NeoBiota 84: 281–317 (2023)
doi: 10.3897/neobiota.84.95687
https://neobiota.pensoft.net

REVIEW ARTICLE

A peer-reviewed open-access journal
NeoBiota
Advancing research on alien species and biological invasions

Eradication programs against non-native pests and pathogens of woody plants in Europe: which factors influence their success or failure?

Sofia Branco[1], Jacob C. Douma[2], Eckehard G. Brockerhoff[3], Mireia Gomez-Gallego[4], Benoit Marcais[4], Simone Prospero[3], José Carlos Franco[1], Hervé Jactel[5], Manuela Branco[1]

1 *Centro de Estudos Florestais, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, 1349-017, Lisbon, Portugal* **2** *Centre for Crop Systems Analysis, Wageningen University, Wageningen, Netherlands* **3** *Swiss Federal Research Institute WSL, Zürcherstrasse 111, CH-8903, Birmensdorf, Switzerland* **4** *Université de Lorraine, INRAE, UMR IAM – Interactions Arbres-Microorganismes, Nancy, F-54000, France* **5** *INRAE, University of Bordeaux, Biogeco, F-33612, Cestas, France*

Corresponding author: Sofia Branco (sofiabranco@isa.ulisboa.pt)

Academic editor: Andrea Battisti | Received 28 September 2022 | Accepted 6 March 2023 | Published 18 May 2023

Citation: Branco S, Douma JC, Brockerhoff EG, Gomez-Gallego M, Marcais B, Prospero S, Franco JC, Jactel H, Branco M (2023) Eradication programs against non-native pests and pathogens of woody plants in Europe: which factors influence their success or failure? In: Jactel H, Orazio C, Robinet C, Douma JC, Santini A, Battisti A, Branco M, Seehausen L, Kenis M (Eds) Conceptual and technical innovations to better manage invasions of alien pests and pathogens in forests. NeoBiota 84: 281–317. https://doi.org/10.3897/neobiota.84.95687

Abstract

When a non-native species succeeds in establishing in a new habitat, one of the possible responses is to attempt its eradication. In the present study, we analysed European eradication programmes against non-native pests and pathogens of woody plants (PPWP) from 1945 to date. Our main goal was to identify which factors affect the success of an eradication programme, reinforcing guidelines for future eradication of PPWP. Data on eradication campaigns were obtained from online databases, scientific and grey literature, and Plant Protection Organizations' reports. Factors influencing eradication success for both arthropods and pathogens were analysed with LASSO regression and decision tree learning.

A total of 848 cases officially declared as eradication attempts were documented in our database (8-fold higher than previous reports). Both the number of programmes and their rate of success increased sharply over the last two decades. Only less than 10% of the non-native organisms affecting woody plants were targeted for attempted eradication despite the high economic and ecological impacts caused by some species for which no efforts were undertaken. Almost one-third of the officially declared cases of eradication concerned organisms that were still restricted to the material with which they were introduced. For these cases the success rate was 100%. The success rate of established species was only 50% for arthropods and 61% for pathogens. The spatial extent of the outbreak was the factor that most affected the outcome of eradication campaigns. The eradication success decreased abruptly above 100 ha for arthropods and 10 ha for pathogens. Additionally, other variables were shown to influence the outcome of eradication programmes, in particular the type of environment, with the highest eradication success rate found in nurseries and glasshouses, with successful outcomes increasing if quarantine measures were applied and when monitoring included asymptomatic plants. Particular species traits may reduce eradication success: parthenogenetic arthropods, saprotrophic pathogens, wind dispersal, the possibility to remain asymptomatic indefinitely, and the existence of resting spores or stages.

In conclusion, small affected areas, quick response, and efficient implementation of quarantine restrictions, together with particular species traits, may allow a high probability of eradication success. Preparedness at the country and European level would allow a larger number of target species to be included in future eradication programmes.

Keywords
Biological invasions, pest and pathogen management, surveillance

Introduction

The rate of biological invasions has sharply increased over the last century mainly due to globalization trends, including intensified travel, population growth, migratory fluxes, liberalisation of international trade and the consequent increase in global trade (Pimentel 2002; Ghelardini et al. 2016; Brockerhoff and Liebhold 2017; Seebens et al. 2017). Additionally, global climate change may also contribute to the increase of invasions by alien species (Sala et al. 2000). Forest ecosystems, including those close to nature, forest plantations, and urban forests have been highly affected by invasive species (Liebhold et al. 2012; Desprez-Loustau et al. 2016). The resulting negative impacts on biodiversity, ecosystem services, socio-economy, and human health provide compelling reasons to develop and implement the best management strategies to prevent biological invasions and to mitigate their consequences. In optimal circumstances, we need to know how to avoid these consequences through prevention or prompt eradication.

The first line of defence against biological invasions relies on preventing the introduction of non-native organisms into a new area. This is considered the most effective strategy for dealing with invasive species and is achieved through international quarantine measures, such as banning the import of goods from contaminated regions or requiring that these goods can only be imported after appropriate phytosanitary treatments (Haack et al. 2014; Sequeira and Griffin 2014; Sikes et al. 2018). Despite the biosecurity systems adopted by many countries to detect and intercept potentially dangerous organisms arriving through trade and travel routes (Sequeira and Griffin 2014), a huge proportion of them remains undetected (Brockerhoff et al. 2006; Meurisse et al. 2019). The situation is aggravated by the fact that phytosanitary measures generally target only known species on quarantine lists (Desprez-Loustau et al. 2016). Luckily, not all invading populations succeed in establishing in non-native habitats. In fact, most invasions fail, either because the new habitat climate is unsuitable or host plants are not available (Paap et al. 2022). Also, low-density populations may be subject to extinction due to environmental and demographic stochasticity and to Allee effects

(Liebhold and Bascompte 2003). Still, many populations of non-native organisms succeed to overcome phytosanitary measures and become established and potentially invasive in a new region. In such cases, adequate surveillance systems may allow for their early detection and implementation of appropriate suppression measures (Liebhold and Kean 2019). Eradication may then be the best option for alien species for which high impacts are expected, preventing the indefinite accumulation of deleterious effects and economic impacts. However, the costs of eradication may exceed its benefits if the area colonised by an established invading population is too large, requiring substantial resources while the likelihood of eradication success is low (Tobin et al. 2014). In such cases, containment might be a better alternative to stop or slow down the spread of an invasive organism (Myers et al. 2000; Brockerhoff et al. 2010; Goheen et al. 2017).

Several factors are well accepted as contributing to the success of an eradication programme, among which, early detection and quick response are crucial (Brockerhoff et al. 2010; Pluess et al. 2012b; Liebhold et al. 2016; Hansen et al. 2019). Further, enough resources must be allocated from the start to the end of the program. Funding agencies or governments may be inclined to abandon the efforts once the pest or pathogen densities are no longer causing significant economic or ecological impacts, although invasive populations may decline naturally towards extinction once they are suppressed below an Allee effect threshold (Simberloff 2002; Liebhold and Tobin 2008; Liebhold et al. 2016). In addition, eradication measures are doomed to fail if some stakeholders allow the invaders to persist on their properties. In these cases, mandatory cooperation is required to carry out the required procedures. Also, public awareness-raising campaigns are needed to increase community support (Pluess et al. 2012b). The availability of effective surveillance tools is crucial as they determine the capacity to accurately delimit the infested area, even when populations are at low densities. For instance, eradication of an invasive insect is estimated to be 20-fold more likely to succeed when an attractant is available (Tobin et al. 2014; Liebhold et al. 2016; Suckling et al 2021). Finally, success depends also on the availability of highly effective eradication techniques, either increasing mortality or reducing reproduction. The combination of more than one eradication technique is considered to guarantee better results (Blackwood et al. 2012, 2018).

Previous reviews have attempted to better identify which factors determine the success of an eradication programme (e.g., Brockerhoff et al. 2010; Pluess et al. 2012a, b; Tobin et al. 2014; Smith et al. 2017). Based on a data set of 136 eradication campaigns against invasive alien invertebrates, plants and pathogens, Pluess et al. (2012a) identified the area infested at the beginning of the eradication programmes as the sole factor significantly determining the success of eradication attempts. In another study, Pluess et al. (2012b), using a dataset of 173 eradication campaigns against 94 species worldwide (51% of which were successful), identified several other factors influencing eradication success and differences among taxonomic groups. Bacteria and viruses were the most likely, and fungi were the least likely to be eradicated. Infested area, reaction time, and application of sanitary measures, such as the prohibition of movement of possibly infested material or equipment, most affected the success or failure of programmes. Eradication in man-made habitats was also more likely to succeed than campaigns carried out in semi-natural or natural habitats. In another study, Tobin et al. (2014) analysed 672 programmes targeting 130 arthropod species. The authors also identified a negative association between the success rate and the size of the infested area. However, their analysis indicated that the detectability of the target pest was one of the most critical factors associated with eradication success. The method of detection and the primary feeding guild of the target species also contributed to the success or failure of eradication campaigns. A higher success rate was observed for Diptera and Lepidoptera and a lower one for Coleoptera, which was attributed to the existence of effective and cost-efficient semiochemical lures. Noteworthy was that data used by Tobin et al. (2014) were compiled into a web-based database – the Global Eradication and Response DAtabase ("GERDA", Kean et al. 2022 available for public consultation. This database includes information on eradication programmes targeting terrestrial arthropods and plant pathogens in 108 countries, and by the end of 2021, 1048 eradication programmes were reported. For pathogens, Smith et al. (2017) analysed GERDA data from 190 plant pathogen eradication programmes to identify treatment efficiency and found *in vitro* tissue culture in combination with thermotherapy as the most successful, to eradicate viral or bacterial pathogens. Although the information in GERDA is extremely valuable for accessing global trends and drivers of eradication success and failure, both the distribution of invasive pests and pathogens and the number of eradication attempts have continued to increase far beyond those reported in this database (Suckling et al. 2021).

In the present study, a systematic analysis of European eradication programmes against non-native pests and pathogens of woody plants (PPWP) is addressed. We note that in some cases of pests or pathogens, the species might be native to one region of Europe but non-native to other regions. An example is the oak processionary moth (*Thaumetopoea processionea*) which is native to Central Europe and non-native in the UK. For pathogens there are a few cases for which the species origin was unknown. The main goal of our analysis was to identify key determinants of eradication success/failure against non-native PPWP in the European region (considered all countries in the European Continent except for Russia) so that guidelines can be developed for countries that are subject to EU legislation. Explanatory variables applicable for the European region, and countries subject to common legislation, may differ from other world regions, so the results of previous studies may not be able to fully explain the causes of success or failure of eradication programmes in this specific region. To this aim we collected and made available a comprehensive dataset of eradication attempts against PPWP for the European region, with data not previously available in other databases as GERDA. A new methodological approach was also proposed, based on LASSO regression and decision trees.

Methods

Data sources

To identify introduced species of insects associated with woody plants in Europe, we used the list provided in Roques et al. (2016) complemented by a search of EPPO reporting services (1974–2021) and a search on Google scholar and Web of Science with many combinations of the keywords "alien (or non-native, or exotic) arthropod (or insect) species Europe", "alien insect arthropod (or insect) + each European country", "first report arthropod (or insect) Europe", "first report arthropod (or insect) + each European country". For pathogens, a list of invasive forest fungi and oomycetes detected in Europe from 1800 to 2008 was retrieved from Santini et al. (2013). Data on introduced species from 2008 until 2021 was retrieved from EPPO reporting services. We then looked for eradication programmes against each species. To identify eradication attempts against all pathogen groups (bacteria, nematodes, fungi + oomycetes and viruses or viroids), the EPPO A1 and A2 and alert lists were initially consulted for pathogens of woody plants, and all eradication programmes were searched in EPPO reporting services (1974–2020). To identify eradication attempts for both arthropods and pathogens, the EPPO Global Database (https://gd.eppo.int) was the main online database we consulted. This information was complemented with information from GERDA – Global Eradication and Response Database (http://b3.net.nz/gerda/index.php) and a search in the scientific and grey literature, including works published in scientific journals, conference proceedings, presentations, and books. Published information was searched through Google Scholar and Web of Science, using the "species name", "alien arthropod", alien insect", "plant (or tree) pathogen", "Europe (or individual countries)" and the words "eradication" and "containment" as keywords, in different combinations. Additionally, eradication reports or technical reports, pest alerts, and press releases from National and Regional Plant Protection Organizations (**NPPOs** and **RPPOs**) were consulted. The time range for eradication attempts ranged from 1945 to 2021. Finally, additional information was kindly provided by some countries' NPPOs and RPPOs. For detailed information on some of the eradication cases which were not available in the English language, advanced searches were conducted on Google by introducing the species name and limiting results to the country for which information was missing. The information and reports obtained from these searches were then translated to extract the information required for our analyses.

Terms criteria

Non-native and invasive species

We used the following definitions for the terms:

- Non-native (=non-indigenous) – an introduced species that does not occur naturally in an area, but was introduced as the result of deliberate or accidental human activities, or expanded its range as a result of human activities.
- Invasive – a species whose introduction and dispersal threatens ecosystems, habitats or species, with socio-economic and/or environmental damage and/or harm to human health (CBD 2008)
- Emerging – a species that has increased its population with time becoming injurious.

