection and prevention of pest introduction. Data uncertainty limits the application of pathway models in plant health practice. However, when used to compare different scenarios of regulation, it is possible to explore and rank the effectiveness of risk reduction options.

Supplementary data

Supplementary data are available at *Forestry* online.

Acknowledgements

The research described in this paper was financially supported by the European Food Safety Authority (EFSA) project Service contract CT/EFSA/PLH/2011/04: Lot 2 'Development of probabilistic models for quantitative pathway analysis of plant pests introduction for the EU territory'. The positions and opinions presented in this article are those of the authors alone and are not intended to represent the views or scientific works of EFSA. Special thanks are due to Olaf Mosbach Schultz, Giuseppe Stancanelli and

Tomasz Oszako for constructive feedback. We are also grateful to the panel of forestry experts and pest risk assessment experts with whom we discussed the structure of the wood pathway model during a workshop in September 2014 at the Forestry House in Brussels. We thank Jean-Marc Henin (Service public de Wallonie, Belgium), Harald Mauser (EFI, Belgium), Andrei Orlinski (EPPO, France) and Tomasz Oszako (EFSA, Italy) for insightful discussions; Cécile Robin (INRA, France) for information about interception of the oak wilt fungus in Europe; Jean-Luc Flot, Jean-Baptiste Daubree, Matthieu Vicaire and Aline Vinck (DGAL; French Ministry of Agriculture) for information about inspection procedures.

Conflict of interest statement

None declared.

Funding

Service contract (CT/EFSA/PLH/2011/04: Lot 2) on probabilistic pathway models.

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