Modeling disease expression of *Phytophthora ramorum* to estimate potential economic impacts in European forests

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The pathogen

- *Phytophthora ramorum* is a generalist, airborne plant pathogen, affecting over 170 plant species (EPPO, 2025; APHIS, 2024)
- Introduced to North America and Europe in the mid-1990s
  - Established in **forest** ecosystems and **nursery** industry (Harris et al., 2021; Defra, 2015; Webber, 2007; Rizzo et al., 2005)
- Causal agent of:
  - **Sudden Oak Death** in the US: mortality of million oaks and tanoaks (Frankel and Palmieri, 2014; Goheen et al., 2007; Rizzo et al., 2007)
  - **Sudden Larch Death** in the EU: extensive dieback of larch plantations (Beltran et al., 2024; Jung et al., 2018; Ministère de l'Agriculture et de la Souveraineté alimentaire, 2017; Brasier and Webber, 2010)
- Other important hosts: *Rhododendron,* European beech, various woody ornamentals (Jung et al. 2018; Brasier and Webber, 2010; Grünwald et al., 2008; Ivors et al., 2004)

Forest Research (n.d.)

Thomas Jung (n.d.)

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Significance

Reported damage costs in the forest industry:

- **Oregon**
  - US$21 million to US$1.24 billion over 20 years (Hall and Albers, 2009)
  - Annual harvest losses could reach US$100 million (Kliejunas, 2010)
- **California**
  - US$7.5 million for SOD management and US$135 million property value losses over 2010-2020 (Kovacs et al., 2010)
- **United Kingdom**
  - £4.2 million annual costs and £91.5 million cumulative losses for 2010-2017 (Eschen et al., 2023; Forestry Commission, n.d.)

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Regulatory status in Europe

2002 — Decision 2002/757/EC

Mandatory surveys in nurseries and natural environments

2004-2016 — Four amendments

- 2004/426/EC
- 2007/201/EC
- 2013/782/EU
- (EU) 2016/1967

***RAPRA project (2004-2007)**

2013 — EPPO A2 List

Presence in the EPPO region

2019 — Regulation (EU) 2019/2072

EU isolates:
A1 Quarantine pest (Annex II A)

2021 — Regulation (EU) 2021/2285

Non-EU isolates:
Regulated Non-quarantine Pest (RNQP, Annex IV)

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Motivation

- Lack of **quantitative assessment** of *P. ramorum* potential impacts on the EU forestry*
  - Only a qualitative assessment by the RAPRA project (Kehlenbeck, 2008)
- Lack of information on where *P. ramorum* **symptom expression** and **tree mortality** may occur in the EU
  - Previous research explored the potential distribution based on climatic suitability for establishment (Ireland et al. 2013; Venette and Cohen, 2006)

    Where are climatic conditions suitable for P. ramorum survival?

*or nursery industry

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Objective of the study

Assess the potential direct damage costs of *P. ramorum* in European forests

- Two ecologically and economically important tree genera:
  - **Larch** (*Larix* spp.)
    - Larch needles support higher sporulation rates of the EU1 lineage than *Rhododendron* (Harris and Webber, 2016)
  - **Beech** (*Fagus* spp.)
    - "the most successful Central European plant species" (Leuschner et al., 2006)
- We focus on regions where *P. ramorum* disease expression is most likely to occur, accounting for:
  - Climatic conditions
  - Host availability

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Modeling disease expression

CLIMEX niche model

- Refined **parameter values** for climatic suitability, **focusing on sporangia production**
- 515 unique *P. ramorum* **occurrence records** (globe) + 3569 records for Oregon
  - Only from **symptomatic trees**
- Updated climate dataset 'CliMond CM_TC10: World', 10-arc minute, centered in 1995, current climate (C. Duffy, unpublished data)

- **Model fitting was based on Europe and Oregon** (where EU1 lineage is reported)
- We retained grid cells with EI ≥ 26 (optimal conditions)