According to (ISPM no. 5) the term "alien" only applies to individuals or populations that have entered by human agency into the area. However, in some cases it is not clear whether the introduction was human-mediated or just the result of natural spread. Here we consider all the non-native species independently of the introduction pathways, which in some cases are unknown.

For both arthropods and pathogens, the full list of species for which eradication was considered also includes species that are native to parts of Europe, but non-native in the regions where eradication was attempted. For arthropods these include the species *Dendroctonus micans* (Kugelann), *Ips typographus* (Linnaeus), *Lymantria dispar* (Linnaeus) *Thaumetopoea processionea* (Linnaeus) and *Thaumetopoea pityocampa* (Denis & Schiffermüller) and for pathogens the species *Phytoplasma mali* (Seemüller & Schneider, 2004), *Phytoplasma pyri* (Seemüller & Schneider, 2004), Plum pox virus and *Dothistroma septosporum* (Dorogin) Morelet. For three species of fungi the origin is still unknown: *Cylindrocladium buxicola* (Henricot & Culham, 2002), *Dothistroma pini* Hulbary, and *Plenodomus tracheiphilus* (Petri) Gruyter, Aveskamp and Verkley. We included in the analysis all the pathogens for which an eradication programme was implemented, including non-native (either for Europe or for the region where the programme was implemented) and species of unknown origin.

Established and post-border interceptions

Although commonly referred to as "under eradication" in EPPO and NPPO reports and GERDA, some of the cases reported as "subject to eradication" corresponded to measures taken against a detected pest or pathogen that was still restricted to the material with which it was introduced or for which only adult insects were found. We considered these cases as post-border interceptions. According to FAO (2019), an establishment corresponds to a reproducing population that has already spread from the material in which it was introduced and is expected to perpetuate for the foreseeable future.

For both arthropods and pathogens, an establishment was considered "new" to an area if no report of the particular species was made previously from that area. Also, we considered an establishment as new if it occurred in an area previously infested, but where the population was assumed to have been previously eradicated, with an official declaration of eradication by the relevant authorities. For arthropods, we also considered an establishment as new when it was located within an isolated demarcated area – to guarantee non-overlapping demarcated areas between newly detected establishments. For pathogens, the demarcated area of the infected plants was often not reported, due to the high number of reported cases in nurseries and associated commercial confidentiality. We thus considered a new establishment when the pathogen was first detected in a given NUTS III unit (Nomenclature of territorial units for statistical purposes, created by Eurostat).

Infested/infected and demarcated areas

The infested/infected areas comprised the limited areas determined by the pest or pathogen presence. When the extent of these areas was numerically reported, we used the published values (in hectares). When only distribution maps were available, affected areas were measured using either ArcGIS online measure tool or by transposing the points of infested/infected plants to Google Earth Pro (version 7.3.4.8642) and measuring the area delimited by them.

The demarcated area corresponds to the area legally established by each national plant protection organization (NPPO) as subject to eradication and containment measures, and usually comprises an infested core zone, where the pest is present, and a buffer zone around the infested zone. We followed the ISPM no. 5 definition of a buffer zone (FAO 2019).

Datasets

A comprehensive database was constructed including the following information for each case (when available): i) species under eradication, ii) detection date, country, and location; iii) detection method, passive surveillance (i.e. casual observations reported by researchers, technician or citizens) or official survey conducted with that purpose; iv) establishment status (established or post-border interception); v) affected hosts; vi) host type (broadleaves, conifers, palms), vi) control methods used (chemical, host removal, biological, traps); vii) size of the infested area (as exact area information was not always available we defined it in categories ≤ 1 ha, > 1 ≤ 10, > 10 ≤ 100, > 100 ≤ 1000 or > 1000 ha); viii) environments infested (urban/peri-urban, protected green-houses, countryside); ix) climate, categorized as Temperate, Mediterranean or Continental according to Köppen classification system (Peel et al. 2007); x) programme start year, last detection, and date of eradication declared; xi) public education, and xii) the outcome, i.e. legal status (eradicated, under eradication, failure to eradicate). Categories used in each parameter are also described in Table 1 and Suppl. material 1.

For some parameters, information was not always available and so we defined additional criteria. For the establishment status, the pest or pathogen was considered established unless stated that it was found only on the imported plant material and not in other plants at that time or posteriorly to the destruction of the original plant material. For the outcome, we consider a pest or pathogen to be eradicated when there was an official confirmation, or if no further future records were reported. If the official status changed to restricted distribution or containment and it continued to spread, it was considered a failure. Otherwise, it was still considered under eradication.

For pathogens, in many cases, the exact location of detection was not known and thus, we used the NUTS3. If the pathogen was no longer detected during the next two-yearly surveys (or two consecutive surveys when surveys were separated by more than one year) in that region, it was considered eradicated.

Table 1. Variables used as predictors in the modelling analysis and their categories.

List of predictors for arthropods	
Control	
Control methods	Host removal; other (including methods such as chemical, biological or traps; or combo (combination of host removal with other methods)
Restrictions on the movement/ quarantine	Yes; or no
Monitoring method	Visual observation; or visual observation + traps
Response time	≤1 year; or > 1 year
Use of a semiochemical lure	Yes; or no
Environment	
Location	Island; or mainland
Initial infested area	≤1 ha; > 1 ≤ 10 ha; > 10 ≤ 100 ha; > 100 ≤ 1000 ha; or > 1000 ha
Main type of environment affected at start of program	Confined (nurseries, glasshouses and garden centers); urban/peri-urban (private and public gardens, along roadsides of habited areas, industrial areas, etc.); or countryside (orchards and woodlands or forests)
Climate	Mediterranean; Temperate; or Continental (according to Köppen classification)
Species traits	
Host type	Broadleaf; conifer; or palm
Phytophagous specialisation	Monophagous; oligophagous; or polyphagous
Feeding behaviour	External; or Internal feeders
Body size	small (≤ 2 mm); medium (> 2 mm ≤ 10 mm); or large (> 10 mm)
Voltinism	Multivoltine; univoltine; or semivoltine
Main reproduction method	Parthenogenesis; or sexual
Yearly flight duration	< 4 months; ≥ 4 months < 9 months; or ≥ 9 months
Existence of resistant stages	Yes; or no
List of predictors for pathogens	
Control	
Control methods	Host removal or combo (combination with other methods such as chemical or biological)
Restrictions on the movement/ quarantine	Yes; or no
Preventive felling conducted	Yes; or no
Surveys at least annual	Yes; or no
Response time	≤ 1 year or > 1 year
Environment	
Location	Island or mainland
Initial infested area	≤1 ha; > 1 ≤ 10 ha; > 10 ≤ 100 ha; > 100 ≤ 1000 ha; or > 1000 ha
Main type of environment affected at start of programme	Confined (nurseries, glasshouses and garden centers); urban/peri-urban (private and public gardens, along roadsides of habited areas, industrial areas, etc.); or countryside (orchards and woodlands or forests)
Native susceptible hosts in the area	Yes; or no
Species present in adjacent NUTSIII	Yes; or no
Climate	Mediterranean; Temperate; or Continental (according to Köppen classification)
Species traits	
Host type	Broadleaf; broadleaf + conifer; or conifer
Group	Fungi/oomycete; bacteria; nematode; or virus/viroid
Host range	Specialist (one or a few taxonomically related species); or generalist (which infect multiple hosts, and are transmitted efficiently in hosts from different species, often from unrelated taxa)
Incubation period	Time since infection until symptom development: ≤ 1 month; > 1 ≤ 12 months; or > 12 months
Possibility to remain asymptomatic for long periods or indefinitely	Yes; or no
Sporulation/replication ability	High; or low
Existence of resting spores or stages	Yes; or no
Main dispersal mechanism	Wind; biotic vectors; or water
Possible saprotroph	Yes; or no

Some of this information was used only for descriptive analysis whereas other parameters were used in the modelling analysis (Table 1). To obtain a sufficient number of replications per level in a factor, some levels were merged. Cramér's V correlation between variables was estimated with the software package R, for the cases for which information for all the variables were available. (Suppl. material 2).

Statistical modelling

The statistical modelling aimed to predict the probability that the species became established (i.e., no longer found only on primary material) and next, once established, the probability of successful eradication as a function of different explanatory variables. Three main categories of factors were distinguished: i) control options, ii) characteristics of the environment/location of the outbreak, and iii) biological traits of the species. All analyses were performed for arthropods and pathogens separately.

The combined effect of predictors on the probability of eradication successes

When testing how and which combination of predictors affect eradication success, we employed two different statistical methods: LASSO regression and regression trees. Both methods have two features that are important for our analysis: 1) they can handle collinearity between predictors – which is important because some variables might be confounded, for example because a certain management strategy is predominantly applied to particular groups of taxa, and 2) they both select variables based on the ability of the model to predict new outbreak cases (cases that were not seen by the model during the training phase through so-called holdout-validation). The LASSO binomial regression model adds a penalty that scales with the size of the regression coefficient. As a result, the parameter estimates will become smaller, and, importantly, the parameter values of the non-important predictors become zero (Tibshirani 1996). A range of penalties was tested and the penalty that minimises the deviance in the hold-out sample was chosen as optimal. Currently, to the best of our knowledge, no software package exists that performs LASSO regression with random effects. Therefore, for species that had five or more records, a species-specific fixed effect was added to account for inherent differences across species. Regression tree analysis was also employed to identify the main factors that explain eradication success. Regression tree analysis builds a decision tree by splitting the data into branches, and partitioning the data into smaller groups as the tree branches branch out. Each split (branching) represents a split in the explanatory variable with a given probability. The trees are optimized and pruned such that the smallest cross-validation error is obtained. As splits can be different from one branch to another, one can take the interaction between variables into account. In this analysis, every species was given equal weight and thus the records of the same species were weighted by the inverse of the number of records per species. Both methods were used to explain factors that explain the establishment and the eradication success of a species. All methods were fitted in the software package R using the packages 'glmnet' for the LASSO regression, and ''rpart, "partykit"' for the tree regression, respectively.

Results

Descriptive analysis

Eradications and post-border interceptions

A total of 848 cases officially declared as eradication attempts were documented in our database, 314 against arthropods and 534 against pathogens. These cases concerned 49 species of arthropods (47 insect and 2 mite species) and 34 species of pathogens (21 fungi and oomycetes, 8 bacteria, 2 nematodes, and 3 virus/viroids). A large number of reports corresponded to post-border interceptions. These cases represented 49% (154) of reports on arthropods and 19% (87) on pathogens.

In the case of insects, these data show that for only 9% of the compiled list of 487 non-native insect species of woody plants detected in Europe, eradication measures were taken (42/487, Fig. 1). Species that are native to parts of Europe but non-native in other European countries (e.g. UK) were not included in this analysis.

The total number of insect species for which “eradication” measures were taken (both established populations and post-border interceptions), increased in the last two decades (Fig. 1). Still, the numbers are very modest when compared with the total number of non-native species introduced in Europe, reaching a maximum of 18% of the total number of introduced species in the last twenty years (25/136). For invasive fungi and oomycetes in European forests, eradication was attempted in only 12% of the cases (17/146).

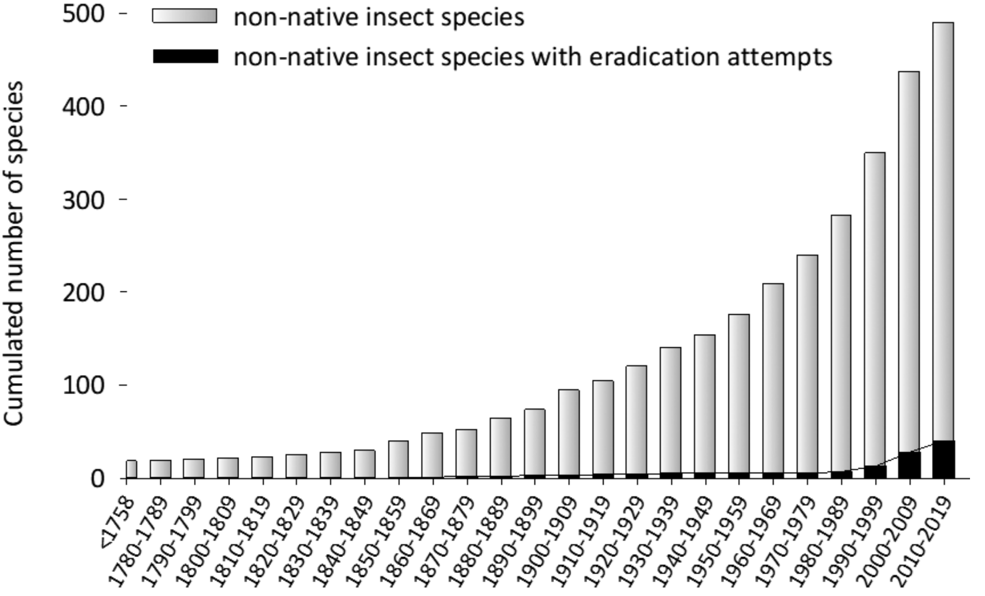

Figure 1. Cumulative number of non-native species of insects of woody plants for which eradication of established or intercepted populations was attempted, and the cumulated number of alien insect species reported for Europe until 2019.

