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Abstract
<p>Task 5.1 of Work Package (WP) 5 involves reviewing available literature on the existing and potential economic costs associated with the damages caused by, and management of, the five focus pests of the PurPest project. The outputs of this task also support related tasks within WP5 concerned with forecasting economic costs and benefits of the plant pest prevention technology being developed under this project. Categories to target for reviews of each pest, that are pertinent to their economic consequences, were identified. Targeted searches were then conducted using the Google Scholar and Web of Science databases. Generally, we obtained sufficient information for each of the aforementioned categories for each pest, though knowledge gaps were identified in some areas, particularly surrounding costs associated with exclusionary and preventative measures. Moving forward, we plan to expand these outputs into a review article on the economic consequences of invasive plant pests, using the five focus pests of the PurPest project as case studies.</p>

Public introduction¹
<p>Work Package (WP) 5 of the PurPest project aims to analyse the social and economic impacts of implementing the plant pest prevention technology being developed by the wider PurPest project. It is essential to consider the costs associated with both damages exerted by plant pests, and the currently available options used to prevent and control them, to in turn investigate the potential economic benefits of applying new technologies. As biosecurity and plant pest specialists, our task (Task 5.1) comprises reviewing the available literature for information pertaining to existing and/or potential economic costs associated with the five focus pests of the PurPest project, in the European context. Generally, this includes existing or future distribution of the pests, costs of preventative measures, pest population growth and spread, and costs associated with pest damage and the control options used. Furthermore, the information and data gathered from these reviews will be utilised for other tasks in WP5 that employ mathematical modelling to forecast the potential economic benefits of the plant pest prevention technology being developed by this project. Here, we provide a progress update for Task 5.1 of WP5, and outline plans for future publication of these outputs.</p>

¹ According to Deliverables list in Annex I, all restricted (RE) deliverables will contain an introduction that will be made public through the project WEBSITE

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1 REVIEWING LITERATURE ON COSTS AND DAMAGES

In accordance with Task 5.1 of WP5, we reviewed the available literature for information and data pertaining to the existing and potential damages caused, and consequent economic impacts, for each of the five focus pest species in the PurPest project. This information will support colleagues who will conduct modelling to predict and forecast regional costs associated with these pests (Task 5.2), and a cost-benefit assessment of management scenarios (Task 5.4). The literature that was reviewed was therefore targeted towards the data that is required to construct such economic impact models. Published modelling studies that were consulted to guide the literature reviews include Carrasco et al. (2010), Wessler & Fall (2010), Soliman et al. (2012), and Soliman et al. (2015). Generally, we considered the potential distribution of each pest within Europe to assess the regional risk of invasion and spread. Exclusion and incursion detection measures, and their associated costs, were also reviewed. Biological data pertaining to population growth and spread was considered as this is necessary to inform the spatial extent of potential damage. We then reviewed the existing control measures used against each pest and the costs associated with their application. Finally, damages caused by each pest, and consequent economic cost, were considered both in the absence of control measures and where available, for each existing control measure previously identified. To obtain the relevant literature we searched the Google Scholar and Web of Science databases using the focus pest and variations of the abovementioned categories as key words.

1.1 *Spodoptera frugiperda* (fall armyworm)

Spodoptera frugiperda is a highly polyphagous horticultural pest native to the Americas, with its range recently expanding as an invasive species in Africa, Asia, Australia, and New Zealand (Kenis et al., 2022). Due to its seasonal trans-latitude migratory behaviour, and therefore substantial long-distance dispersal capacity, there is a high risk of invasion to Europe from established populations in North Africa, as well as seasonal infestations in cooler climates (Timilsena et al., 2022; Wang et al., 2023). Very recently, the presence of *S. frugiperda* has been reported in Europe, with detections on Madeira Island in Portugal, and in Greece (EPPO, 2023a, b). With regards to economic injury, this pest is particularly damaging to maize, rice, and sorghum (Kenis et al., 2022), with the greatest losses and the majority of research focusing on the former. Yield loss of maize is also the primary concern in a European context (Babendreier et al., 2022), and our literature review is therefore focused on this crop. Due to the urgency associated with the rapid spread and significant damage throughout its invasive ranges, there is a significant and diverse body of literature surrounding *S. frugiperda* as an invasive species. It was therefore possible to provide an in-depth review on the abovementioned categories for *S. frugiperda*, particularly its potential permanent and seasonal distributions in Europe, biological and ecological characteristics pertaining to its establishment and spread, costs associated with existing control options, and yield loss and associated costs in both control and no control scenarios. However, we were not able to obtain detail on the economic costs of implemented exclusionary measures, which would be useful for overall quantification and forecasting of regional costs and cost-benefit assessment of management scenarios. The full review outline for *S. frugiperda* is provided in Appendix 1.

Information pertaining to the impact and control of *S. frugiperda* in a European context is also covered by recent review articles (Babendreier et al., 2022; Kenis, 2023).

1.2 *Helicoverpa armigera* (cotton bollworm)

Helicoverpa armigera is a highly polyphagous horticultural pest with a widespread natural distribution spanning Africa, southern Europe, Asia, and Australasia (Tay et al., 2013), though has recently invaded South America (CABI, 2023). The trans-latitudinal seasonal migratory behaviour exhibited over long distances by *H. armigera* poses transient risk to European countries (extending to northern Europe) where the climate is not suitable for its permanent establishment (Baker et al., 2014; Kriticos et al., 2015). Although *H. armigera* can damage a wide variety of crops, in southern Europe, economic injury is particularly severe in tomatoes in Italy and Spain, and in cotton in Greece. Other important crops in Europe that are favoured host plants of *H. armigera* include chickpea, cotton, maize, and soybean (Baker et al., 2014). Our review on costs and damages in the European context therefore focused on these crops. Due to the extensive and diverse literature on *H. armigera* as a pest, it was possible to provide an in-depth review on the categories mentioned above for *S. frugiperda*. This includes detailed data on yield loss for each of the abovementioned crops in no control scenarios, and for the identified existing control measures for each crop in control scenarios, which will be useful in informing forecast modelling of economic costs and benefits of management scenarios. However, there are some areas, for example on the impact of control measures, where data is scant for Europe, which represents an important knowledge gap. Additionally, although exclusionary measures are clearly outlined in relevant legislation (EPPO, 2020; UK Government, 2020; VKM, 2021; EPPO 2023), we were not able to obtain detail on the economic costs of implementing such measures. The full review outline for *H. armigera* is provided in Appendix 2.

We are not aware of any peer-reviewed review articles for *H. armigera* as a pest in the European context. However, there exists a disparate variety of published studies and grey literature relevant to the pest status and control of *H. armigera* in Europe, in addition to knowledge gaps that are highlighted by studies in other regions.