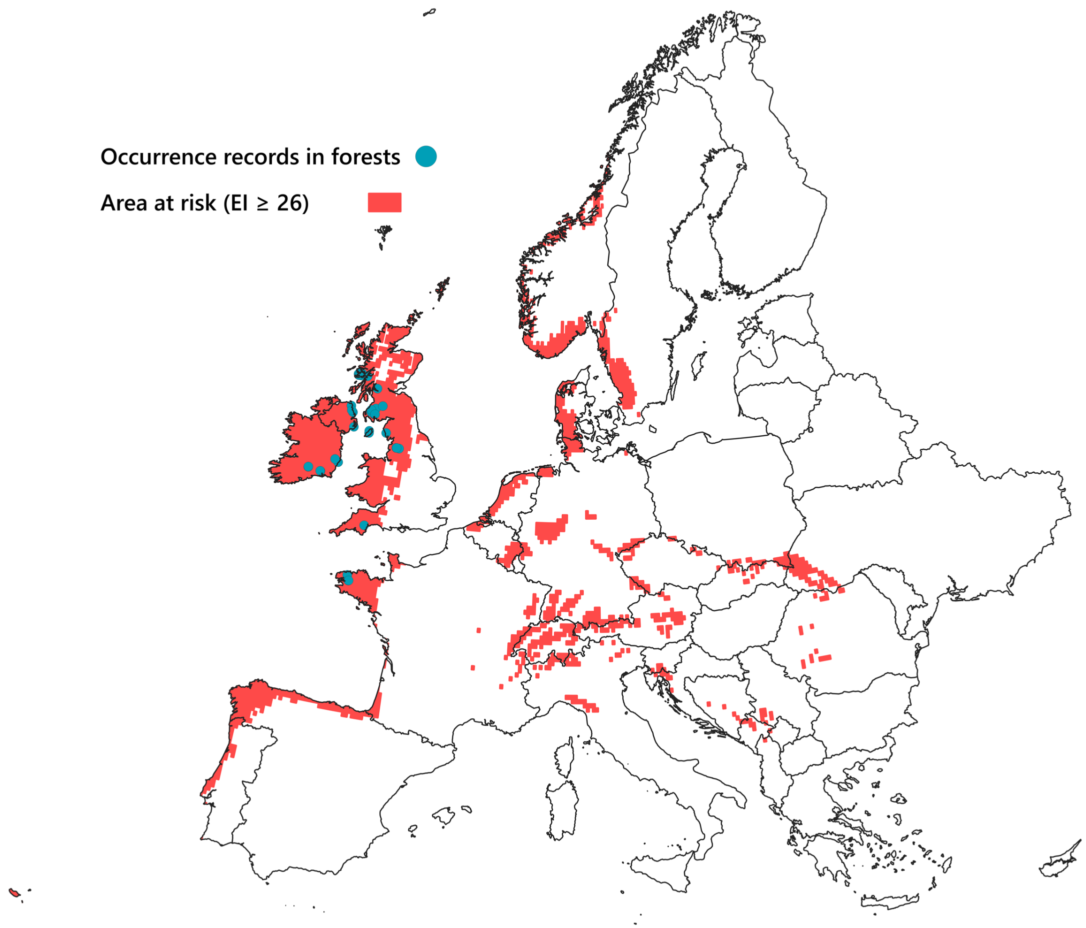

Figure 1. Binary climatic suitability map for *Phytophthora ramorum* in Europe based on refined CLIMEX parameter values and an Ecoclimatic Index threshold of EI ≥ 26. This threshold highlights areas with optimal conditions, where symptomatic infections and tree mortality are expected to occur.

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Area at risk

Table 1. Total land area of each country, area at risk (susceptible area) based on the CLIMEX model output (restricted to EI ≥ 26), and proportion of area at risk relative to the total country area.

Country	Country total area (km^2)	Area at risk (km^2)	Proportion of area at risk (%)
Austria	83 878	14 254	17
Belgium	30 667	7 758	25
Bulgaria	110 996	0	0
Croatia	56 594	1 847	3
Cyprus	9 253	0	0
Czech Republic	78 871	5 347	7
Denmark	42 925	13 611	32
Estonia	45 336	0	0
Finland	338 411	0	0
France	638 475	39 007	6
Germany	357 569	43 100	12
Greece	131 694	0	0
Hungary	93 012	0	0
Ireland	69 947	69 985	100
Italy	302 079	10 859	4
Latvia	64 586	0	0
Lithuania	65 284	0	0
Luxembourg	2 595	72	3
Malta	316	0	0
Netherlands	37 378	11 220	30
Norway	385 207	38 592	10
Poland	311 928	5 838	2
Portugal	92 227	12 651	14
Romania	238 398	4 740	2
Slovakia	49 035	3 757	8
Slovenia	20 273	1 293	6
Spain	505 983	35 888	7
Switzerland	41 285	20 996	51
Sweden	447 424	15 380	3
United Kingdom	243 610	139 577	57
Total	4 895 236	495 772	10