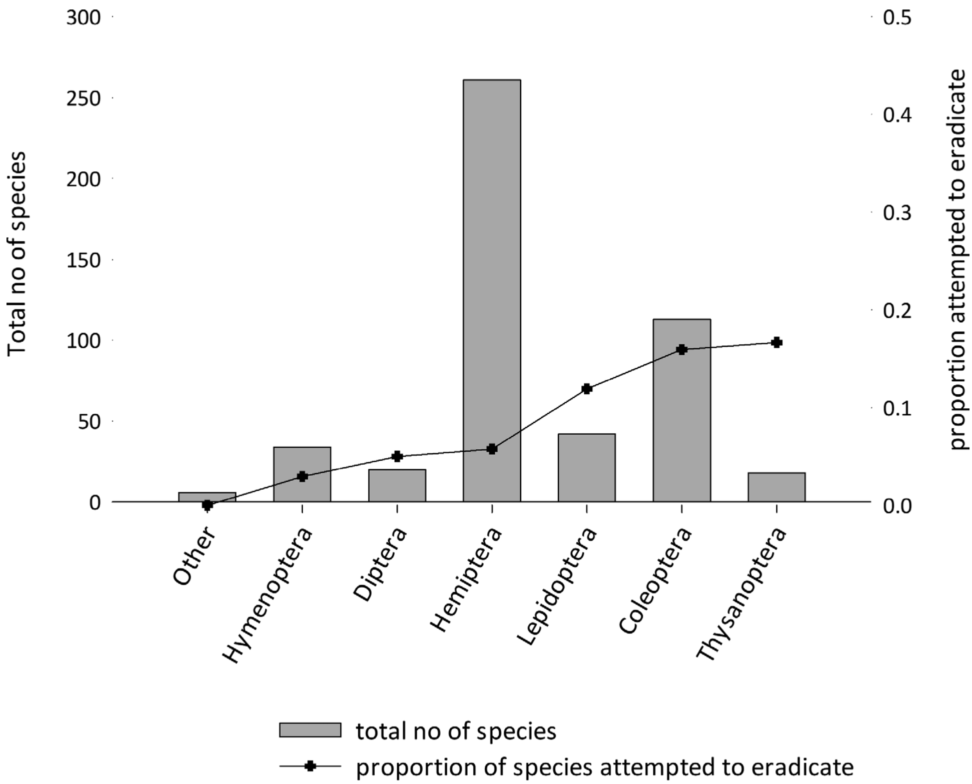

Figure 2. Total number of non-native insect species on woody plants reported for Europe by order (bars) and proportion of species attempted to eradicate (established species).

Post- border interceptions were observed for only a few species. For arthropods, 43% of reported interceptions are linked to the oak processionary moth (*Thaumetopoea processionea*, OPM) in the UK, outside of the containment area in London and South East England where the pest has established, after being accidentally introduced from mainland Europe (DEFRA 2022). OPM has been intercepted in all types of environments, from nurseries to urban and peri-urban areas and in recently established plantations. *Anoplophora chinensis* ranks second in the number of interceptions (21 cases). This beetle was mostly intercepted in nurseries and urban and peri-urban environments, associated with imported *Acer* spp. plants for planting and bonsais (Branco et al. 2021). The remaining interceptions are distributed among 20 species (Suppl. material 1), mostly found in nurseries, garden centres or other confined environments (68% of cases).

Concomitantly, there is a discrepancy between the number of alien insect species reported and the number of eradication attempts by taxa. Most of the non-native species (52%) are hemipteran sap suckers, but eradication was attempted for only 6% of these (Fig. 2). Coleopterans represent 42% of the reported eradication attempts against insects and 96% of these attempts were against wood borers (Cerambycidae, Curculionidae, Buprestidae).

For pathogens, 11 species have been intercepted outside of import-associated inspections, mostly in confined environments (72%). *Phytophthora ramorum* ranks first in the number of interceptions (63%), distributed among 12 European countries, followed by *Cryphonectria parasitica* (13%), the causal agent of chestnut blight, for which most interceptions were reported in the UK, where it has only recently established (Hunter et al. 2013; Romon-Ochoa et al. 2022).

Detection

For arthropods 49% of detections occurred during official surveys (53/108). The remaining cases were detected by passive surveillance which corresponded mostly to members of the public who reported symptoms of infested plants or sightings of adult insects to the competent phytosanitary authorities, by operators of nurseries and greenhouses and growers. In contrast, pathogen detections occurred mostly during official surveys, in 90% (247/275) of cases.

Success of eradication programmes in Europe

Eradication measures taken against organisms still restricted to the primary material with which they were introduced, here defined as post-border interceptions, were 100% successful. From here on we will consider only eradication programmes targeted at established populations in Europe. In total, 160 programmes were launched against 41 species of arthropods (Fig. 3) and 447 programmes against 31 species of pathogens (Fig. 4). The proportion of successes and failures varied greatly among species.

Arthropod species and feeding guilds

Attempts to eradicate arthropods were mostly concentrated on bark and wood borers, followed by sap-suckers, and defoliators. Other guilds were rarely targeted. In 50% of the concluded programmes (55/111), species were confirmed eradicated. Eradication is still in progress in 46 cases (29%). Three species rank the highest in the number of eradication attempts: *Anoplophora glabripennis* (39), *A. chinensis* (18) and *Rhynchophorus ferrugineus* (17). Eradication success differed greatly between species (Fig. 3). The highest eradication success was reported for *A. glabripennis* (100% – 23 cases), although many programmes (16) are still in progress. Eradication has never been successful for 13 arthropod species. Leading among these cases are sap-suckers, notably the psyllid *Trioza erytreae*, for which six programmes were launched, four of which failed and two are still ongoing (EPPO- Global database 2022). Although the area increased over which this pest is distributed, an effective biological control programme has been launched with the introduction of the parasitoid *Tamarixia dryi* (JC Franco, unpublished data).

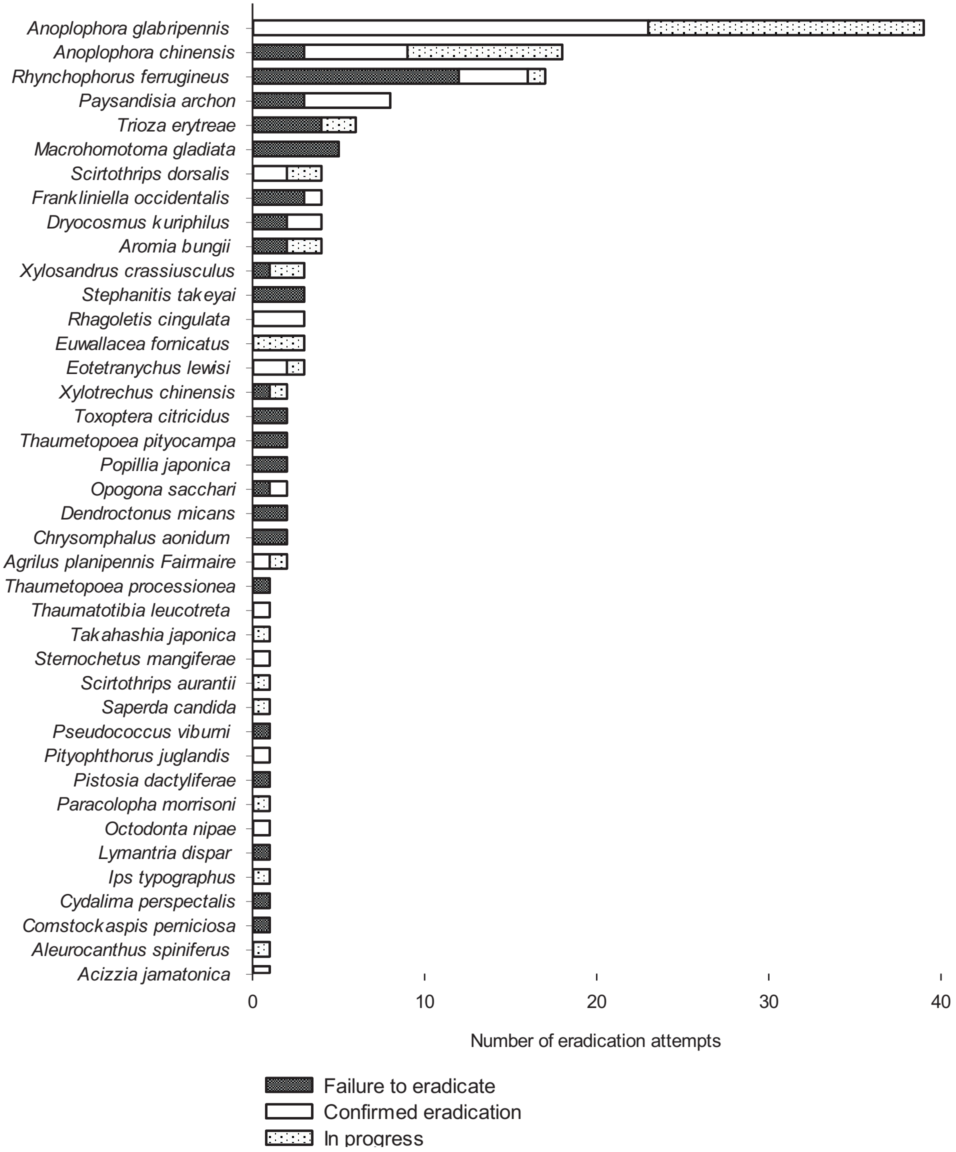

Figure 3. Arthropod species for which eradication was attempted in Europe.

Pathogen species and groups

Concluded programmes against established pathogens accounted for 359 cases. In addition, 80 cases are still in progress and for 8 cases the outcome is still unknown. Eradication programmes targeted 31 species, including fungi/oomycete, bacteria, nematodes and viruses (Fig. 4). The success rate for the concluded programmes is 61%, with little variation between groups.

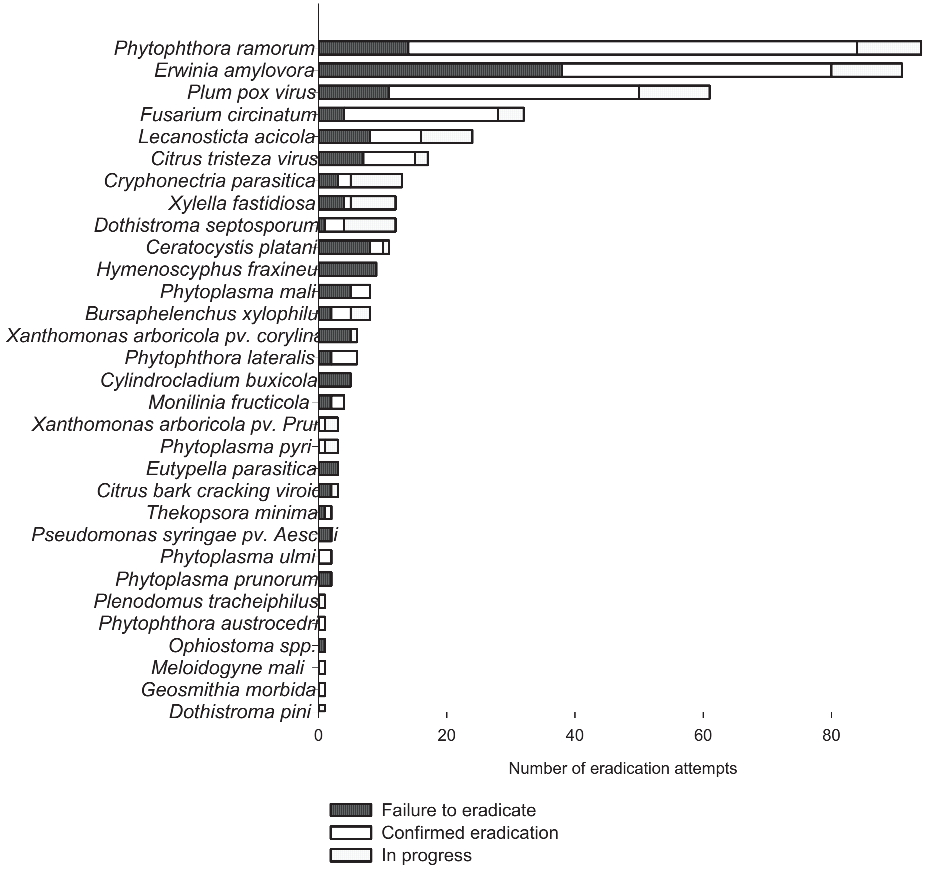

Figure 4. Pathogen species for which eradication was attempted in Europe.

As observed for arthropods, eradication of pathogens was mostly focused on a few species. Three species alone account for over half of total eradication attempts: *Phytophthora ramorum* (21%), *Erwinia amylovora* (21%) and *Plum pox virus* (PPV) (14%). *Phytophthora ramorum* (sudden oak death) was first detected in Europe on *Rhododendron* and *Viburnum* plants in nurseries (Werres et al. 2001) and later in infected Japanese larch trees, *Larix kaempferi*, in the United Kingdom (Brasier and Webber 2010). *Erwinia amylovora* or fireblight is a pathogen of plants in the family Rosaceae (CABI 2019). Plum pox virus disease, commonly known as sharka, is one of the most destructive diseases of stone fruits from the genus *Prunus* (CABI 2019).