1.3 *Halyomorpha halys* (brown marmorated stink bug)

Halyomorpha halys is a highly polyphagous pest native to Asia, and is invasive in North America and Europe (CABI, 2023). This pest was accidentally introduced into Europe (Switzerland) around 2004 (Haye et al., 2015), and is now widespread across the majority of mainland Europe (CABI, 2023). It can damage a wide variety of fruit and vegetable crops, though in Europe, extensive damage has predominantly been reported from fruit growing regions in Italy (Moraglio et al., 2020) with some additional data being available for Switzerland and Austria. Due to data availability, the costs and damages portion of our review therefore primarily focused on apples, though limited data for Europe necessitated a reliance on studies in North America. Generally, the substantial interest in *H. halys* as an invasive species provided an abundance of literature to review on the categories mentioned above for *S. frugiperda*. However, because *H. halys* is already widespread throughout Europe, much of this information needs to be considered within this context, particularly with regards to how the data is used to inform the modelling work on forecasting regional costs, and the costs and benefits of management scenarios. For instance, CLIMEX models on the potential distribution of *H. halys* in Europe may not be as useful for a pest that is now widespread throughout the predicted suitable areas, though some areas predicted to be unsuitable may still be considered for a wider assessment of regional impact. Similarly, exclusionary and detection measures undertaken in other countries, such as New Zealand (Jamieson et al., 2022), to prevent incursion are not relevant to Europe, and these aspects should be considered at the level of in-field detection. Furthermore, much of the data on the impact of control measures on yield loss is only available for insecticide applications in the

US, with very little available for Europe. Many of the insecticides used in the US are also banned in Europe, or under temporary emergency license for use against *H. halys*. There is limited data available for the impact of other control measures on crop losses from *H. halys*. The full review outline for *H. halys* is provided in Appendix 3.

Although peer-reviewed articles exist that cover *H. halys* as an invasive pest, including in the European context, these were published at a time when substantial damages were only beginning to be realised in some areas in Europe (e.g. Haye et al., 2015; Lee et al., 2015; Bariselli et al., 2016). These articles may therefore not completely represent the current situation for *H. halys* with regards to research and reporting of economic damages and control options.

1.4 *Phytophthora ramorum*

Phytophthora ramorum is an oomycete plant pathogen with a very wide host range (Sansford et al., 2009) that emerged simultaneously in the US and Europe in the 1990's and is now widespread in both continents. In the US it primarily caused oak decline in forests (Grünwald et al., 2019). In Europe, it initially primarily caused damage to ornamental plants in nurseries and plantings where it occurs commonly (Jung et al., 2016), but in 2009 a host shift occurred in the United Kingdom to coniferous forest trees, particularly economically and environmentally important larch trees, which have experienced widespread decline and mortality (Brasier & Webber, 2010; Jung et al., 2018). Shortly after, a separate unique lineage of *P. ramorum* was identified in the United Kingdom (Van Poucke et al., 2012). These events triggered renewed biosecurity concerns regarding *P. ramorum* in Europe. Recently, the origin of *P. ramorum* has been unveiled in the laurosilva forests of East Asia and eight new lineages of *P. ramorum* have been detected in Japan and Vietnam (Jung et al., 2021). The epidemiological complexity of the disease in Europe (and North American and Asian lineages which currently do not occur in Europe) meant that it was important to distinguish between diseases of ornamental plants in nurseries and outplantings, cankers of tree species in parks and forests associated with infected ornamental shrubs, the "Sudden Larch Death" epidemic, and the different lineages when conducting our review. The broad categories outlined for the herbivorous insect pests, related to exclusionary measures, detection, spread, damages, and control, were also applicable to review for *P. ramorum*. We were able to obtain consistent detail when reviewing literature amongst these categories for the differently impacted sectors. Crucially, it was possible to provide cost estimates for each component of exclusionary measures, incursion detection, and specific control measures used, as these calculations were conducted in an impact assessment for *P. ramorum* in the United Kingdom (Sansford et al., 2009). These data will be very useful in informing parameters for cost forecasting models. However, we were not able to obtain information on the costs of the remaining EU phytosanitary requirements surrounding transport and destruction of nursery plants infected with the European lineages of *P. ramorum*, and it may be useful to pursue this information in the future. The full review outline for *P. ramorum* is provided in Appendix 4.

Although a relatively recent review paper exists on the ecology and evolution of *P. ramorum* (Grünwald et al., 2019), covering both the US and Europe, we are not aware of any publications that cover its impact and management.

1.5 *Bursaphelenchus xylophilus* (pinewood nematode)

Bursaphelenchus xylophilus is native to North America. It invaded Asia more than 100 years ago and more recently also Europe, where it is currently present in Portugal and Spain (Mallez et al., 2014). It is transmitted by different native Cerambycid beetles of the genus *Monochamus*, which

are widespread in Europe (GBIF, 2023). The nematode is the causative agent of pine wilt disease (PWD) in the invaded areas. As a vectored disease-causing agent, there are fundamentally multiple limiting factors that could influence the distribution of disease expression, comprising the distribution of suitable coniferous host plants, the distribution of *Monochamus* spp. vectors, and climatic limitations on the ability of *B. xylophilus* to cause disease expression (Sousa et al., 2001; Evans et al., 2009; Gruffud et al., 2016). It was therefore important to consider this complexity in our review. All of the above-mentioned categories targeted for review have been extensively studied for *B. xylophilus*, including in the European context, and we were able to obtain in-depth information for each category. A number of modelling studies focusing on Europe, that include entry, establishment, spread, damage, control, and economic cost components, were particularly useful for obtaining detailed data on these aspects that is relevant to the European context, despite the majority of the EPPO region currently being free of *B. xylophilus*. This includes expansive information on exclusion and detection measures compared to the other pest species covered by the PurPest project, which is of utmost importance for a pest with a currently restricted distribution in Europe. The full review outline is provided in Appendix 5.

Although aspects related to existing and potential damages and economic costs of pinewood nematode have been extensively studied, including in the European context, we are not aware of any recent published review articles on this pest from a European focus. However, Soliman et al. (2012) provides a framework for modelling the economic impacts of invasive species, using the pinewood nematode as a case study.

1.6 Publication plan

There is scope to combine and expand the above-outlined literature reviews into an impactful review article. There is variation in the existence and extent of recent review articles that cover costs and damages amongst the five focus pests of the PurPest project. However, together these species comprise five representative case studies of EU priority pests that span different taxonomies, sectoral impacts, and stages of the invasion process. We therefore plan to construct a Europe-focused review article covering studies and assessments on the existing and potential costs associated with the damage caused by, and the control of, these five plant pests. The aim of reviewing this information is to address wider discussion points on the importance and implications of accurately investigating and quantifying economic consequences of priority pests, the extent to which this is achieved and harmonised amongst priority pests, and the interdisciplinary approaches required to more effectively study this crucial issue.

2 CONCLUSION

We have thus far conducted targeted literature reviews for information pertinent to the damages and economic costs of the five pest species covered by the PurPest project, with this information also supporting Tasks 5.2 and 5.4 of WP5. We generally obtained comprehensive information for the identified categories related to economic costs for each pest, though some important knowledge gaps were highlighted in some areas. Current knowledge, in addition to knowledge gaps, on the economic costs of invasive priority plant pests will be addressed by using these five focus pests of the PurPest project as case studies.