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Host availability

Distribution of tree species presence in Europe (Brus et al., 2012)

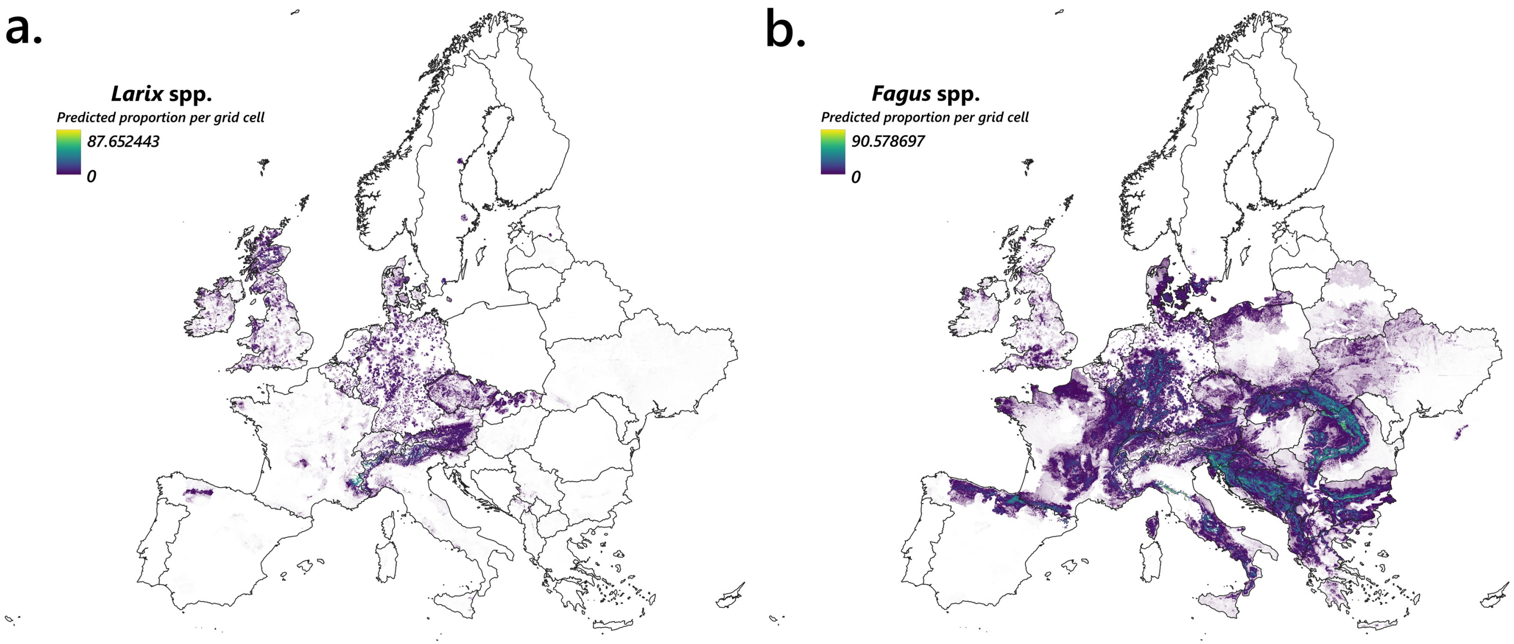

Figure 2. Predicted proportion of two primary forest hosts of *Phytophthora ramorum* in Europe at 1 km^2 **(a.)** *Larix* spp., and **(b.)** *Fagus* spp. (almost exclusively *F. sylvatica*; *F. orientalis* only occurs in the southeastern Balkans).