Temporal and spatial trends

For both arthropods and pathogens, the total number of eradication programmes against established populations increased abruptly in the last two decades, (Fig. 5). The success rate of eradication attempts against arthropods reached 72% in the period 2011–2020. In contrast, all programmes that started before 2000 failed. For pathogens, the success

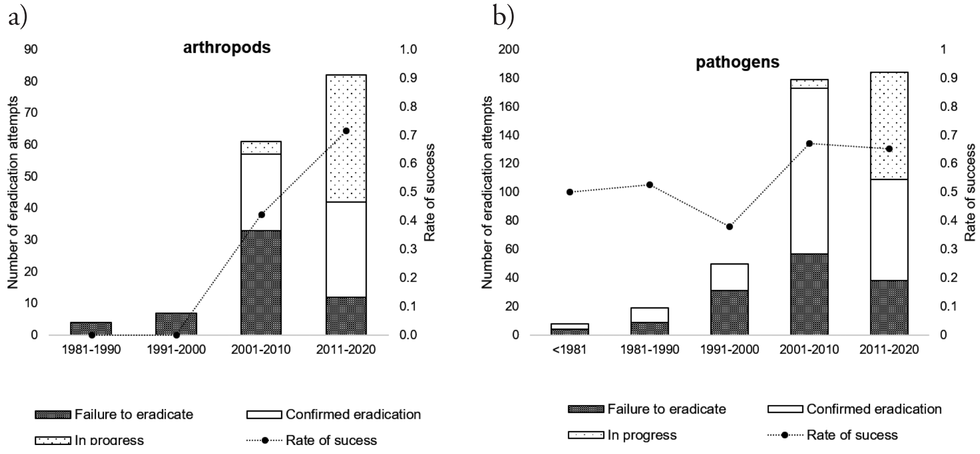

Figure 5. Eradication attempts in Europe by decade and corresponding rate of success of programmes targeting **a** arthropods and **b** pathogens.

rate has also increased, being highest for the last two decades (approximately 65%). In the decades prior to 2000, the success rate was moderate, ranging between 40% and 52%.

In terms of geographic distribution, the highest number of eradication attempts per country were reported for France (81), Spain (61), Italy (57) and Germany (56) (Fig. 6). A clear concentration of eradication programmes exists in Western Europe (Fig. 6), with many of these programmes still ongoing.

Reaction time and duration of programmes

For arthropods, most of the attempts were carried out within one year after first detection (84%), and 10.6% were carried out in the second year, with similar success rates (53% in both cases). All five programmes starting later than 2 years after detection failed. Similarly, for pathogens, 89% of the eradication programmes were launched within one year after the first detection, with a success rate of 66%. The rate of success dropped to 42% and 25% when they were launched in the second or third year, respectively. Of the 12 programmes launched more than three years after detection, one is still in progress and the remaining failed.

The duration of failed eradication programmes was on average 5.8 ± 4.5 years (mean ± SD) for arthropods and 6.5 ± 6.5 for pathogens. For successful programmes, the duration from the start until the last detection was shorter, with 2.0 ± 2.6 and 2.0 ± 3.2 years for arthropods and pathogens respectively. Still, monitoring could continue for several years after the last observations of the species.

Area affected

For both arthropods and pathogens, the success rate was the highest for infestations restricted to small areas (Fig. 7). For infested areas < 1 ha, the success rate was 82% and

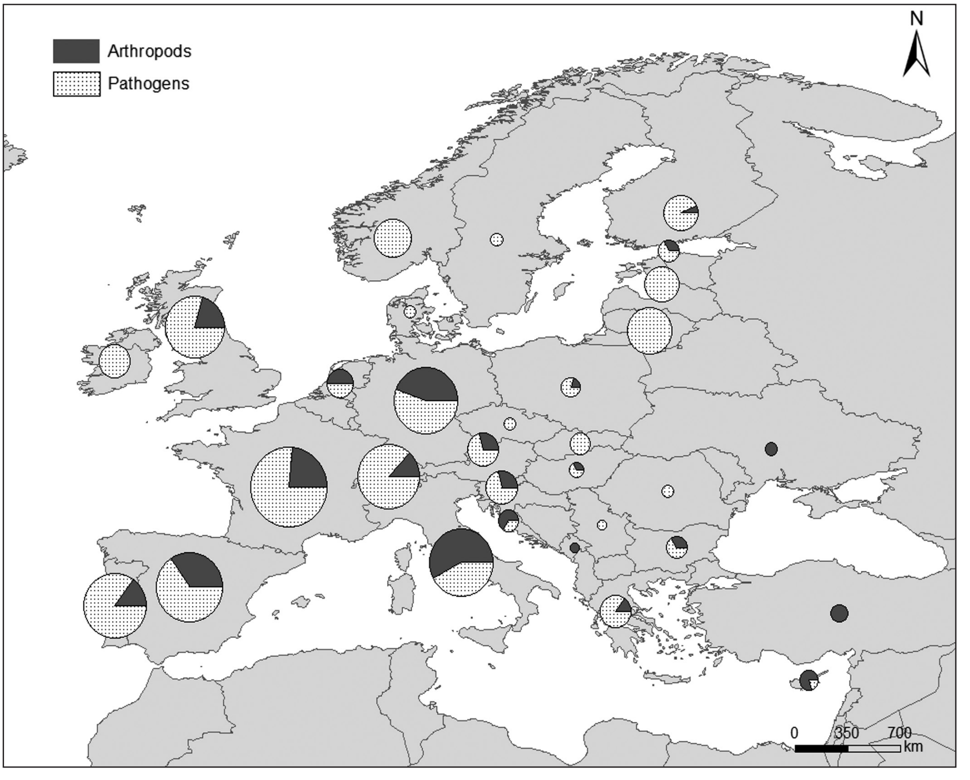

Figure 6. Eradication attempts against arthropods and pathogens in Europe, by country. The size of each pie is proportional to the number of eradication attempts in that country.

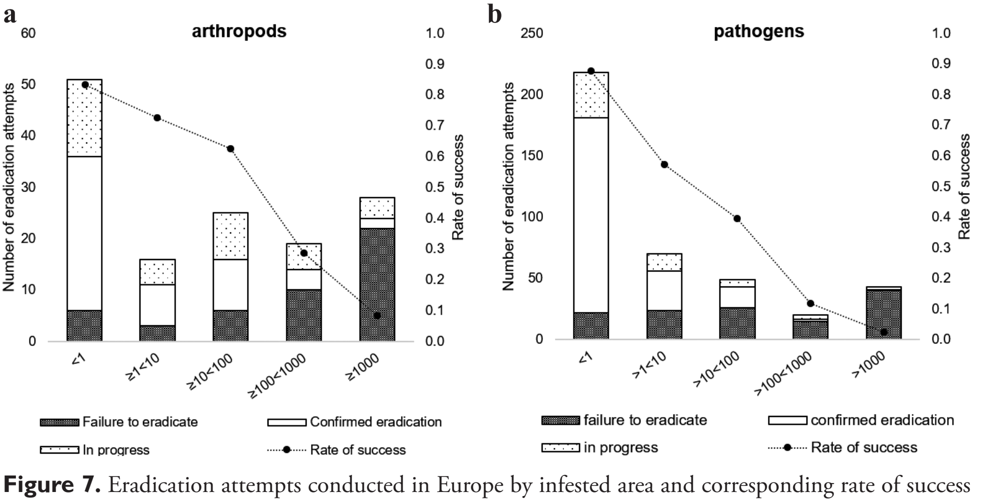

Figure 7. Eradication attempts conducted in Europe by infested area and corresponding rate of success against **a** arthropods and **b** pathogens. Information on the approximate area affected at the time of programme start was retrieved for 139/160 cases for arthropods and 408/447 cases for pathogens.

90%, for arthropods and pathogens, respectively (Fig. 7). Success decreased with an increase in the affected area, with the sharpest decrease observed for pathogens.

For areas above 1000 ha, success for pathogens was only achieved once out of 40 concluded programmes (2.5%). This unique success concerned *E. amylovora* in Norway. The programme started in 1986 in an infested area of 30,000 ha where all the hosts were removed (i.e., all *Cotoneaster*, *Sorbus* and *Pyracantha*). Within the quarantine area (70,000 ha), the production and sale of all common fire blight hosts was prohibited and bee hives were moved to areas that were free from hosts of *E. amylovora*. From 1993 to 2000, no new detections were made and the outbreak was declared eradicated in 1998. Although fire blight was again detected within the restriction zone in 2000, it is unknown whether a re-emergence or a new introduction occurred (Sosnowski et al. 2009).

Climate

Regarding the role of climate, for arthropods, the lowest eradication success was reported in Mediterranean climates (Köppen Csa, Csb) (29%), and higher success rates were observed for temperate (Köppen Cfa, Cfb) (63%) and continental climates (Köppen Dfb) (67%). For pathogens, the success rate related to climate varied depending on the group considered: i) for fungi and oomycetes the highest rate of eradication success was reported in Mediterranean climates (93%), intermediate for continental (71%), and the lowest for temperate climates (60%); ii) for bacteria the lowest success rate was again reported for temperate climates (34%), yet the highest success rate was registered in continental climates (77%), with an intermediate rate of success for Mediterranean climates (46%); iii) for viruses and viroids, the eradication success was low in the Mediterranean and temperate climates, with 62% and 64%, respectively, and high in continental ones (93%). Most attempts to eradicate nematodes were conducted in Mediterranean climates, with an overall success rate of 67%.

Detection site and affected hosts

New establishments of arthropods were most often detected in urban or peri-urban areas, including residential and industrial areas (65% of cases). The rate of eradication success was highest (74%) in confined environments, where the plant materials were delimited (nurseries, glasshouses and garden centres), intermediate in residential areas (52%), and lowest (26%) in the countryside (orchards, woodlands /forests). Pathogen detection, on the other hand, occurred in the countryside in 50% of cases (mostly orchards, Fig. 8), followed by confined environments (30% of cases), and only 20% of cases were first reported in urban and peri-urban areas. The rate of pathogen eradication success was also high in confined environments (86%) and similar for the remaining environments (50% for countryside and 51% for urban/peri-urban).

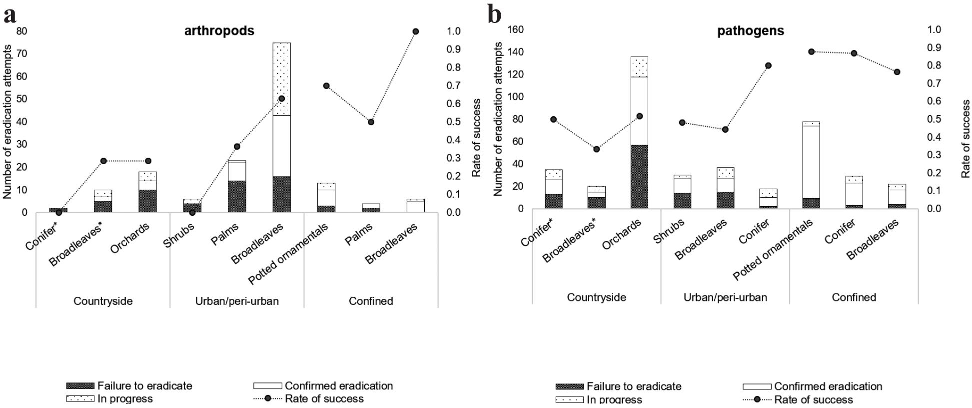

Figure 8. Eradication attempts conducted in Europe against **a** arthropods and **b** pathogens, by detection site and with the corresponding rate of success. Information on the main type of environment affected at the time of the programme start was retrieved for 157/160 cases for arthropods and 405/447 cases for pathogens. * in woodlands or forests.

Most eradication programmes targeted PPWPs attacking broadleaves (79%, both for arthropods and pathogens). For arthropods attacking broadleaves in urban and peri-urban areas, the eradication success rate was 63%, while in the five cases reported in confined environments, the success rate was 100%. The lowest success rates were reported for pests on countryside woodland and forest conifers and on urban and peri-urban shrubs, where all six launched eradication programmes have failed (Fig. 8). For pathogens, the eradication success rate on different host plants was overall similar in countryside and urban and peri/urban environments (Fig. 8), albeit slightly lower on broadleaves in woodlands and forests (30%) and on ornamentals in urban environments (44%). The only exception was the high success rate reported for pathogens attacking conifer pests in urban environments with an 80% success rate.

Eradication methods

Information on the eradication methods applied was available for 149 out of 160 cases for arthropods and for 427 out of 447 cases for pathogens. Eradication methods consisted mainly of host removal or destruction of host plants, which was used in 81% and 99.8% of the programmes against arthropods and pathogens, respectively. For arthropods, this proportion increases to 94% when only wood borers were considered.

When host removal was used alone, or in combination with other methods, the rate of success was 58% (48/82) for arthropods and 62% (217/350) for pathogens. Host removal was commonly combined with quarantine or movement control restrictions imposed by legislation, preventing the movement of host plants or potential host plant material outside of the demarcated areas. For nurseries, these measures usually implied that for a given period of time, neither potentially affected, nor susceptible plants, could be traded. In the field, the quarantine area usually included the infested zone and a buffer zone delimited around the infested/infected zone, which together represented the demarcated area of the outbreak. When host removal was combined with quarantine measures the success rate increased to 70% for arthropods and 65% for pathogens. When treatment of a surrounding area of predefined extent around the focus zone was imposed, either by removal of all or part of sensitive hosts or by chemical control measures, the success rate was overall higher, 67% for arthropods and 70% for pathogens, than when no such measures were applied, with 38% for arthropods and 46% for pathogens.