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4 APPENDIX 1

Damages and costs associated with *Spodoptera frugiperda* invasion and control, with consideration to the outlook for Europe

<p>Potential distribution of pest</p> <ul style="list-style-type: none"> • Species distribution models <ul style="list-style-type: none"> ○ CLIMEX models ○ Other SDM models 	<p>The substantial migratory ability of <i>S. frugiperda</i> allows transient populations to grow and cause devastating damage in North America during the warmer months, where it cannot grow throughout the year. When considering the potential distribution for <i>S. frugiperda</i> in Europe, we must therefore distinguish between areas of predicted permanent establishment, and predicted transient (seasonal) growth.</p> <ul style="list-style-type: none"> • Predicted permanent establishment: Timilsena et al. (2022) presents CLIMEX model with an irrigation scenario, as irrigation is what allows permanent populations of <i>S. frugiperda</i> in areas it occurs in North Africa that would otherwise be too dry (Mediterranean and Nile River coasts). Europe is predicted to be almost entirely unsuitable for permanent establishment, but small areas of southern Italy, Spain and Portugal may be suitable (see Timilsena et al., 2022, Figure 2c). • Predicted transient (seasonal) growth: Timilsena et al. (2022) also presents a model showing only growth, including an irrigation scenario. A few areas in Europe with humid-continental or Mediterranean climates could support a few generations per year, similar to the transient populations that occur in North America. This is particularly true for Italy and France (see Timilsena et al., 2022, Figure 2d for detail). • Wang et al. (2023) also presents a similar CLIMEX model, but does not consider an irrigation scenario. However, the authors also include an invasion risk model for Europe based on the areas predicted to be suitable for transient populations, and a migratory trajectory model where the moths originate in North Africa. Invasions risk each year is highest for southern Portugal, southern Spain, southern France, and Italy (see Wang et al., 2023, Figure 3 for detail). This information may be useful for considering potential distribution since populations are unlikely to be permanent in Europe.
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Distribution of host crop plants
(regarding potential overlap with pest)

- Maize
- Other primary host crop plants
- Other host crop plants
- Spatial extent of host crop plants in Europe
- Relevant information on spatial extent within countries.

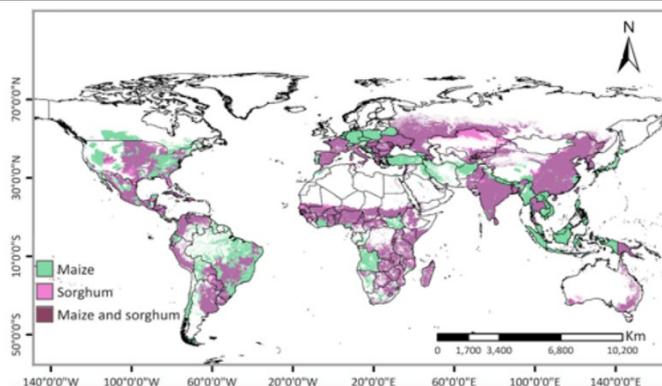


Figure S4 of supplementary material from Timilsena et al. (2022) showing global distribution of maize and *Sorghum* (cereal). These are the main host plants of the “corn” strain of *S. frugiperda*. One or both of these host plants are grown in all areas of potential migratory distribution in Europe, shown by the CLIMEX models described above, suggesting its potential distribution is not limited by host plant availability. This is the most pertinent information regarding the distribution of host plants in the context of overlap with potential distribution of *S. frugiperda*. Population dynamics of *S. frugiperda* more influenced by climate than by number of hosts available (Caniço et al., 2020).



Figure 4.1 in Kraehmer et al. (2017) shows rice distribution in Europe. This is the preferred host of the “rice” strain of *S. frugiperda*, which also occurs in Africa (Mendesil et al., 2023). Demonstrates some overlap with predicted potential migratory distribution of *S. frugiperda* as described in CLIMEX models above. However, rice occurrence in Europe could limit the distribution of migratory *S. frugiperda* rice strain populations in areas such as France and southern Germany, where the climate is predicted to be suitable for seasonal occurrence of the pest. Perhaps not as pertinent to the project as maize.

<p>Entry and exclusion</p> <ul style="list-style-type: none"> • Likelihood of entry and establishment <ul style="list-style-type: none"> ○ Invasion pathways? ○ No exclusionary measures ○ Exclusionary measures ○ How costs of exclusionary measures effects probability of entry and establishment 	<p>Because invasion risk of <i>S. frugiperda</i> is related to seasonal migratory populations from North Africa (Wang et al., 2023), exclusionary measures must be considered in this context. However, invasion risk from importation of fresh produce/plant products is also subject to EU emergency measures (EFSA, 2018; Gilioli et al., 2022). The latest iteration of these measures is provided in the revised Commission Implementing Regulations for <i>S. frugiperda</i> (EU, 2023). This includes requirements for the importation of fruits of <i>Capsicum</i>, <i>Momordica</i>, <i>Solanum aethiopicum</i>, <i>Solanum macrocarpon</i>, and <i>Solanum melongena</i>, and for plants of <i>Asparagus officinalis</i>, <i>Crysanthemum</i>, <i>Dianthus</i>, <i>Pelargonium</i>, and <i>Zea mays</i>. This stipulates that these may only be imported if they originate from a country where the pest is not known to occur, or from a more specific area free from the specified pest, as defined by the NPPO concerned. If these two conditions cannot be met, then other phytosanitary activities can be undertaken in the country of origin to meet importation requirements – see Article 10 of the aforementioned Commission Implementing Regulations (EU, 2023) for this detail. EFSA (2018) details some “hotspots” of likely entry once products are imported into, and distributed throughout, the EU based on the relative proportion of consumers. See Figure 11 in EFSA (2018) for detail, but obvious hotspots include Andalusia and Catalonia in Spain, and Lombardy in Italy. We could not obtain data regarding the costs of preventative measures (e.g. border controls). However, information exists on the likelihood of invasion (see Wang et al., 2023; Gilioli et al., 2022; EFSA, 2018).</p>
<p>Detection of incursions</p> <ul style="list-style-type: none"> • Time of incursion detection • Expenditure on detection (and how it relates to time of detection) 	<p>Monitoring/detection very important for migratory invasive insects, as early detection can enable timely application of control measures (Wan et al., 2021).</p> <p>Pheromone traps</p> <p>A number of commercially produced pheromone lures for <i>S. frugiperda</i> are available for purchase</p> <ul style="list-style-type: none"> • Scentry Lures: USD\$34 for 10 lures. Effective for 4-6 weeks. • Trécé fall armyworm lure: USD\$45.32 for 25 lures. Effective for 4-6 weeks. • Russel IPM fall armyworm lure: €208.83 for 50 lures. Effective for 4-6 weeks. • Delta trap (Cruz et al., 2012): Russel IPM delta trap €97.98 for 20 traps.