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Host availability

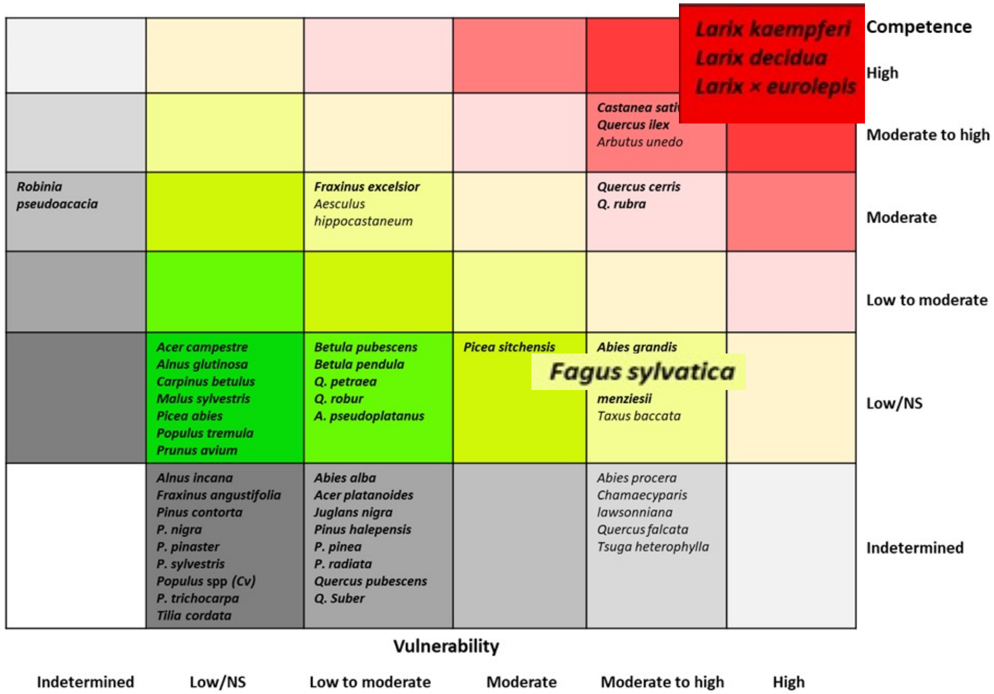

Figure 3. Classification of susceptibility (competence and vulnerability) to *Phytophthora ramorum* of forest tree species (ANSES opinion Collective expert appraisal report, 2018).

- **Larch** is highly susceptible (both **vulnerable** and **competent** host)
- **European beech** is highly **vulnerable** but not as competent (dead-end host)
  - **Need for transmissive leaf hosts in the proximity that produce sporangial inoculum** (Anonymous, 2007; Brasier et al., 2004)

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Host availability

- Composite binary map representing the distribution of **five key sporulating hosts**:
  - *Pseudotsuga menziessi* (Douglas fir)
  - *Fraxinus excelsior* (common ash)
  - *Castanea sativa* (sweet chestnut)
    - RPP threshold of ≥0.5 ("medium-high") species presence per grid cell (Beck et al., 2023)