For arthropods, the combination of host removal with chemical treatments was reported in 31% of concluded cases, with an overall success rate of 37%. Chemical treatment without host removal was reported only in 20 cases with low success (25% success rate). Other control methods such as biological control or traps were seldom used, alone or in combination with other methods (used in 8% and 9% of programmes, respectively).

Against pathogens, disinfection of associated material, such as production machinery and tools used was reported for *E. amylovora* and *F. circinatum* (EPPO- Global database 2022), which in combination with other methods resulted in a 76% eradication success rate. The use of chemical control with either fungicides or antibiotics was only reported for 6 concluded cases (50% success rate). For pathogens transmitted or potentially transmitted by insects, vector control was used in several cases (28 concluded), and against *E. amylovora* the prohibition of beehive movement was often imposed.

Monitoring

For arthropods, visual observation was the only monitoring method used in 43% of the eradication programmes. Detection dogs were used in 29 eradication programmes against the two *Anoplophora* species, and tree climbers were further used for monitoring *A. glabripennis*, for which these methods were frequently used simultaneously, with a 100% success rate. However, it is important to note that 16 eradication programmes against this species are still in progress.

For pathogens, monitoring consisted of visual observation for symptoms and the sampling of plant material for laboratory analysis, either by morphological or, more commonly, by molecular methods. For some species, such as *P. ramorum* and the pine wood nematode (PWN), only symptomatic plants were commonly sampled, whereas for others, such as Citrus Tristeza Virus (CTV) and *F. circinatum* sampling of asymptomatic hosts is regularly conducted. For *E. amylovora* and PPV for example, an overall higher success rate of eradication was observed when asymptomatic plants were also sampled (60% and 92%, vs 51% and 74%, respectively). Annual surveys at places of production or other specified areas are mandatory in some cases, and were conducted in 84% of concluded cases. Conducting annual surveys provided a higher success rate (67%, 185/276) than when surveys were conducted less frequently (44%, 16/36). For *P. ramorum* in the UK, in addition to visual inspection in nurseries and ground surveys, aerial surveys were also used in forested areas with larch (*Larix* spp.), looking for visible symptoms. This method was also used for *Phytophthora lateralis* in UK forests. When symptoms were detected, confirmation was then attained by laboratory analysis of plant samples. In many European countries, traps were also commonly used to monitor vectors of pathogens transmitted or potentially transmitted by insects.

EPPO recommendations

Of the eradication attempts reported, the vast majority were against species present in EPPO Alert, A1 or A2 lists (EPPO 2021) with or without legal mandatory measures. Only 14% of cases against arthropods and 9% against pathogens were against species not included in EPPO lists. The success rate in these cases was only 10% and 38%, respectively.

Society and citizens' engagement

Information about the citizens' education and the engagement of stakeholders during the eradication programmes is scarce. The involvement of citizens was reported for 75/160 cases of arthropod eradication programmes. In approximately half of these cases (51%), involvement was limited to the reporting of insects or symptoms to the phytosanitary authorities. For the remaining cases, involvement was compulsory, imposed by legislation, such as the obligation to report sightings or to cut infested/infected trees. Targeted species were *A. glabripennis*, *A. bungii*, *D. kuriphilus*, *R. cingulata*, *R. ferrugineus*, *S. dorsalis*, *Toxoptera citricidus*, and *T. erytreae*. A volunteer collaboration was recorded in 15 cases, concerning *A. chinensis*, *A. glabripennis*, *D. kuriphilus* and *R. ferrugineus*. By contrast, a mainly negative attitude was recorded against the eradication of *A. glabripennis* in Kent, UK. The negative perception was due to unwillingness to cut historical trees or because citizens were angry claiming that contractors were cutting the wrong trees (Porth et al. 2015). Actions for the education of citizens and public information about the ongoing eradication program were expressed in half of the programmes, whereas for the other half, no information was available. Public education for signs and symptoms of pathogens was reported for 62% of the programmes, mostly through the availability of web pages and leaflets given to producers and owners of nurseries and garden centres. Public involvement was mandatory for many of the targeted species. A negative attitude against a programme was only expressed in one case, targeting *Xylella fastidiosa* in Italy. The growers expressed resistance to the massive olive tree culling imposed by European Union containment regulations, including old, historical trees and to the use of insecticides for vector control in organic farming (which prohibits the use of chemical pesticides) (Nadeau 2015). Prosecutors in southern Italy accused the researchers of spreading the disease and halted the European Union – ordered cull of olive trees (Abbott 2015).

Correlation between variables

The results of the Cramers' V index for the nominal variables highlighted a strong correlation between some of the variables (Suppl. material 2). For arthropods strong associations (V > 0.5) were estimated for variables mainly related with species traits, such as feeding guild and a number of other species traits (Suppl. material 2). Also, for pathogens strong associations were estimated between species traits. These correlations are solved by LASSO and regression trees, as both methods select variables based on their added predictive ability.

Statistical modelling

Results for establishment probability are given in Suppl. material 3. Here the results of LASSO regression and decision tree analysis are reported for the eradication success of programmes against established populations.

Arthropods

The LASSO regression results showed that the area affected at the start of the eradication programme was the most important factor affecting the outcome of eradication success. For areas ≤ 1 ha and > 1 ≤ 10 ha, success is similar, but above this threshold, there is a negative relationship between the area affected and the probability of a successful eradication (β = -0.72 for > 10 ≤ 100 ha; β = -1.29 for > 100 ≤ 1000 ha and β =-2.69 for > 1000 ha; coefficients are reported at a log odds scale). Other environmental factors affecting the outcome of eradication success were the main type of environment affected at the start of the program, with a higher success rate in confined environments than in the countryside (β = 0.66), and a slightly higher success rate in mainland than in island locations (β = 0.01). Regarding control measures, only the implementation of quarantine/movement restrictions was positively associated with eradication success (β = 0.52). For species traits, internal feeders had a higher probability of eradication success than external feeders (β = 0.66), oligophagous species had a lower probability of eradication success (β =-0.22), and the group of fruit/seed feeders and gall makers had higher eradication success (β =-0.32). Considering the species targeted, *A. glabripennis* was associated with a higher eradication success (β = 2.35) than species for which less than five cases were reported. The optimal penalty value (λ) for the model was 0.028.

In the regression tree analysis, the optimised tree resulted in only one split, with higher eradication success for areas below 10 ha than for larger infested areas (82.6% vs 28.6%). When the area as explanatory factor was removed, a secondary tree was obtained (Fig. 9) for which eradication success was higher when quarantine/movement restrictions were implemented (69%) than when they were not (31%). The variables host type, location and phytophagous specialisation were also excluded from this tree construction due to association with the affected area. Further tree divisions highlighted the main type of environment affected, the main reproduction method, and climate as explanatory variables affecting eradication success.

Pathogens

The LASSO regression estimated that the affected area was the most important factor associated with eradication failure and the higher the area the stronger the association

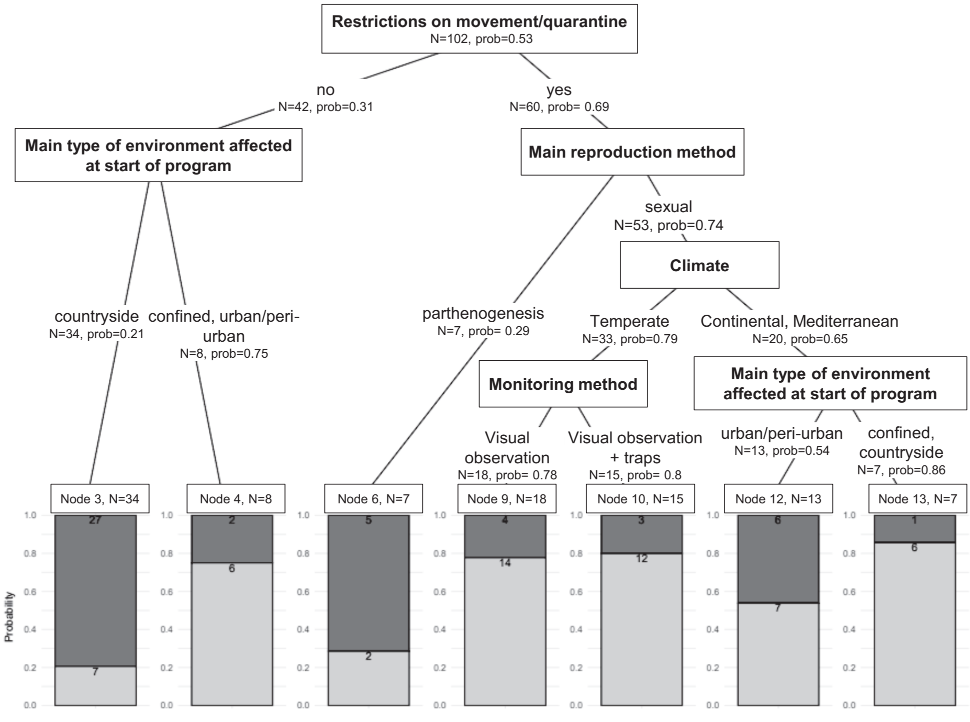

Figure 9. Optimal classification tree (after removing the size of the affected area) for factors affecting eradication success and failures of 102 eradication programmes against non-native arthropods of woody plants in Europe. In the model, every species was given equal weight and thus the records of the same species were weighted by the inverse of the number of records per species. Light grey in bars represents successful eradication, dark grey represents failure to eradicate.

(>1 ≤ 10 ha: β = -0.798; > 10 ≤ 100 ha: β = -1.825; > 100 ≤ 1000 ha: β = -3.246; > 1000 ha: β = -4.334). The type of environment affected also influenced the outcome, with success more likely in confined than in urban/peri urban (β = -0.196) and countryside environments (β = -0.237). Eradication success was more likely when the eradication programme started within the first year after detection (β = 0.369), in temperate than Mediterranean climates (β = 0.434), when surveys were conducted at least annually (β = 0.566), and when host removal alone was used compared to combined methods (β = 0.063). Possible saprotrophic species were harder to eradicate, although the effect was small (β = -0.050). At the species level, *Fusarium circinatum* (β = 0.771), Plum pox virus (β = 0.438) and *Cryphonectria parasitica* (β = 0.223) were easier to eradicate than species with lower than five eradication attempts, and *Hymenoscyphus fraxineus* (β = -2.013), *Phytoplasma mali* (β=-0.998), *Xanthomonas arboricola* pv. *Corylina* (β = -2.453), *Xylella fastidiosa* (β = -0.511), Citrus tristeza virus CTV (β=-0.059) and *Lecanosticta acicula* (β = 0.196) were harder to eradicate. The optimal penalty value (λ) for the model was 0.011.

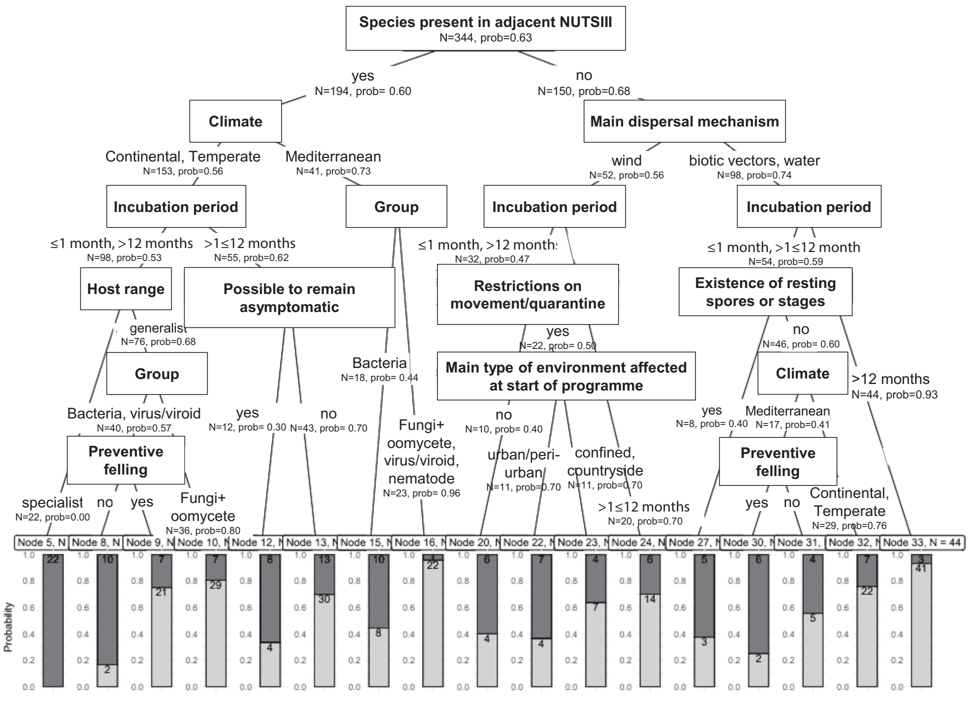

Figure 10. Optimal classification tree (after the area affected removed) for factors affecting eradication success and failures of 344 eradication programmes against pathogens of woody plants in Europe. In the model, every species was given equal weight and thus the records of the same species were weighted by the inverse of the number of records per species. Light grey in bars represents successful eradication, dark grey represents failure to eradicate.