	<ul style="list-style-type: none"> • Bucket trap (Niassy et al., 2021): USD\$237.50 for 50 traps (greatlakesipm.com). • One trap every 0.5-2 ha (FAO, 2017). • Meagher et al. (2019) details cost analysis for different trap designs.
<p>Establishment and spread (dispersal)</p> <ul style="list-style-type: none"> • Suitable areas for establishment <ul style="list-style-type: none"> ○ SDM models ○ Host distribution • Probability of established colony growth <ul style="list-style-type: none"> ○ Host plant density ○ Radial increase velocity (new propagules) <ul style="list-style-type: none"> ▪ Intrinsic growth rate ▪ Diffusion constant (km²/unit time) ○ Allee effect severity/no Allee effect 	<p>For suitable areas for establishment, refer to “potential distribution of pest”.</p> <p>Population growth Host plant density redundant, just an assumption?</p> <p>Intrinsic growth rate</p> <ul style="list-style-type: none"> • At 25°C: 0.181/day on maize (Altaf et al., 2022), 0.205/day on maize (Gebretsadik et al., 2023). <p>Temperature effects on development time (egg to adult)</p> <ul style="list-style-type: none"> • Minimum threshold for development = 12.57°C (Du Plessis et al., 2020). • 18°C: 71.44 days, 22°C: 41.64 days, 26°C: 29.29 days, 30°C: 22.38 days, 32°C: 20.27 days (optimum = 26-30°C) (Du Plessis et al., 2020). • Development time in degree days: 391.61 degree days (Du Plessis et al., 2020). • Used as a starting point to calculate population growth at different temperatures? May be important for <i>S. frugiperda</i> as might need to capture when negative growth rates start as this is relevant for seasonal migratory populations where temperature limits their permanent occurrence. <p>Diffusion constant (spread)</p> <ul style="list-style-type: none"> • Short range dispersal: discussed and calculated by Maino et al. (2021), but this has negligible influence on population dynamics of <i>S. frugiperda</i>, which is dominated by long-range dispersal. • Long range dispersal: Wolf et al. (1990) observed cloud of migrating <i>S. frugiperda</i> travelling 400km in 7.7 hours (overnight). Hard to quantify over such large spatial scales. In North America, has been observed in Ontario, which suggests that within a year, populations can travel over 2000km from their permanent range (Southern US). As part of a dispersal/population growth model, Maino et al. (2021) conservatively estimated a dispersal distance of 90 km per night (see paper for details of calculation), which hypothetically allowed moths to reach Ontario during warmer months, but is comfortably within the maximum migration range measured of 400km in one night. This does not take into account wind-mediated dispersal overseas where they are forced to continue flying (e.g. presumed to have reached New Zealand from Australia by crossing Tasman Sea).

	<p>Wang et al. (2023) (Section 2.3.2) summarises results from other studies with useful information regarding long-distance dispersal. <i>S. frugiperda</i> can fly for three consecutive nights in favourable weather conditions, but will stop flying when temperature drops below 13.1°C and when rainfall is greater than 1mm/h. Maximum single flight time could be as high as 36.5 hours (e.g. if flying oversea and forced to continue).</p> <p>Allee effects not empirically quantified, so would need to be an assumption and perhaps run as a scenario? Maino et al. (2021) assumed 1 moth per hectare per week is required to maintain population.</p>
<p>Control costs of invaded areas</p> <ul style="list-style-type: none"> • Cost of detection in invaded unit of area • Unit of area where pest detected (can this be used to infer pest density?) • Cost of control measures in area • See Carrasco et al. (2012) WCR paper for equations for cost taking into account damages based on pest density. 	<p>I have included here the control measures that are currently applied to <i>S. frugiperda</i>, and that are seen as being viable options for Europe (Babendreier et al., 2022).</p> <p>Cost of detection Refer to pheromone trap costs in “detection of incursions”. Important for <i>S. frugiperda</i> as IPM underpinned by monitoring is a main management strategy (Wan et al., 2021).</p> <p>Unit of area where pest detected Assumption?</p> <p>Cost of control measures Overall management costs For smallholder maize farmers in Africa, should not spend more than US\$7.88/ha on <i>S. frugiperda</i> management for economic equilibrium (Hruska et al., 2019). Probably not transferrable to Europe given the very low prices received for their production.</p> <p>Chemical control</p> <ul style="list-style-type: none"> • Governments donated US\$1.97 million and US\$330,000 worth of pesticides and PPE. • Babendreier et al. (2022) lists the chemical insecticides that are promising/effective against <i>S. frugiperda</i> and are already approved for use in the EU. The Australian risk assessment for <i>S. frugiperda</i> (Kearns et al., 2020) provides the cost of application per hectare (Australian dollars) for five of these: alpha-cypermethrin (\$2.80), spinetoram (\$122.79), emamectin benzoate (\$72), indoxacarb (\$4.00), chlorantraniliprole (\$39.60). However, chemical insecticides would be last resort options in Europe, and likely to be based on damage thresholds (see bottom of damages section). Employment of biologically-based and environmentally friendly methods would reduce pesticide costs.

	<ul style="list-style-type: none"> • Amount spent on pesticides per farmer in Ghana: USD\$25.3, at USD\$9.3/ha (Rwomushana et al., 2018). • Amount spent on pesticides per farmer in Zambia: USD\$14.2, at USD\$8.1/ha (Rwomushana et al., 2018). <p>Pheromones (mating disruption)</p> <ul style="list-style-type: none"> • Pheromone dispenser (Pherogen) has regulatory approval in US and Kenya (EPA, 2018; CABI, 2021). Application costs between \$24 and \$35 per hectare (Ssali, 2022). • Aerial application of pheromone was approved in Kenya before the dispenser (Kenis et al., 2022), but this would be much less cost-effective. <p>Insecticidal viruses (SfMNPV)</p> <ul style="list-style-type: none"> • Kenis et al. (2022 – see table 3) summarises <i>S. frugiperda</i> mortality caused by the <i>S. frugiperda</i> multiple nucleopolyhedrovirus (SfMNPV) in countries where it is used as a biopesticide, with studies showing efficacy. This paper also lists the commercialized products with SfMNPV as the active ingredient. • Fawligen: USD\$3-\$5 per acre (Agbitech, 2023). This is the only one that I could find cost for. <p>Entomopathogenic nematodes ?</p> <p>Likely to be available in Europe as some that are effective against <i>S. frugiperda</i> are already commercially available in Europe, but not currently applied for <i>S. frugiperda</i> outside of research at this stage (Babendreier et al., 2022).</p>
<p>Damages and their costs</p> <ul style="list-style-type: none"> • Cost of damage per unit area invaded (again, does unit area infer density?) <ul style="list-style-type: none"> ○ Maize ○ Rice ○ Forage? ○ Other crops? • See Carrasco et al. (2012) WCR paper for equations for cost taking into account damages based on pest density. • Damage thresholds 	<p>Production and value for all crops can be found at (FAOSTAT, 2023). Kraehmer et al. (2017) also covers rice production in Europe. Has map of rice growing areas, production and value in each country. For now, I will focus on maize as this is of primary importance to Europe (and the project).</p> <p>Crop loss</p> <p>The most commonly consumed structures of the maize plant are the young leaves, whorl, tassels, and ears. However, damage to the foliar structures generally does not translate to high yield losses compared to feeding on the ear (Hruska, 2019; Kenis et al., 2022). Early foliar loss may not correlate to yield loss (Overton et al., 2021).</p> <p>Crop loss no control</p> <ul style="list-style-type: none"> • Experimental study showed 15% yield loss in first year when 98% of plants were artificially infested at the vegetative stage (not reproductive stage with ears). No significant yield reduction observed when 31% of plants were infested. In the second year, 18% yield

reduction was observed when 100% of plants were infested (Cruz & Turpin, 1983).