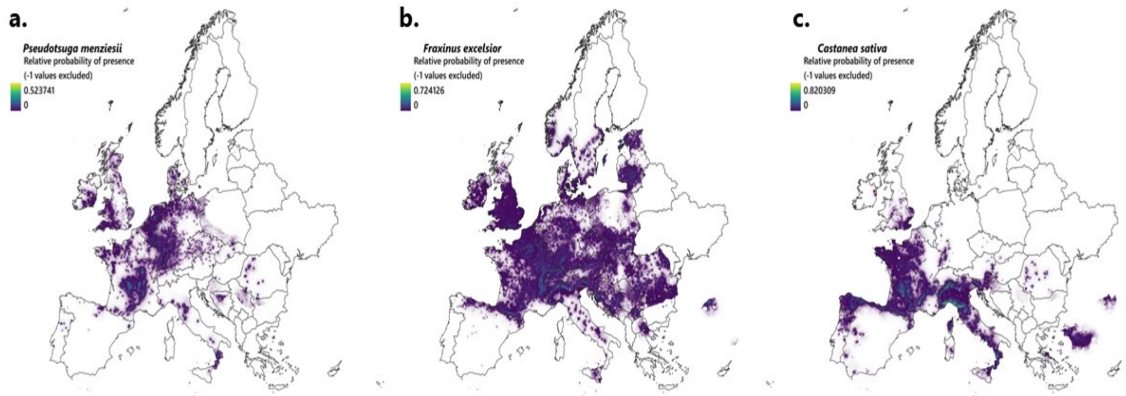

Figure 4. Relative probability of presence (RPP) of **(a.)** *Pseudotsuga menziessi* **(b.)** *Fraxinus excelsior,* and **(c.)** *Castanea sativa* in Europe. Each grid cell has a resolution of 1 km^2. Values of -1 (uncertain or no data) have been excluded (de Rigo et al., 2016a, 2016b, 2016c).

Host availability

- Composite binary map representing the distribution of **five key sporulating hosts**:
  - *Pseudotsuga menziessi* (Douglas fir)
  - *Fraxinus excelsior* (common ash)
  - *Castanea sativa* (sweet chestnut)
  - *Larix* spp. (larch)
  - *Rhododendron ponticum*

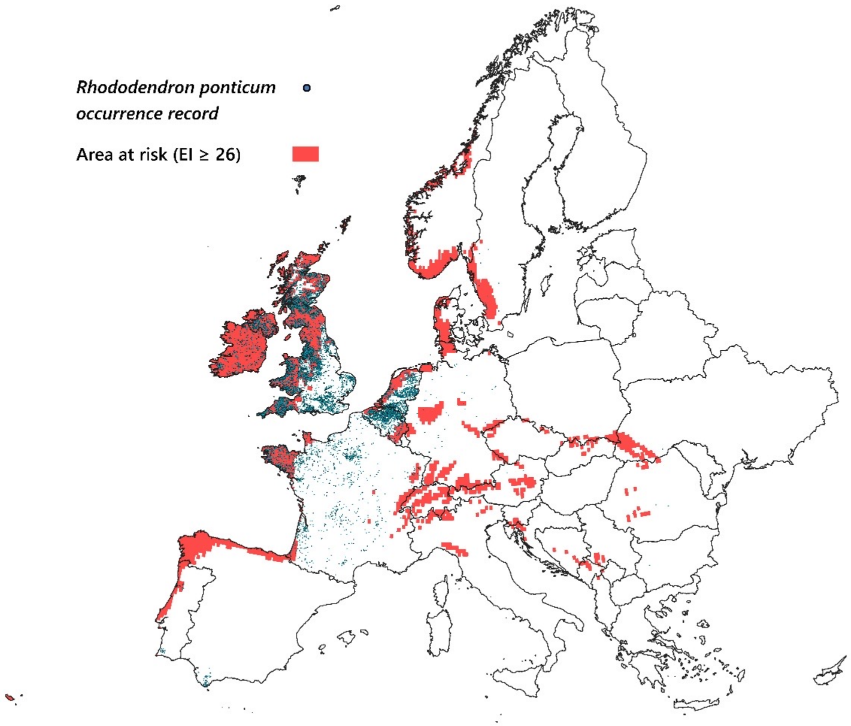

Figure 5. Occurrence records of *Rhododendron ponticum* (blue points) across Europe and projected risk area of *Phytophthora ramorum* disease expression (EI ≥ 26).

Area at risk

Table 2. Country-level distribution of *Larix* spp. and *Fagus* spp. in Europe, and their extent within climatically suitable zones (EI ≥ 26). For *Fagus* spp., the last column represents the subset where beech co-occurs with at least one sporulating foliar host (*P. menziesii*, *F. excelsior*, *C. sativa*, *Larix* spp., and *R. ponticum*).