In the regression tree analysis, the optimized tree resulted in only one split where the area was the only variable included, like the results for arthropods. However, here the separation occurred for areas below 1 ha, which had higher eradication success than larger areas (88.1% vs 34.6%). When the area was removed from the model (Fig. 10), the presence of the species in adjacent NUTSIII units resulted in the first split, with higher eradication success when the species was not yet present in adjacent NUTS. The variables host type and location were also removed due to their close association with area. Other environmental factors affecting the outcome of an eradication programme included the climate and the main type of environment affected at the start of the program. Several species traits were shown to influence the probability of a successful eradication, namely the main dispersal mechanism, the host range, the incubation period, the possibility to remain asymptomatic for long periods or indefinitely and the existence of resting spores or stages. Differences in the influence of these factors between groups were observed. Regarding control and monitoring options, the implementation of restrictions on movement/quarantine and preventive felling affected the outcome of an eradication programme.

Discussion

Temporal and spatial trends

An increasing number of non-native forest pests and pathogens was observed in the last century in Europe (Santini et al. 2013; Roques et al. 2016, 2020; Ghelardini et al. 2017). Here we report a concomitantly increasing number of eradication programmes conducted in Europe against pests and pathogens affecting woody plants. However, eradication was attempted for only 9% of the non-native insect species and for 12% of the pathogens. In contrast, for hundreds of species eradication was ever attempted. Nevertheless, these figures are better than those reported for alien insects in North America, where eradication was attempted for only 1.8% of established species (Liebhold et al. 2016).

We may deduce that species with higher economic or ecological impacts were those selected for eradication programmes. A low benefit: cost ratio has been suggested as one of the reasons for eradication not to be attempted (Kean et al. 2022). Still, there are species with high economic impact, such as *Gonipterus platensis* in the Iberian Peninsula (Cordero-Rivera et al. 1999; Valente et al. 2018) for which eradication was never attempted. Several possible reasons for not attempting to eradicate an invasive population have been proposed (Liebhold et al. 2016; Kean et al. 2022): 1) the fact that the pest or pathogen was already too widespread or abundant, or that spread was too rapid; 2) an underestimation of the potential impacts of the pest or pathogen; 3) the lack of adequate surveillance mechanisms to detect an invasion early enough; 4) the lack of effective control tools; 5) the existence of open pathways for re-introduction; 6) or policymakers did not consider eradication to be a realistic option. Since the decision to carry out an eradication programme is typically taken at the national level, and frequently imposed at the European level, this leads to responsibilities in the scientific community in transferring information to policymakers so that more species could be targeted. We hope this revision work may contribute in this regard.

At the European level, eradications were more concentrated in Western regions with minor numbers in the northern and eastern European countries. In part, this distribution coincides with the hotspots of first detections in Europe (Branco et al. 2019), that is the countries where most incursions of high-impact invaders occurred. But there is still a contrast between the high number of first detections in central-eastern countries and the low number of eradication attempts.

Overall eradication success

An optimistic conclusion of our study is that the overall rate of eradication success has been increasing over time for both pathogens and arthropods, and especially for the latter. In the last decade, eradication success attained levels of 76% for arthropods and 68% for pathogens. Yet, these figures include officially declared eradication measures taken against PPWP on imported materials or against adult insects, i.e. before establishment. The success for arthropods is similar to that reported by Tobin et al.

(2014) (78%), whereas for pathogens it is higher than the 55% reported by Smith et al. (2017), with both of these studies being based on data from the Global Eradication Database GERDA. However, care should be taken with the interpretation of these results, as we found they might be overestimated. In fact, a significant part of successful programmes commonly referred to as "eradication" in EPPO and NPPO reports, and consequently in GERDA, concern non-established species; i.e. arthropods or pathogens that were still restricted to the materials with which they were introduced. We propose that these cases could be more accurately defined as interceptions not associated with import inspections. Cases in which pests and pathogens were still restricted to the materials with which they were introduced were mostly found in nurseries and in greenhouses, but a few of them were also on trees already planted in the field. An example of this latter situation was reported in 2019 on oak trees recently planted in the UK, imported from the Netherlands and Germany, which carried oak processionary moth caterpillars. These trees were destroyed and this was considered a successful eradication (UK GOV 2019). In the present study, we treated these cases as "post-border interception". In total, we counted 241 cases in this category and the eradication success rate in these cases was 100%. This outstanding result confirms that the surveillance of plant materials imported and moved inside countries should be done with incessant efforts. A higher investment in surveillance and detection has been identically defended by many authors (Simberloff 2003; Tobin et al. 2014; Ganley and Bulman 2016; Liebhold et al. 2016). Many previous studies considered these cases as eradications as in the GERDA database. However, if one considers eradication in *sensu stricto* only for the programmes against established species, the rate of eradication success is significantly lower. In fact, when we consider only the established species, the overall eradication success rate decreases to 50% for arthropods and 61% for pathogens. However, despite being lower than in other reviews, this value is still relatively high. Furthermore, the success rate of programmes has been increasing in recent decades. Therefore, more optimism is justified about the likelihood of eradication programmes being successful and worthwhile.

On the other hand, eradication success relies on external drivers, and some species might be particularly difficult to eradicate which may be related to environmental factors or species traits. With this aim, we tried to understand the main factors determining eradication success.

Eradication success: Time and space

One of the most consensual conclusions of previous studies is that eradication success is greater the smaller the affected area. Tobin et al. (2014) reported that eradication was 1.3 times less likely for every log10 increase in the infested area for arthropods, and Pluess et al. (2012a) identified a critical threshold of 4905 ha for the infested areas of alien invertebrates, plants, and plant pathogens, above which the probability of successful eradication reduced to half (66.7% vs 32.5%). Not surprisingly, our results are consistent with this conclusion, although our thresholds are different. Additionally, our analyses indicated lower thresholds than in previous studies: below thresholds of 10 ha for arthropods and below 1 ha for pathogens, the success rate is very high, corresponding to 82% for arthropods and 90% for pathogens. But above these thresholds eradication success significantly decreases. Still, an eradication success of 60% was attained between 10 ha and 100 ha for arthropods and between 1 ha to 10 ha for pathogens. This means that for infested areas up to these sizes, eradication may still be considered feasible. Nevertheless, if circumstances are favourable, even eradication of infestations over larger areas may be successful, provided sufficient resources are available. Interestingly, the decreasing slope was steeper for pathogens than for arthropods, which suggests that the factor area is likely to be even more important for the former group. The length of time elapsed since the first detection also led to a decrease in the success rate, as previously mentioned by Pluess et al. (2012b). However, it is difficult to separate the factor time from the area (as the affected areas usually increase over time). Therefore, the main recommendation is that governments and organizations involved should invest in surveillance and detection to achieve detection as soon as possible. Furthermore, preparedness in terms of having tools and plans available is critical to enable timely responses to newly detected incursions to start eradication programmes quickly and increase their likelihood of success. This also implies being well informed about new potential risk organisms and how to eradicate them when they arrive, prior to their invasion.

We observed that species with a higher number of eradication attempts are also those with the highest eradication success. This may reflect increased knowledge on how to deal with these particular invasive species, accumulated in the previous eradication attempts, which would also facilitate a quick reaction before its spreading and becoming then impossible to eradicate.

Blackburn et al. (2011) proposed a conceptual framework for biological invasions which has recently been updated by Paap et al. (2022) to accommodate forest pathogens. Both frameworks are composed by a series of stages, namely transport, introduction, establishment and spread, each stage having a particular barrier that a population needs to overcome to reach the next stage. Different management options may apply at different stages, and early detection of the invader and a fast response time, increase the feasibility of successful eradication. For instance, in nurseries and greenhouses PPWP are usually detected in the introduction phase, when populations still must overcome the limited distribution barrier. This applies to the reported cases still restricted to the primary material in which it was introduced, which had 100% eradication success. By contrast, ash dieback, caused by *H. fraxineus*, is an example of a species that was identified as invasive too late, when large areas of European forests were already invaded and there was no possibility to react anymore (Pautasso et al. 2013).

The similarity of symptoms to native or previously introduced species can mask the presence of invasive species for long periods, as occurred for *Phytophthora cinnamomi* and *Heterobasidion irregulare*, with similar symptoms as *Phytophthora* × *cambivora* and *Heterobasidion annosum*, respectively (Brasier et al. 1993; Vettraino et al. 2005; Garbelotto et al. 2022). For these cases, the development and/or implementation of new genomic biosurveillance tools is critical, so that the taxonomy of the invasive organism can be clarified unequivocally and effective eradication program can be started rapidly (Hamelin and Roe 2020; Luchi et al. 2020).

All these cases reinforce the concept that we should be able to identify potential invaders before they leave the country of origin to be prepared in advance. A good example is the case of *P. ramorum*, the causal agent of sudden oak death in California. The high potential risk identified early for this species, and the fear of having a similar epidemic in Europe, boosted the early detection and the rapid implementation of containment measures. However, not all potential invaders with high economic and ecological impacts have demonstrated this potential in its native region or other invaded regions. Frequently, an organism only becomes emergent in the invaded range, since resistance of native host plants and the communities of natural enemies keep them at low or imperceptible levels in its native range (Elton 1958; Jeffries and Lawton 1984; Wolfe 2002).

Environmental drivers and species traits

As expected, species found in confined or limited environments, usually subject to frequent intervention, such as greenhouses, are easier to eradicate. The same results were found by Pluess et al. (2012b). Both pathogens and arthropods became established more easily, and thus more difficult to eradicate, in urban or peri-urban areas and in the countryside (woodlands, forests or orchards) than in confined environments. An interesting outcome from our work is that urban and peri-urban areas have similar establishment probabilities and equal difficulties of eradication as countryside. The relevance of urban forests and urban trees for the establishment and spread of invasive forest species has been gaining relevance (Poland and McCullough 2006; Paap et al. 2017; Branco et al. 2019; Dale et al. 2022; Nunes et al. 2023) which is reinforced by our results.

Climate may play a role in the success of eradication programmes. Warmer climates may favour higher growth rates for arthropod populations. On the other hand, Mediterranean climates with harsher summer conditions, or a continental climate with severe winters may explain a lower probability of establishment and a higher probability of eradication success for some groups of insect pests and pathogens in these conditions. Still, a general trend of climate in the eradication success did not emerge from our analysis. The differences in the climate of origin and the one of the invaded range could have played a role in the eradication of specific species. Additional studies could address this hypothesis. Further, our dataset does not completely allow to disentangle climate effects from other factors, namely cultural and socio-economic ones.

Regarding species traits, we could associate some traits with a higher difficulty of eradication. For arthropods, the most remarkable outcome is the extremely low success in eradicating Hemipteran species. This is probably explained by several traits shared by many hemipteran species, such as the high dispersal ability, frequently mediated by wind and their difficulty of detection at low densities due to their often small size and cryptic stages, high fecundity and short life cycles. Concomitantly, in the LASSO models, species traits associated mostly with hemipterans in our group of species, such as parthenogenesis, were found to be relevant. An example is the psyllid *T. erytreae*, for which six eradication programmes were launched, and none succeeded, despite the huge effort invested in it. For pathogens, as expected, eradication proved to be harder for species with high saprotrophic abilities, for species dispersed by wind, for species that may remain indefinitely asymptomatic and for species with resting spores or stages. Unexpectedly, however, species with intermediate incubation periods (>1 ≤ 12 months) were overall easier to eradicate than those with shorter (≤ 1 month) or longer periods (>12 months). Short incubation periods may lead to faster population growth and dispersal thus challenging eradication efforts. The concomitant harder difficulty to eradicate species with incubation periods longer than one year may be associated with poor detection before planting infected material: if disease symptoms may appear after plantation, with a lag that may reach several years for some pathogens, the infected area may become large, hampering eradication success (Migliorini et al. 2015). This highlights the need for detection attempts on asymptomatic plants that indeed improved the eradication prospect (see later).

When calculating correlation between variables, most strong associations (V = 0.5) were obtained between pairs of different species traits, both for arthropods and pathogens. These correlations are justified given the high number of cases concentrated on only a few species. The statistical modelling used were able to deal with collinearity to an extent: for the LASSO regression when multiple variables are correlated they will be penalized leading to one unique predictor becoming important; for the tree-regression it chooses the variables that lead to the best split in the data. Nevertheless, it is important to note, that potentially some of the correlated variables could have been used as surrogate in the LASSO or tree regression.

Management options

An outstanding result of our study is that management options did not emerge as a relevant predictor variable of eradication success. This might be due to the fact that host plant removal, almost always combined with other treatments, was the commonly used management strategy for both arthropods and pathogens. Chemical control alone leads to very low success rates (25%). Other management options are very species-specific, such as the use of tree climbers for *A. glabripennis* monitoring, nest removal for oak and pine processionary moth control, and vector control for several vector transmitted pathogens and thus, do not allow extrapolation to general guidelines. Also, generally similar eradication measures were applied everywhere for a given species, because frequently these measures are mandatory according to European regulations.