- Africa: study from 12 maize-producing countries that without control, *S. frugiperda* could cause yield losses of 4.1 to 17.7 million tonnes per year, which translates to estimated losses of between USD\$1 billion to USD\$ 4.7 billion annually (Rwomushana et al., 2018. See table five for each country).
- Africa: Similar study to the above of 12 countries estimated total yield losses of between 8.5 and 21 million tonnes per year, translating to losses between USD\$2.5 billion to USD\$6.3 billion annually (Day et al., 2017). This, and above study, based on farmer surveys.
- Zimbabwe: average of 12% yield loss (Baudron et al., 2019).
- Kenya: 33% losses in high-potential maize production areas (De Groote et al., 2020)
- Global: USD\$9.4 billion annually.
- Literature review found global average of yield losses for maize crops where management was unknown, and no management applied, was 34.11% and 25.17%, respectively (Overton et al., 2021).

Crop losses with management

- Brazil: up to 34% reduction in grain yield with annual losses of USD\$400 million, whilst spending USD\$600 million annually on control (Mendesil et al., 2023).
- Literature review found global average of yield losses for maize crops managed with insecticides were 21.26%. For GM maize crops (*Bt* toxin), average yield losses were 11.07% (Overton et al., 2021).
- Deshmukh et al. (2020) studied corn yield from plots after application of a number of the insecticides listed above as efficacious and permitted for use in EU. The untreated control produced the lowest yield (3,246 kg/ha). The highest corn yields were from plots treated with chlorantraniliprole (6,650 kg/ha), emamectin benzoate (6,517 kg/ha), and spinetoram (6,467 kg/ha). Indoxacarb treated plots produced a corn yield of 5,673 kg/ha.
- Another study found that after spinetoram treatments, leaf damage in maize plots averaged a damage score of 2, whereas untreated plots averaged a damage score of 7 (damage score assignment described in section 2.3 in paper) (Sisay et al., 2019).
- Ethiopia: 11.5% yield loss even after control and management strategies used by farmers (Kassie et al., 2020. See Table 4 for types of management used).
- Kenya, Uganda, and Tanzania: 86.7% reduction in plant damage per plot using push-pull management

	<p>approach, compared to monocrop plots. Resulted in grain yields being 2.7 times higher in the push-pull plots (Midega et al., 2018).</p> <ul style="list-style-type: none"> • Botanical pesticides in Zambia: artificial infestations recorded 68.2% yield losses in no control plots, 40.8% in Chinaberry extract treatment plots, 14.3% in Garlic treatment plots, 32.5% in Neem oil treated plots, and 34.9% in cypermethrin (chemical insecticide) treated plots (Siazemo & Simfukwe, 2020). • Mexico: push-pull crop plots showed higher percentage of undamaged plants compared to monoculture plots. One push-pull approach showed about 80% undamaged plants, whereas monoculture control plots showed about 30% undamaged plants. Same approach showed mean yield of around 7.5 tonnes/hectare, whereas the monoculture plots showed an average of about 3.5 tonnes/hectare (Guera et al., 2021). • Field study showed optimal application of SfMNPV (the aforementioned insecticidal virus) reduced damage from 33% to 20% of plants two weeks after application. A second application one week later further reduced damage to under 15% of plants (Gómez et al., 2013). • A similar study applied SfMNPV 3 and 17 days after <i>S. frugiperda</i> larval emergence. After 24 days, 58.9% of plants in the untreated crops showed feeding damage, whereas around 25% of plants in the SfMNPV treated crops showed feeding damage (Barrera-Cubillos et al., 2017). • <i>Difficult to find damage comparisons for the control tools outlined in the control costs sections (trials report impact on insect population and not yield/crop damage). If more detail needed, we can try to consider further.</i> <p>Relationship between pest density and yield loss</p> <ul style="list-style-type: none"> • Overton et al. (2021) collected data from the literature and assessed the trend between <i>S. frugiperda</i> density and yield loss. For maize, at mid-growth stages (reproductive stages), the trend shows approximately 50% yield reduction at 25% infestation, 60% reduction at 50% infestation, 75% reduction at 75% infestation, and 100% reduction at 100% infestation. However, data from where the plant growth stage was not specified, the trend in yield loss remained relatively constant at approximately 20% between infestation levels of 25-100%. • Same study: for maize at mid-growth stages, yield reduction increases linearly from approximately 5% at density of 5 larvae per plant, to about 15% at 20 larvae per plant. For late-growth stages, yield loss
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remains relatively constant at approximately 15% between 5 and 20 larvae per plant.

Damage thresholds

A review by Overton et al. (2021) includes reviewing the literature on thresholds. Table 2 in this paper provides a very comprehensive list of thresholds reported in different countries, the crop type, and the type of threshold (e.g. economic injury level, action threshold). This table should be referred to for threshold data. Kenis et al. (2022) argues that because large variations exist in injury resulting from given levels of *S. frugiperda* infestation, more conservative thresholds should be employed.

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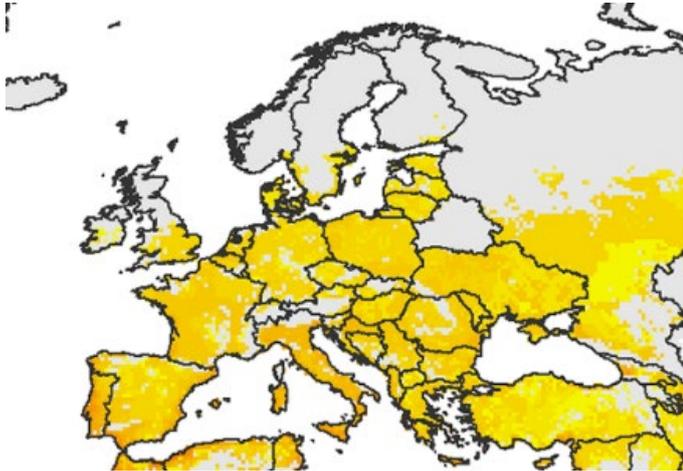
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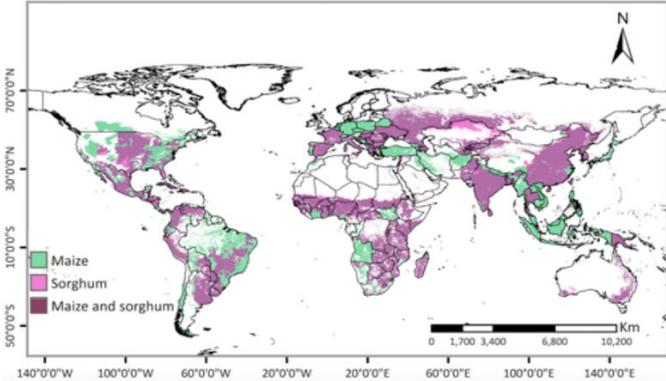
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5 APPENDIX 2