Country	Total *Larix* spp. area (km^2)	*Larix* spp. area within EI≥26 (km^2)	Total *Fagus* spp. area (km^2)	*Fagus* spp. area with foliar host co-occurrence within EI≥26 (km^2)
Austria	**2 027**	652	**3 748**	336
Belgium	162	77	765	98
Bulgaria	9		**7 487**	
Croatia	0		**4 415**	
Cyprus				
Czech Republic	**1 009**	134	1 583	133
Denmark	278	42	1 148	8
Estonia	8		0	
Finland	0		0	
France	1 239	38	**13 482**	44
Germany	**3 021**	384	**16 224**	665
Greece	3		1 714	
Hungary	18		1 055	
Ireland	304	304	154	71
Italy	**2 795**	502	**8 003**	499
Latvia	7		2	
Lithuania	0		2	
Luxembourg	1		203	0
Malta				
Netherlands	187	3	131	3
Norway	0		10	0
Poland	21	6	3 369	18
Portugal	0		0	
Romania	3		**17 130**	
Slovakia	410	55	**4 091**	207
Slovenia	119		**4 043**	
Spain	150		**4 085**	2
Switzerland	717	281	2 108	188
Sweden	151		638	0
United Kingdom	**2 285**	1 745	1 011	304
Total	14 926	4 223	96 599	2 577

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Spread

– Radial range expansion spread model (Schneider et al., 2020; Robinet et al., 2012; Wesseler and Fall, 2010):

$$IA_t = \begin{cases} (rr \cdot t)^2 \cdot \pi & if IA_t < SA \\ SA & otherwise \end{cases}$$

where,

IA_t = affected area after t years (km^2)

rr = radial range expansion rate (km yr^{-1}); we used three rates (observed dispersal distances in Oregon) (Peterson et al., 2015):

Slow (0.25 km yr^{-1}), Moderate (2.01 km yr^{-1}), and Fast (4.26 km yr^{-1})

SA = susceptible area (km^2)

– For "**EU as a single unit**" we use **average host proportions** across the study area to obtain the host area affected ($IA_{t,h}$): 0.43% for larch; 3.19% for beech.

– For **country-level**, we use the **host proportion of each country** relative to its susceptible area (SA_i) to obtain host area affected in country i ($IA_{t,h,i}$)

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Host tree mortality

Mortality rate scenarios:

- "EU as a single unit" → 10%, 30%, 50%, 70%, 90%
- Country-level → 10%, 50%, 90%

We assume a **linear delay in mortality** between the initial year of infestation and subsequent tree mortality:

$$\boldsymbol{m_t} = \begin{cases} \boldsymbol{m} & \boldsymbol{if\ t \geq d_h} \\ \boldsymbol{m \cdot \frac{t}{d_h}} & \boldsymbol{if\ t < d_h} \end{cases}$$

where,

$\boldsymbol{m_t}$ = mortality rate (%) at year *t*

$\boldsymbol{m}$ = maximum mortality rate

$\boldsymbol{d_h}$ = delay for each host *h* until *m* is reached. We set d_h = 4 for larch (Dun et al., 2024; Dun, 2021), and d_h = 6 for beech (due to lower susceptibility compared to larch)

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Direct economic impact

- **Partial budgeting, "no-control" scenario** (Soliman et al., 2015; Kriticos et al., 2013; Wesseler and Fall, 2010)
  - Persistent and unmanaged spread until full occupancy of the susceptible area
  - Direct economic impacts → loss in standing stock (timber)
- The potential direct economic damage costs ($\boldsymbol{DD_{h,t}}$) for host *h*, at year *t* are computed as:

$$DD_{h,t} = IA_{t,h} \cdot VT_h \cdot m_t \cdot p_h$$

where,

$IA_{t,h}$ = affected host area (km^2) at year *t*

VT_h = average timber volume (m^3/km^2) by host *h* (23830 m^3/km^2 for larch; 23047 m^3/km^2 for beech) (Schelhaas et al., 2006 - EFISCEN Inventory Database)

m_t = mortality rate (%) at year *t*

p_h = average timber market price (€59.6/m^3 for larch; €74.3/m^3 for beech) (Forest Research, 2025; UNECE, 2023)

Direct economic impact

– Future economic losses were discounted to their present values:

$$PVD_h = \frac{DD_{h,t}}{(1+r)^t}, \qquad t = 1, 2, 3 \dots$$

where,

PVD_h = present value of direct damage costs per host *h*

$(1+r)^t$ = discount factor, where *r* = 4.49% (average discount rate for 2023-2024 for most EU MSs; European Commission, n.d.)