Another main significant outcome of our review is the importance of quarantine measures for the success of arthropod eradication. For pathogens, however, the implementation of such measures was relevant only when the target organisms were wind-borne. The intensification of surveys, at least in an annual rhythm, was shown to be relevant both for the detection of pathogen infection before establishment and for the success of eradication. Giving up the efforts of surveillance and control after a while, especially when the populations are under low levels and difficult to detect, is a common error leading to unsuccessful eradication campaigns (Simberloff 2002;

Liebhold and Tobin 2008; Tobin et al. 2014). Therefore, persisting in monitoring for several years after the last detection can be crucial for the success of programmes. Tobin et al. (2014) reported that the existence of a sensitive monitoring tool (such as pheromone traps) was one of the most important predictors in the success of an eradication campaign against arthropods. However, in our study, the use of a semiochemical lure neither affected the outcome of an eradication campaign nor the probability of establishment, and the use of traps for monitoring only slightly increased the eradication success. In the study by Tobin et al. (2014), however, the authors highlighted that when *Lymantria dispar* and *Ceratitis capitata* were excluded from the analysis, the use of targeted traps or lures was no longer significant in the outcome of an eradication attempt. The high efficiency of the available semiochemical lures for these two species may contrast with the lures currently available for the arthropod species targeted for eradication in Europe. For *A. glabripennis*, for e.g., a recent study has shown that the available pheromone traps, although recommended for monitoring and mass trapping of this insect, are inefficient at intercepting the pest (Marchioroand Faccoli 2021). For pathogens, we observed that an overall higher success rate of eradication was observed when asymptomatic plants were also sampled (60% to 92%), compared to when only symptomatic trees were sampled 51% to 74%.

Conclusions

We conducted a thorough review of the eradication programmes carried out in Europe against arthropods and pathogens of woody plants and their successes or failures. Contrary to the general scepticism regarding the potential success of eradication measures, our review demonstrates that eradication programmes can be very successful, especially when detections occurred at an early stage of invasions and when the infested areas were still small. Difficulties in eradication are naturally higher in the countryside conditions in comparison with confined environments. In this respect, pests and pathogens of woody plants are as difficult to eradicate in urban and peri-urban areas as in rural forests and orchards.

We should be aware that the high success reported in previous studies and databases results in part from the inclusion of cases in which pests and pathogens were still restricted to the primary plant material with which they were introduced. After removing these cases the overall success dropped to 50%. Thus, particular attention should be paid to imported primary plant materials, involving the awareness of different actors and not only Plant Protection Inspectors.

It is surprising that eradication efforts in Europe targeted only a small group of non-native species (<10% of the non-native organisms affecting woody plants). Since the decision to carry out an eradication program is taken at the national level and frequently imposed also at the European level, we believe that more species could be considered for eradication if policymakers would be better informed about the advantages of eradication measures and actions taken quickly to ensure success of eradication.

This leads to responsibilities for the scientific community in transmitting these pieces of information to policymakers.

Management strategies used in eradication programmes are very species specific and there is no general golden rule in this respect. Still, most of the successful programmes invested in integrating multiple methods combined with relentless and persistent monitoring.

Acknowledgements

This work was funded by the European Union's Horizon 2020 Program for Research and Innovation under grant agreement no. 771271 "HOMED"

S. Branco, M. Branco, and J.C Franco were supported by Forest Research Centre (CEF), (UID/AGR/00239/2019 and (UIDB/00239/2020). and by the Laboratory for Sustainable Land Use and Ecosystem Services–TERRA (LA/P/0092/2020), research units funded by the Foundation for Science and Technology (FCT), Portugal.

We would also like to thank the plant protection organizations of the following countries (or regions), for kindly providing additional information on the reported eradication attempts: Austria- Federal Ministry Of Agriculture, Regions And Tourism; Belgium- Federal Agency for the Safety of the Food Chain; Croatia- Agency for Agriculture and Food; Finland- Plant Health Unit Ruokavirasto / Finnish Food Authority; France- Département de la Santé des Forêts (C. Husson); Germany- Julius Kühn-Institute – Federal Research Centre for Cultivated Plants, Institute for National and International Plant Health; Hungary- National Food Chain Safety Office; Italy (Piemonte)- Settore Fitosanitario e Servizi Tecnico-Scientifici, Regione Piemonte; Lithuania- State Plant Service under the Ministry of Agriculture; Netherlands- Netherlands Plant Protection Organization; Slovenia- Ministry of Agriculture, Forestry and Food; Spain- Área de Sanidad Vegetal y Forestal de Sanidad e Higiene Vegetal y Forestal; Switzerland- Federal Office for Agriculture, Plant Health and Varieties; United Kingdom – Department for Environment, Food and Rural Affairs.

References

Abbott A (2015) Italian scientists under investigation after olive-tree deaths. Nature 522(7554): 13–15. https://doi.org/10.1038/nature.2015.17651

Blackburn TM, Pyšek P, Bacher S, Carlton JT, Duncan RP, Jarošík V, Wilson JR, Richardson DM (2011) A proposed unified framework for biological invasions. Trends in Ecology & Evolution 26(7): 333–339. https://doi.org/10.1016/j.tree.2011.03.023

Blackwood JC, Berec L, Yamanaka T, Epanchin-Niell RS, Hastings A, Liebhold AM (2012) Bioeconomic synergy between tactics for insect eradication in the presence of Allee effects. Proceedings of the Royal Society B: Biological Sciences 279(1739): 2807–2815. https://doi.org/10.1098/rspb.2012.0255

Blackwood JC, Vargas Jr R, Fauvergue X (2018) A cascade of destabilizations: Combining Wolbachia and Allee effects to eradicate insect pests. Journal of Animal Ecology 87(1): 59–72. https://doi.org/10.1111/1365-2656.12756

Branco M, Nunes P, Roques A, Fernandes MR, Orazio C, Jactel H (2019) Urban trees facilitate the establishment of non-native forest insects. NeoBiota 52: 25–46. https://doi.org/10.3897/neobiota.52.36358

Branco S, Faccoli M, Brockerhoff EG, Roux G, Jactel H, Desneux N, Gachet E, Mouttet R, Streito JC, Branco M (2021) Preventing invasions of Asian longhorn beetle and citrus longhorn beetle: Are we on the right track? Journal of Pest Science 21: 1–26. https://doi.org/10.1007/s10340-021-01431-x

Brasier C, Webber J (2010) Sudden larch death. Nature 466(7308): 824–825. https://doi.org/10.1038/466824a

Brasier CM, Robredo F, Ferraz JF (1993) Evidence for *Phytophthora cinnamomi* involvement in Iberian oak decline. Plant Pathology 42(1): 140–145. https://doi.org/10.1111/j.1365-3059.1993.tb01482.x

Brockerhoff EG, Liebhold AM (2017) Ecology of forest insect invasions. Biological Invasions 19(11): 3141–3159. https://doi.org/10.1007/s10530-017-1514-1

Brockerhoff EG, Liebhold AM, Jactel H (2006) The ecology of forest insect invasions and advances in their management. Canadian Journal of Forest Research 36(2): 263–268. https://doi.org/10.1139/x06-013

Brockerhoff EG, Liebhold AM, Richardson B, Suckling DM (2010) Eradication of invasive forest insects: Concepts, methods, costs and benefits. New Zealand Journal of Forestry Science 40(suppl.): S117–S135.

CABI (2019) Invasive Species Compendium. CAB International, Wallingford.

CBD [Convention on Biological Diversity] (2008) Alien Species that Threaten Ecosystems, Habitats or Species [Article 8(h)], United Nations. Climate-Data.org. https://en.climate-data.org/europe

Cordero-Rivera A, Santolamazza-Carbone S, Andrés JA (1999) Life cycle and biological control of the Eucalyptus snout beetle (Coleoptera, Curculionidae) by *Anaphes nitens* (Hymenoptera, Mymaridae) in north-west Spain. Agricultural and Forest Entomology 1(2): 103–109. https://doi.org/10.1046/j.1461-9563.1999.00016.x

Dale AL, Feau N, Berube JA, Ponchart J, Bilodeau GJ, Hamelin RC (2022) Urban environments harbor greater oomycete and *Phytophthora* diversity, creating a bridgehead for potential new pathogens to natural ecosystems. Environmental DNA 00(5): 1–13. https://doi.org/10.1002/edn3.300

DEFRA [Department for Environment, Food and Rural Affairs] (2022) Department for Environment, Food and Rural Affairs. https://www.gov.uk/guidance/managing-oak-processionary-moth-in-england#oak-processionary-moth-opm-thaumetopoea-processionea

Desprez-Loustau M-L, Aguayo J, Dutech C, Hayden K, Husson C, Jakushkin B, Marçais B, Piou D, Robin C, Vacher C (2016) An evolutionary ecology perspective to address forest pathology challenges of today and tomorrow. Annals of Forest Science 73(1): 45–67. https://doi.org/10.1007/s13595-015-0487-4

Elton CS (1958) The Ecology of Invasions by Animals and Plants. Methuen, London. https://doi.org/10.1007/978-1-4899-7214-9

EPPO [European and Mediterranean Plant Protection Organization] (2021) EPPO activities on plant quarantine. https://www.eppo.int/ACTIVITIES/quarantine_activities

EPPO – Global Database (2022) Global Database. https://gd.eppo.int/

FAO (2019) Glossary of Phytosanitary Terms. International Standard for Phytosanitary Measures No. 5. FAO, Rome, 35 pp.

Ganley RJ, Bulman LS (2016) Dutch elm disease in New Zealand: Impacts from eradication and management programmes. Plant Pathology 65(7): 1047–1055. https://doi.org/10.1111/ppa.12527

Garbelotto M, Lione G, Martiniuc AV, Gonthier P (2022) The alien invasive forest pathogen *Heterobasidion irregulare* is replacing the native *Heterobasidion annosum*. Biological Invasions 25(8): 1–5. https://doi.org/10.1007/s10530-022-02775-w

Ghelardini L, Pepori AL, Luchi N, Capretti P, Santini A (2016) Drivers of emerging fungal diseases of forest trees. Forest Ecology and Management 381: 235–246. https://doi.org/10.1016/j.foreco.2016.09.032

Ghelardini L, Luchi N, Pecori F, Pepori AL, Danti R, Della Rocca G, Capretti P, Tsopelas P, Santini A (2017) Ecology of invasive forest pathogens. Biological Invasions 19(11): 3183–3200. https://doi.org/10.1007/s10530-017-1487-0

Goheen EM, Kanaskie A, Navarro S, Hansen E (2017) Sudden oak death management in Oregon tanoak forests. Forest Phytophthoras 7(1): 45–53. https://doi.org/10.5399/osu/fp.7.1.4030

Haack RA, Britton KO, Brockerhoff EG, Cavey JF, Garrett LJ, Kimberley M, Lowenstein F, Nuding A, Olson LJ, Turner J, Vasilaky KN (2014) Effectiveness of the International Phytosanitary Standard ISPM No. 15 on reducing wood borer infestation rates in wood packaging material entering the United States. PLoS ONE 9(5): e96611. https://doi.org/10.1371/journal.pone.0096611

Hamelin RC, Roe AD (2020) Genomic biosurveillance of forest invasive alien enemies: A story written in code. Evolutionary Applications 13(1): 95–115. https://doi.org/10.1111/eva.12853

Hansen E, Reeser P, Sutton W, Kanaskie A, Navarro S, Goheen EM (2019) Efficacy of local eradication treatments against the sudden oak death epidemic in Oregon tanoak forests. Forest Pathology 49(4): e12530. https://doi.org/10.1111/efp.12530

Henricot B, Culham A (2002) *Cylindrocladium buxicola*, a new species affecting *Buxus* spp., and its phylogenetic status. Mycologia 94(6): 980–997. https://doi.org/10.1080/15572536.2003.11833155

Hunter GC, Wylder B, Jones B, Webber JF (2013) First finding of *Cryphonectria parasitica* causing chestnut blight on *Castanea sativa* trees in England. New Disease Reports 27(1): 1–1. https://doi.org/10.5197/j.2044-0588.2013.027.001

Jeffries MJ, Lawton JH (1984) Enemy free space and the structure of ecological communities. Biological journal of the Linnean Society 23(4): 269–286. https://doi.org/10.1111/j.1095-8312.1984.tb00145.x

Kean JM, Suckling DM, Sullivan NJ, Tobin PC, Stringer LD, Smith GR, Kimber B, Lee DC, Flores Vargas R, Fletcher J, Macbeth F, McCullough DG, Herms DA, et al. (2022) Global eradication and response database. http://b3.net.nz/gerda

Liebhold A, Bascompte J (2003) The Allee effect, stochastic dynamics and the eradication of alien species. Ecology Letters 6(2): 133–140. https://doi.org/10.1046/j.1461-0248.2003.00405.x

Liebhold AM, Kean JM (2019) Eradication and containment of non-native forest insects: Successes and failures. Journal of Pest Science 92(1): 83–91. https://doi.org/10.1007/s10340-018-1056-z

Liebhold AM, Tobin PC (2008) Population ecology of insect invasions and their management. Annual Review of Entomology 53(1): 387–408. https://doi.org/10.1146/annurev.ento.52.110405.091401