Damages and costs associated with *Helicoverpa armigera* invasion and control, with consideration to the outlook for Europe

<p>Potential distribution of pest</p> <ul style="list-style-type: none"> • Species distribution models <ul style="list-style-type: none"> ○ CLIMEX models ○ Other SDM models 	<p><i>H. armigera</i> is widespread throughout much of southern Europe (Greece, Portugal, Spain), and some of eastern Europe (Albania, Bulgaria, Romania, Ukraine). For the rest of Europe, it is either present with a restricted distribution or few occurrences, or absent (EPPO, 2023a). Some countries in which it is absent, it was either previously present or eradicated (Croatia, Czech Republic, Estonia, Latvia, Norway, United Kingdom). Transient populations also occur in Finland (EPPO, 2023a; CABI, 2021).</p> <p>However, a CLIMEX model (Kriticos et al., 2015) suggests that many of these areas in Europe where it is not widespread, are suitable for widespread establishment:</p>  <p>This indicates that there is potential for <i>H. armigera</i> to become much more widespread throughout Europe. However, these predictions are contrary to what current knowledge (and current distribution) of <i>H. armigera</i> in Europe indicates, given that Mediterranean areas are part of its native range. It is only able to overwinter (and therefore establish permanent populations) in the southernmost parts of Europe that experience relatively warm winters. This includes Portugal, Spain, Sardinia, southern Italy, and Greece. Other areas where it is known to occur in Europe represent transient migratory populations (from sources in southern Europe and North Africa) that can complete one or more generations during warmer months, but that do not overwinter and</p>
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	<p>permanently establish (Lammers & Macleod, 2007; Baker et al., 2014; Riaz et al., 2021). The CLIMEX model shows potential for establishment north of this boundary due to the diapause parameters used, which allows the diapausing population to terminate diapause and continue development at 10 °C. However, data shows that in the Greek population, 16 °C is required to complete the termination of diapause (Mironidis et al., 2010).</p>
<p>Distribution of host crop plants (regarding potential overlap with pest)</p> <ul style="list-style-type: none"> • Maize • Other primary host crop plants • Other host crop plants • Spatial extent of host crop plants in Europe • Relevant information on spatial extent within countries. 	<p><i>H. armigera</i> is highly polyphagous (CABI, 2021) and therefore host plant distribution is not likely to influence its potential distribution throughout Europe. However, the most important crop hosts, on which it is a major pest, are cotton, pigeonpea, chickpea, tomato, sorghum, and cowpea (CABI 2021), with maize and rice also being important crop hosts (Riaz et al., 2021). <i>H. armigera</i> is already widespread in many of the European countries with substantial tomato production (Greece, Portugal, Spain, Albania, Romania, Ukraine) (FAOSTAT, 2021).</p>  <p>Above figure (Figure 4 supp material from Timilsena et al. (2022)) shows the widespread production of maize and sorghum throughout Europe. This again demonstrates how host plant availability is unlikely to limit the distribution of <i>H. armigera</i> in Europe, in relation to climatic suitability and transient migratory populations.</p>
<p>Entry and exclusion</p> <ul style="list-style-type: none"> • Likelihood of entry and establishment <ul style="list-style-type: none"> ○ Invasion pathways? ○ No exclusionary measures ○ Exclusionary measures 	<p>Due to the long-distance migratory ability of <i>H. armigera</i> during favourable conditions in late summer, and its apparent inability to establish north of southern Europe, the most important invasion pathway is seasonal long-distance migration from southern Europe and North Africa, causing transient populations (Keszthelyi et al., 2013; Baker et al., 2014).</p>

- How costs of exclusionary measures affects probability of entry and establishment

H. armigera is on the EPPO A2 list, with the recommendation for phytosanitary measures being that imported plants for planting should originate from an area where *H. armigera* is absent, or from a place of production where it has not been detected for 3 months (EPPO, 2020). However, it is unclear whether, and to what extent, many European countries have adopted this guidance.

H. armigera is a quarantine pest in Norway (EPPO, 2023b). Regarding specific requirements for the import of certain plants, in relation to *H. armigera* exclusionary regulations, plants intended for planting of *Dendranthema*, *Dianthus*, and *Pelargonium* must have no signs of *H. armigera* observation at the place of production since the beginning of the last complete cycle of vegetation. If this condition cannot be met, the plants must have undergone appropriate treatment to protect them from *H. armigera*. The same also applies for the same plants with regards to domestic production and sale (Norwegian Food Safety Authority, 2000; VKM, 2021).

H. armigera is also a regulated quarantine pest in the UK, and it appears that the same regulations described above for Norway would also apply here, as these are based on the original EU directive and are not mentioned in the specific amendments made to this in the UK legislation after Brexit (UK Government, 2020).

Baker et al. (2014) summarises the EU requirements that prohibit plant imports (regulated for *H. armigera*) for all member states. In addition to the requirements listed above for Norway and the UK, tubers of *Solanum tuberosum* cannot be imported from any third countries with the exception of Switzerland. Furthermore, plants of tuber-forming *Solanum* species intended for planting cannot be imported from third countries. Plants of Solanaceae intended for planting cannot be imported from third countries other than European and Mediterranean countries.

No data on the costs of these exclusionary measures are available.

<p>Detection of incursions</p> <ul style="list-style-type: none"> • Time of incursion detection • Expenditure on detection (and how it relates to time of detection) 	<p>Pheromone traps</p> <p>Pheromone lures for <i>H. armigera</i> for detection, monitoring, and control, have been developed and refined for a number of decades. These have been used to effectively detect incursions, for example in Argentina in 2013 (Murúa et al., 2014). There is a number of studies attesting to the efficacy of pheromone trapping, including testing different lure types, trap designs, and placements (e.g. Baker et al., 2011; Guerrero et al., 2014; Karakasis et al., 2021; Karakantza et al., 2023). Karakasis et al. (2021) tested three lures for monitoring in cotton crops in Greece, for which I could find prices for two:</p> <ul style="list-style-type: none"> • Russell IPM lure: €3.25 per lure. 40 day field life (controlbio.es). • Trécé Pherocon lure: USD\$45.32 for 25 lures. 4-6 week field life (greatlakesipm.com). <p>Karakantza et al. (2023) found that black striped funnel traps were most effective for use with pheromone lures:</p> <ul style="list-style-type: none"> • Black stripe funnel trap: €16.40 each (nexles.com/eu). • Bucket trap (Guerrero et al., 2014): €183.96 for set of 25 (nexles.com/eu) (MothCatcher trap). • Scentry Heliothis trap (Guerrero et al., 2014): US\$406.59 for 5 traps (greatlakesipm.com). <p>Light traps</p> <p>Light traps (particularly light trap networks) are widely used for effective monitoring and detection of <i>H. armigera</i> seasonal migration (e.g. Feng et al., 2009; Keszthelyi et al., 2013; Keszthelyi et al., 2016; Specht et al., 2021). I was not able to find costs for such light traps, but they are commonly said to be very low cost. Furthermore, some European countries have existing networks of light traps that can be used. For example, Hungary has a network of 63 light traps throughout the country (Keszthelyi et al., 2013), and the UK has 84 (Cook & Shortall, 2022; Rothamsted Research, 2023).</p> <p>I was not able to find any data for labour and diagnostic costs for <i>H. armigera</i> detection.</p>
<p>Establishment and spread (dispersal)</p> <ul style="list-style-type: none"> • Suitable areas for establishment <ul style="list-style-type: none"> ○ SDM models ○ Host distribution • Probability of established colony growth <ul style="list-style-type: none"> ○ Host plant density ○ Radial increase velocity (new propagules) 	<p>For suitable areas for establishment, refer to “potential distribution of pest”.</p> <p>Population growth</p> <p>Host plant density an assumption? Greenhouses for Northern Europe/UK? Could not find data on how host plant density effects population dynamics of <i>H. armigera</i>.</p> <p>Intrinsic growth rate</p>