– The Average Annual Costs (AAC_h) were computed as:

$$AAC_h = r \cdot \sum_{t=1}^{\infty} PVD_h$$

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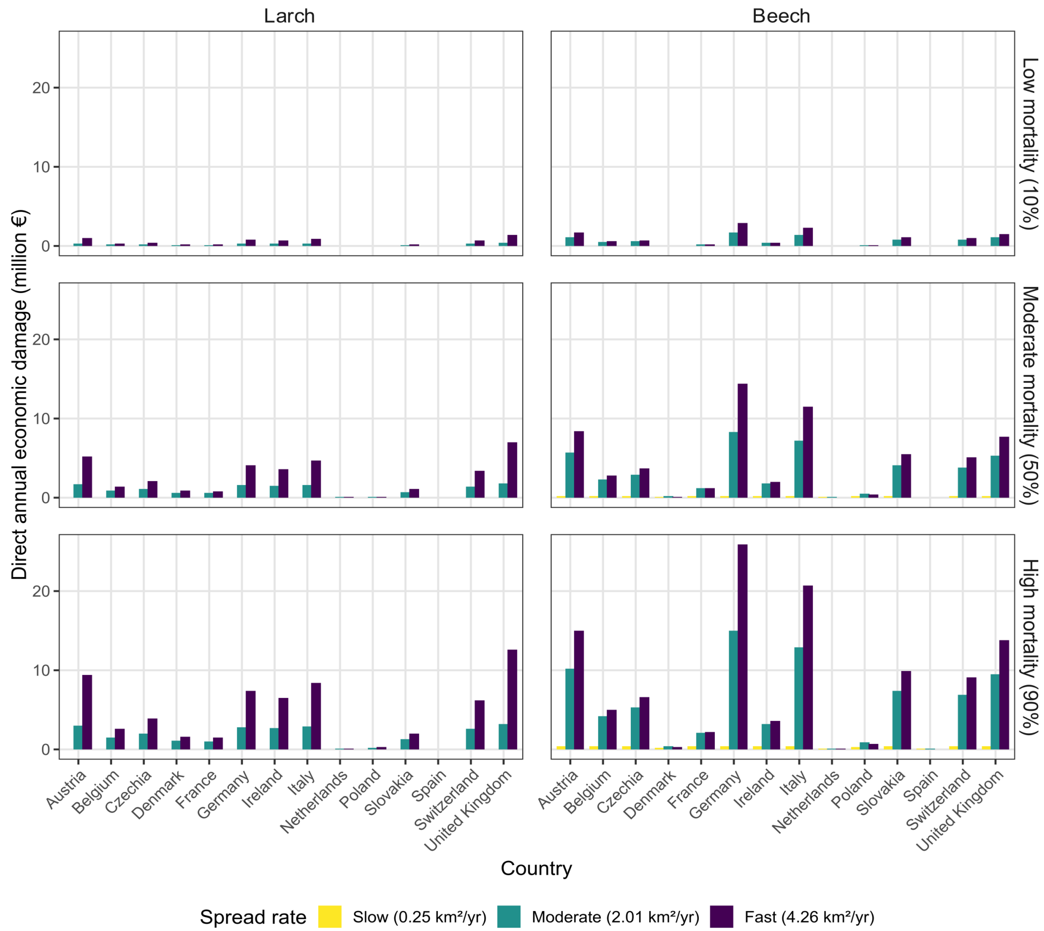
Direct economic impact

Mortality rate (%)	Spread rate (km yr^{-1})	Larch (€ million yr^{-1})	Beech (€ million yr^{-1})
10	**0.25**	0.2	1.3
	2.01	6.6	12.4
	4.26	13.1	14.5
30	**0.25**	0.5	3.9
	2.01	19.8	37.1
	4.26	39.2	43.6
50	**0.25**	0.8	6.6
	2.01	33.1	61.8
	4.26	65.3	72.7
70	**0.25**	1.1	9.2
	2.01	46.3	86.5
	4.26	91.4	101.8
90	**0.25**	1.4	11.8
	2.01	59.5	111.2
	4.26	117.5	130.9

Table 3. Average annual direct damage costs (€ million yr^{-1}) due to *Phytophthora ramorum* for *Larix* spp. and *Fagus* spp. in Europe under a no-control scenario, for different mortality and spread rate scenarios. Host proportions for the EU as a single unit aggregation equal 0.43% for larch and 3.19% for beech (on the total land area). We used an average timber price of €59.6/m^3 for larch (softwood sawlog) and of €74.3/m^3 for beech (roundwood logs).