Liebhold AM, Brockerhoff EG, Garrett LJ, Parke JL, Britton KO (2012) Live plant imports: The major pathway for forest insect and pathogen invasions of the US. Frontiers in Ecology and the Environment 10(3): 135–143. https://doi.org/10.1890/110198

Liebhold AM, Berec L, Brockerhoff EG, Epanchin-Niell RS, Hastings A, Herms DA, Kean JM, McCullough DG, Suckling DM, Tobin PC, Yamanaka T (2016) Eradication of invading insect populations: From concepts to applications. Annual Review of Entomology 61(1): 335–352. https://doi.org/10.1146/annurev-ento-010715-023809

Luchi N, Ioos R, Santini A (2020) Fast and reliable molecular methods to detect fungal pathogens in woody plants. Applied Microbiology and Biotechnology 104(6): 2453–2468. https://doi.org/10.1007/s00253-020-10395-4

Marchioro M, Faccoli M (2021) Successful Eradication of the Asian Longhorn Beetle, *Anoplophora glabripennis*, from North-Eastern Italy: Protocol, Techniques and Results. Insects 12(10): e877. https://doi.org/10.3390/insects12100877

Meurisse N, Rassati D, Hurley BP, Brockerhoff EG, Haack RA (2019) Common pathways by which non-native forest insects move internationally and domestically. Journal of Pest Science 92(1): 13–27. https://doi.org/10.1007/s10340-018-0990-0

Migliorini D, Ghelardini L, Tondini E, Luchi N, Santini A (2015) The potential of symptomless potted plants for carrying invasive soilborne plant pathogens. Diversity & Distributions 21(10): 1218–1229. https://doi.org/10.1111/ddi.12347

Myers JH, Simberloff D, Kuris AM, Carey JR (2000) Eradication revisited: Dealing with exotic species. Trends in Ecology & Evolution 15(8): 316–320. https://doi.org/10.1016/S0169-5347(00)01914-5

Nadeau BL (2015) The battle of olives. Scientific American 313(5): 52–59. https://doi.org/10.1038/scientificamerican1115-52

Nunes P, Robinet C, Branco M, Franco JC (2023) Modelling the invasion dynamics of the African citrus psyllid: The role of human-mediated dispersal and urban and peri-urban citrus trees. In: Jactel H, Orazio C, Robinet C, Douma JC, Santini A, Battisti A, Branco M, Seehausen L, Kenis M (Eds) Conceptual and technical innovations to better manage invasions of alien pests and pathogens in forests. NeoBiota 84: 369–396. https://doi.org/10.3897/neobiota.84.91540

Paap T, Burgess TI, Wingfield MJ (2017) Urban trees: Bridge-heads for forest pest invasions and sentinels for early detection. Biological Invasions 19(12): 3515–3526. https://doi.org/10.1007/s10530-017-1595-x

Paap T, Wingfield MJ, Burgess TI, Wilson JR, Richardson DM, Santini A (2022) Invasion frameworks: A forest pathogen perspective. Current Forestry Reports 21(1): 1–6. https://doi.org/10.1007/s40725-021-00157-4

Pautasso M, Aas G, Queloz V, Holdenrieder O (2013) European ash (*Fraxinus excelsior*) dieback–A conservation biology challenge. Biological Conservation 158: 37–49. https://doi.org/10.1016/j.biocon.2012.08.026

Peel MC, Finlayson BL, McMahon TA (2007) Updated world map of the Köppen-Geiger climate classification. Hydrology and earth system sciences 11(5): 1633–44. https://doi.org/10.5194/hess-11-1633-2007

Pimentel D [Ed.] (2002) Biological Invasions: Economic and Environmental Costs of Alien Plant, Animal and Microbe Species. CRC Press, Boca Raton. https://doi.org/10.1201/9781420041668

Pluess T, Cannon R, Jarošík V, Pergl J, Pyšek P, Bacher S (2012a) When are eradication campaigns successful? A test of common assumptions. Biological Invasions 14(7): 1365–1378. https://doi.org/10.1007/s10530-011-0160-2

Pluess T, Jarošík V, Pyšek P, Cannon R, Pergl J, Breukers A, Bacher S (2012b) Which factors affect the success or failure of eradication campaigns against alien species? PLoS ONE 7(10): e48157. https://doi.org/10.1371/journal.pone.0048157

Poland TM, McCullough DG (2006) Emerald ash borer: Invasion of the urban forest and the threat to North America's ash resource. Journal of Forestry 104(3): 118–124. https://doi.org/10.1093/jof/104.3.118

Porth EF, Dandy N, Marzano M (2015) "My garden is the one with no trees:" residential lived experiences of the 2012 Asian longhorn beetle eradication programme in Kent, England. Human Ecology: an Interdisciplinary Journal 43(5): 669–679. https://doi.org/10.1007/s10745-015-9788-3

Romon-Ochoa P, Kranjec Orlović J, Gorton C, Lewis A, van der Linde S, Pérez-Sierra A (2022) New detections of chestnut blight in Great Britain during 2019–2020 reveal high *Cryphonectria parasitica* diversity and limited spread of the disease. Plant Pathology 71(4): 793–804. https://doi.org/10.1111/ppa.13523

Roques A, Auger-Rozenberg MA, Blackburn TM, Garnas J, Pyšek P, Rabitsch W, Richardson DM, Wingfield MJ, Liebhold AM, Duncan RP (2016) Temporal and interspecific variation in rates of spread for insect species invading Europe during the last 200 years. Biological Invasions 18(4): 907–920. https://doi.org/10.1007/s10530-016-1080-y

Roques A, Shi J, Auger-Rozenberg MA, Ren L, Augustin S, Luo YQ (2020) Are invasive patterns of non-native insects related to woody plants differing between Europe and China? Frontiers in Forests and Global Change 15(2): e91. https://doi.org/10.3389/ffgc.2019.00091

Sala OE, Chapin FS III, Armesto JJ, Berlow E, Bloomfield J, Dirzo R, Huber-Sanwald E, Huenneke LF, Jackson RB, Kinzig A, Leemans R (2000) Global biodiversity scenarios for the year 2100. Science 287(5459): 1770–1774. https://doi.org/10.1126/science.287.5459.1770

Santini A, Ghelardini L, De Pace C, Desprez-Loustau ML, Capretti P, Chandelier A, Cech T, Chira D, Diamandis S, Gaitniekis T, Hantula J (2013) Biogeographical patterns and determinants of invasion by forest pathogens in Europe. The New Phytologist 197(1): 238–250. https://doi.org/10.1111/j.1469-8137.2012.04364.x

Seebens H, Blackburn TM, Dyer EE, Genovesi P, Hulme PE, Jeschke JM, Pagad S, Pyšek P, Winter M, Arianoutsou M, Bacher S, Blasius B, Brundu G, Capinha C, Celesti-Grapow L, Dawson W, Dullinger S, Fuentes N, Jäger H, Kartesz J, Kenis M, Kreft H, Kühn I, Lenzner

B, Liebhold A, Mosena A, Moser D, Nishino M, Pearman D, Pergl J, Rabitsch W, Rojas-Sandoval J, Roques A, Rorke S, Rossinelli S, Roy HE, Scalera R, Schindler S, Štajerová K, Tokarska-Guzik B, van Kleunen M, Walker K, Weigelt P, Yamanaka T, Essl F (2017) No saturation in the accumulation of alien species worldwide. Nature Communications 8(1): e14435. https://doi.org/10.1038/ncomms14435

Seemüller E, Schneider B (2004) '*Candidatus Phytoplasma mali*','*Candidatus Phytoplasma pyri*' and '*Candidatus Phytoplasma prunorum*', the causal agents of apple proliferation, pear decline and European stone fruit yellows, respectively. International Journal of Systematic and Evolutionary Microbiology 54(4): 1217–1226. https://doi.org/10.1099/ijs.0.02823-0

Sequeira R, Griffin R (2014) The biosecurity continuum and trade: Pre-border operations. The Handbook of Plant Biosecurity. Springer, The Netherlands, 119–148. https://doi.org/10.1007/978-94-007-7365-3_5

Sikes BA, Bufford JL, Hulme PE, Cooper JA, Johnston PR, Duncan RP (2018) Import volumes and biosecurity interventions shape the arrival rate of fungal pathogens. PLoS Biology 16(5): e2006025. https://doi.org/10.1371/journal.pbio.2006025

Simberloff D (2002) Today Tiritiri Matangi, tomorrow the world! Are we aiming too low in invasives control? Turning the tide: the eradication of invasive species, 4–12.

Simberloff D (2003) Eradication—Preventing invasions at the outset. Weed Science 51(2): 47–253. https://doi.org/10.1614/0043-1745(2003)051[0247:EPIATO]2.0.CO;2

Smith GR, Fletcher JD, Marroni V, Kean JM, Stringer LD, Vereijssen J (2017) Plant pathogen eradication: Determinants of successful programs. Australasian Plant Pathology 46(3): 277–284. https://doi.org/10.1007/s13313-017-0489-9

Sosnowski MR, Fletcher JD, Daly AM, Rodoni BC, Viljanen-Rollinson SL (2009) Techniques for the treatment, removal and disposal of host material during programmes for plant pathogen eradication. Plant Pathology 58(4): 621–635. https://doi.org/10.1111/j.1365-3059.2009.02042.x

Suckling DM, Stringer LD, Kean JM (2021) Trends in Arthropod Eradication Programmes from the Global Eradication Database, Gerda. Area-Wide Integrated Pest Management. CRC Press, 505–518. https://doi.org/10.1201/9781003169239-26

Tibshirani R (1996) Regression Shrinkage and Selection via the Lasso. Journal of the Royal Statistical Society, Series B (Methodological) 58(1): 267–288. https://doi.org/10.1111/j.2517-6161.1996.tb02080.x

Tobin PC, Kean JM, Suckling DM, McCullough DG, Herms DA, Stringer LD (2014) Determinants of successful arthropod eradication programs. Biological Invasions 16(2): 401–414. https://doi.org/10.1007/s10530-013-0529-5

UK GOV (2019) A coordinated response to the oak processionary moth outbreak. Forestry commission Blog. https://forestrycommission.blog.gov.uk/2019/10/11/a-coordinated-response-to-the-oak-processionary-moth-outbreak/

Valente C, Gonçalves CI, Monteiro F, Gaspar J, Silva M, Sottomayor M, Paiva MR, Branco M (2018) Economic outcome of classical biological control: A case study on the Eucalyptus snout beetle, *Gonipterus platensis*, and the parasitoid *Anaphes nitens*. Ecological Economics 149: 40–47. https://doi.org/10.1016/j.ecolecon.2018.03.001

Vettraino AM, Morel O, Perlerou C, Robin C, Diamandis S, Vannini A (2005) Occurrence and distribution of *Phytophthora* species in European chestnut stands, and their association with Ink Disease and crown decline. European Journal of Plant Pathology 111(2): 169–180. https://doi.org/10.1007/s10658-004-1882-0

Werres S, Marwitz R, In't Veld WA, De Cock AW, Bonants PJ, De Weerdt M, Themann K, Ilieva E, Baayen RP (2001) *Phytophthora ramorum* sp. nov., a new pathogen on *Rhododendron* and *Viburnum*. Mycological Research 105(10): 1155–1165. https://doi.org/10.1016/S0953-7562(08)61986-3

Wolfe LM (2002) Why alien invaders succeed: Support for the escape-from-enemy hypothesis. American Naturalist 160(6): 705–711. https://doi.org/10.1086/343872

Supplementary material 1

Eradication database

Authors: Sofia Branco, Manuela Branco

Data type: List of eradication attempts against non-native pests and pathogens of woody plants in Europe (excel document)

Explanation note: Database including the following information for each case (when available): i) species under eradication, ii) detection date, country, and location; iii) detection method (passive surveillance (i.e. casual observations reported by researchers, technician or citizens) or official survey conducted with that purpose; iv) establishment status (established or post-border interception); v) affected hosts; vi) host type (broadleaves, conifers, palms), vi) control methods used (chemical, host removal, biological, traps); vii) size of the infested area (as exact area information was not always available we defined it in categories ≤ 1 ha, > 1 ≤ 10, > 10 ≤ 100, > 100 ≤ 1000 or > 1000 ha); viii) environments infested (urban/peri-urban, protected green-houses, countryside); ix) climate, categorized as Temperate, Mediterranean or Continental according to Köppen classification system (Peel et al. 2007); x) programme start year, last detection, and date of eradication declared; xi) public education, and xii) the outcome, i.e. legal status (eradicated, under eradication, failure to eradicate.

Link: https://doi.org/10.3897/neobiota.84.95687.suppl1

Supplementary material 2

Correlation matrix

Authors: Jacob C. Douma, Sofia Branco

Data type: Results of statistical analysis (excel document)

Explanation note: Correlations between predictor variables, using Cramers' V.

Link: https://doi.org/10.3897/neobiota.84.95687.suppl2

Supplementary material 3

Establishment success analysis, using LASSO regression and decision trees

Authors: Jacob C. Douma, Sofia Branco

Data type: Statistical analysis (word document)

Explanation note: Analysis of the factors affecting establishment success for non-native species of arthropods and pathogens of woody plants in Europe, using LASSO regression and decision trees.

Link: https://doi.org/10.3897/neobiota.84.95687.suppl3