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| <ul style="list-style-type: none"> ▪ Intrinsic growth rate ▪ Diffusion constant (km²/unit time) ○ Allee effect severity/no Allee effect | <ul style="list-style-type: none"> • Mironidis (2014) reports intrinsic growth rate at different temperatures: 0.077, 0.099, 0.135, 0.170, 0.146, 0.117 intrinsic rates of increase at 17.5 °C, 20 °C, 25 °C, 27.5 °C, 30 °C, and 32.5 °C, respectively. • Mironidis & Savopoulou-Soultani (2008) report intrinsic growth rate at alternating temperatures, which may provide a better comparison to natural conditions: 0.09, 0.12, 0.14, 0.12, and 0.12 intrinsic rate of increase at 25-10 °C, 30-15 °C, 32.5-17.5 °C, 35-20 °C, and 35-27.5 °C, respectively. • Degree days required may be useful: In northern Greece, which represents one of the northern limits of permanent <i>H. armigera</i> populations, the emergence of 10, 25, 50, 75, and 90% of adults from diapausing pupae required 153, 199, 252, 303, and 347 degree-days, respectively (Mironidis et al., 2010). This may be important for considering population growth in areas where permanent populations can establish vs. where only transient (seasonal) migratory populations may occur. Mironidis & Savopoulou-Soultani (2008) estimated the number of degree-days required for egg to adult development at 476.19 under constant temperature, and 769.23 under alternating temperatures. Mironidis (2014) estimated the number of degree-days required for egg to adult development at 625 under fluctuating temperatures. <p>Diffusion constant (spread)</p> <ul style="list-style-type: none"> • <i>H. armigera</i> larvae undergo some level of short-distance dispersal in response to high population density on host plants (Kakimoto et al., 2003). However, how this impacts the spread and diffusion of populations would be negligible due to the considerable long-range migratory dispersal that <i>H. armigera</i> adults are capable of (Jones et al., 2019). • Adult movement between feeding sites (nectar sources), and between oviposition sites (crops), usually occurs downwind and can reach up to 10km in a night (Fitt, 1989). • Migratory dispersal occurs at heights between 1-2km and only occurs at night (e.g. after dusk until before dawn). The speed of northward migrations of <i>H. armigera</i> in China during early summer varied between 27 and 44 km/h (Feng et al., 2004). In the same area during mid-summer, the speed of northward migration was between 21.96 – 51.84 km/h (Feng et al., 2005a). • Southerly return migrations of <i>H. armigera</i> (back to areas that support permanent populations) from the same area in China occur during autumn, with aerial movement speeds between 30-33km/h, with flight durations of around 10 hours (Feng et al., 2005b). |
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	<ul style="list-style-type: none"> • A similar study measured northward (early summer) and return migrations (autumn) in China over the Bohai sea. Ariel movement speeds were between 24-41km/h, and flight duration varied between 8-11 hours (Feng et al., 2009). • Such detailed assessments of migration behaviour do not exist for Europe. However, a study in Hungary (Keszthelyi et al., 2013), where populations are transient but widespread every year, found that the first outbreak from migratory populations in 1993 spread to 20% of the country, whereas in 2001, the migratory population outbreaks covered 94% of Hungary. During more arid summers, <i>H. armigera</i> begin to be trapped in mid-May, with numbers peaking during August and the last moths being trapped in late October. During more humid summers, moths begin to be trapped in mid-July, with numbers peaking in September and the last moths being trapped in early October. However, precise origin/s of these migrants is not known. • Baker et al. (2014) references others as positing that adults originating from permanent populations in southern Europe and North Africa can migrate up to 1000 km to reach the UK and Ireland. It is not stipulated whether this occurs during single (i.e. one night) or multiple (i.e. stopovers along the way, multiple nights) flight events. <p>Allee effects</p> <ul style="list-style-type: none"> • Nothing specific for <i>H. armigera</i>.
<p>Control costs of invaded areas</p> <ul style="list-style-type: none"> • Cost of detection in invaded unit of area • Unit of area where pest detected (can this be used to infer pest density?) • Cost of control measures in area • See Carrasco et al. (2012) WCR paper for equations for cost taking into account damages based on pest density. 	<p>Cost of detection</p> <ul style="list-style-type: none"> • See “detection of incursions” section <p>Unit of area where pest detected</p> <ul style="list-style-type: none"> • Assumption? Simulated? <p>Cost of control measures</p> <ul style="list-style-type: none"> • Currently applied control methods against <i>H. armigera</i> in Europe span a range of chemical, biological, and cultural² methods (Baker et al., 2014). Application costs data are scant for Europe, but are abundant for the America’s and India. Here are presented the costs of application in studies outside of Europe, for the methods (including specific chemicals) that are used against <i>H. armigera</i> in Europe (Baker et al., 2014) (Indian Rs. converted to US\$). <p>Chemical control</p> <ul style="list-style-type: none"> • Indoxacarb: US\$19.81/ha (Perini et al., 2016); US\$30.29/ha (Singh et al., 2014).

²Cultural methods that are applied include reductions in the application of nitrogen fertilisers, the control of weeds to remove potential pest reservoirs, the selection of resistant crop varieties, and harrowing and ploughing of the soil in order to destroy the pupae or expose them to environmental extremes (Gengotti, 2005).

- Spinosad: US\$33.00/ha (Perini et al., 2016); US\$18.02/ha (Jagtap et al., 2020).
- Methoxyfenozide: US\$20.31/ha (Perini et al., 2016).
- Lambda-cyhalothrin: US\$17.50/ha (Perini et al., 2016).
- Cypermethrin: US\$41/ha (Hossain, 2007).
- Chlorpyrifos: US\$117.25/ha (Mahmudunnabi et al., 2013).
- Found one study in Europe (Spain): endosulfan €39.14/ha; methomyl €32.30/ha; chlorpyrifos €37.00/ha; deltamethrin €34.75/ha; cypermethrin €24.82; thiodicarb €75.55/ha (Torres-Vila et al., 2003).