Direct economic impact

Figure 6. Average annual direct damage costs (€ million yr^{-1}) due to *Phytophthora ramorum* for *Larix* spp. and *Fagus* spp. by country, under a no-control scenario, for three spread rates. Timber prices used: €59.6/m^3 for larch and €74.31/m^3 for beech. Countries with zero estimated losses across all scenarios and for both hosts – Bulgaria, Croatia, Estonia, Finland, Greece, Latvia, Lithuania, Luxembourg, Norway, Portugal, Romania, Slovenia, and Sweden – do not appear in this figure.



Summing up…

- **Suitable areas** for *P. ramorum* disease expression are mainly clustered **along the Atlantic façade, parts of the Alps, and southern Scandinavia**
  - The UK accounts for more than 42% of the climatically suitable zone
- **Uneven distribution of economic losses in the EU**:
  - **Larch**: Highest risks in the UK, Italy, and Germany (72% of total losses)
    - €106-117 million annual losses under worst-case scenario assumptions
  - **Beech**: Highest risks in Italy, Germany, and Austria (70% of total losses)
    - €96-130 million annual losses under worst-case scenario assumptions

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Take home message

- ***P. ramorum* is already widespread in nurseries** across the European continent (EPPO, 2025; Jung et al., 2016)
    - As the pathogen spreads via nursery trade, the **likelihood of spillover infestations** into natural parks, gardens, and forest stands **increases**.
    - **Strengthening risk-based inspections**, **enhancing monitoring efforts**, and implementing **Best Management Practices in nurseries** remain key strategies against further pathogen introductions.
- After **three decades of *P. ramorum*** presence in Europe, a large-scale **invasion of Mediterranean forests** appears **unlikely**. **In contrast**, in the **temperate regions** of the continent, extensive larch and beech stands **remain vulnerable**.

Limitations

- Only accounted for natural dispersal
  - Human-mediated dispersal is also an important pathway (e.g., nursery trade) (Grünwald et al., 2012; Cushman and Meentemeyer, 2008)
- Two forestry hosts
  - A broader range of economically important hosts are susceptible to *P. ramorum* (e.g., *Camellia, Viburnum,* rhododendron, etc.) (EPPO, 2025; VKM et al., 2023; Anonymous, 2007)
- "No-control" scenario
  - Worst-case scenario, but does not reflect the ongoing management interventions against *P. ramorum* in the UK, Ireland, and France
- Direct impacts, constant standing stock and prices

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(not an extensive list)

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Thank you!

Get in touch!

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Appendix

Parameters	Description	Unit	Venette and Cohen (2006)	Ireland et al. (2013)	Current study
DV0	Limiting low temperature	°C	2	0	7
DV1	Lower optimal temperature	°C	17	18	14
DV2	Upper optimal temperature	°C	25	22	17
DV3	Limiting high temperature	°C	30	30	24
SM0	Limiting soil moisture		0.4	0.2	0.6
SM1	Lower optimal moisture		0.7	0.7	0.8
SM2	Upper optimal moisture		1.3	1.3	1.3
SM3	Limiting high moisture		3	2	2
TTCS	Cold stress temperature threshold	°C		-8	-8
THCS	Cold stress temperature rate	week^{-1}		-0.02	-0.02
DTCS	Cold stress day-degree temperature threshold	°C	15		
DHCS	Cold stress day-degree rate	week^{-1}	-0.0001		
TTHS	Heat stress temperature threshold	°C	30	31	25
THHS	Heat stress rate	week^{-1}	0.005	0.03	0.005
SMDS	Dry stress threshold		0.2	0.2	0.2
HDS	Dry stress rate	week^{-1}	-0.005	-0.005	-0.005
SMWS	Wet stress threshold		2.5	2	2
HWS	Wet stress rate	week^{-1}	0.002	0.002	0.002

Table. CLIMEX parameter values used for *Phytophthora ramorum* in the literature and the current study. Parameter values without units are dimensionless indices of plant available soil moisture.