Biological control

- *Bacillus thuringiensis* (Bt): US\$13.23/ha (Perini et al., 2016); US\$39.66/ha (Singh et al., 2014); US\$63.09USD/ha (Wakil et al., 2009); US\$25.24/ha (Cherry et al., 2000); US\$17.10/ha (Allahyari et al., 2020).
- *H. armigera* nucleopolyhedrovirus (HaNPV): US\$15.70/ha (Perini et al., 2016); US\$21.63/ha (Singh et al., 2014); US\$4.51/ha (Cherry et al., 2000); US\$31/ha (Hossain, 2007); US\$5.41/ha (Jagtap et al., 2020); US\$22.36/ha (Allahyari et al., 2020).
- Augmentative releases of arthropod natural enemies:
 - *Orius* spp. (predator): 48.80 CHF for 500. Apply 0.5-1 individuals/square meter at 10 day intervals (Andermatt Biocontrol Suisse, 2023).
 - *Chrysoperla carnea* (predator): 19.60 CHF for 500. Apply 5-50 individuals/square meter (Andermatt Biocontrol Suisse, 2023).
 - *Trichogramma* (parasitoid): 9.20 CHF for card with 2400 wasps. Apply 3-20 cards/100 square meters every 14 days (Andermatt Biocontrol Suisse, 2023).
 - *Macrolophus* (predator): 109.10 CHF for 500. Apply 2-3 individuals/square meter at intervals of 7-14 days (Andermatt Biocontrol Suisse, 2023).

Mating disruption

- Pheromone dispensers are now being produced in Europe for mating disruption against *H. armigera*, and trials have demonstrated efficacy at 100 dispensers/ha (Burgio et al., 2020). BioSelibate HA dispensers (Suterra Europe). However, could not find prices for this product.

<p>Damages and their costs</p> <ul style="list-style-type: none"> • Cost of damage per unit area invaded (again, does unit area infer density?) <ul style="list-style-type: none"> ○ Tomato ○ Maize ○ Cotton ○ Soybean ○ Chickpea • Damage thresholds 	<p>Production and value for all crops can be found at FAOSTAT (2023). <i>H. armigera</i> is highly polyphagous and can cause severe damage to a wide variety of crops. In Spain and Italy, the most significant damage occurs to tomatoes, and in Greece, significant damage is incurred to cotton. Migratory outbreaks throughout Europe have caused severe damage to maize, sorghum, oil seed rape, tobacco, rose, chrysanthemum, beans, carrots, sunflowers, bell pepper, soybean, strawberries, chickpeas, alfalfa, onions, potatoes, cucumbers, lettuce, etc. (Baker et al., 2014). Perhaps focus on key crops in certain areas? Not a lot in the way of economic cost calculations, so you may need to use market data to calculate this from yield losses?</p> <p>Crop loss no control</p> <p>Tomato</p> <ul style="list-style-type: none"> • Torres-Vila et al. (2003) measured yield loss at different larval densities (Figure 2 for more detail). 1 larvae/plant: 0-11% yield loss. 2 larvae/plant: 0-17% yield loss. 4 larvae/plant: 0-38% yield loss. 8 larvae/plant: 0-41% yield loss. 16 larvae/plant: 4-62% yield loss. The lower values in these ranges are a result of the study presenting yield loss results for different crop ages, where there was a trend of younger crop age suffering higher yield loss. • Sousa et al. (2020) also reports yield loss as a function of <i>H. armigera</i> larval density. 1 larvae/row meter: 5.6% yield loss. 3 larvae/row meter: 9.5% yield loss. 6 larvae/row meter: 9.8% yield loss. 12 larvae/row meter: 32.1% yield loss. 24 larvae/row meter: 34.4% yield loss. • Cameron et al. (2001) reports that 5.5 larvae per plant caused 27% fruit damage in 1986, and 38% fruit damage in 1987. <p>Maize</p> <ul style="list-style-type: none"> • Severe damage to maize crops has occurred during transient outbreaks north of latitudinal limit for permanent population persistence (Baker et al., 2014). • Could not find data on the relationship between <i>H. armigera</i> density and yield loss for maize. • Wang et al. (2023) measured the percentage of maize plants damaged by <i>H. armigera</i> within a crop over three successive seasons. In 2019, 2020, and 2021, an average of approximately 40%, 50%, and 40% of plants were damaged, respectively. • Kim et al. (2018) presents similar results. In 2013, 2014, and 2015, an average of approximately 48%, 39%, and 41% of harvested corn was damaged by <i>H. armigera</i>. <p>Cotton</p>
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- Particularly relevant to Greece and Spain (Baker et al., 2014; FAOSTAT, 2023).
- Malinga & Laing (2022): in 2018, observed an average of 4.2 *H. armigera* larvae per 12 cotton plants, resulting in an average of 3.1 damaged cotton bolls per 12 plants. In 2017, observed an average of 6.5 *H. armigera* larvae per cotton plant, resulting in an average of 3.5 damaged cotton bolls per plant.
- Kumar & Saini (2008): study in field conditions found that a single *H. armigera* larvae damaged an average of 1.23 squares (pre-flower), 2.75 flowers, and 2.12 bolls whilst developing from 1st instar until pupation.

Soybeans

- Soybeans are an important crop for some European countries (Karges et al., 2022). See Table 1 in Terzić et al. (2018) for details.
- Rogers & Brier (2010b): Two cage experiments that infested soybean plants with either *H. armigera* eggs or larvae and measured yield loss from larval feeding from start of infestation until pupation, at different larval densities. Experiment 1 observed yield loss of 94.40kg/ha at 1 larva/sq meter. Experiment two observed yield loss of 231.70kg/ha at 1 larva/sq meter. However, this yield loss only occurred after a damage threshold of 7.51 larvae/sq meter (so actually 8.51 larvae/sq meter).
- Stacke et al. (2018): yield loss of 7.70 grams/larva for soybean plants infested during full bloom. Yield loss of 10.60 grams/larva for soybean plants infested during early grain stage.
- See tables 1-5 in Ebrahimi et al. (2022) for yield differences in plants damaged by natural *H. armigera* infestation vs. non-damaged plants (too much information to summarise here). Does not measure pest densities.

Chickpeas

- Important host plant, which is economically important in some southern European countries (including where permanent populations of *H. armigera* exist). See Table 5 in Merga & Haji (2019) for value of chickpea production in Spain, Italy, and Greece.
- Singla & Singh (2020): Assessed yield losses in field study with artificial infestation of different densities of *H. armigera* larvae. Densities of 1, 2, 3, 4, 5, and 6, larvae per row meter resulted in yield losses of 17.57, 32.28, 41.48, 52.90, 55.85, and 73.50%.
- Singh et al. (2021): very similar study to above. Densities of 0.5, 1, 1.5, 2, 2.5, and 3 larvae per row meter resulted in yield losses of 6.94, 10.53, 17.65, 28.99, 37.85, and 40.72%.

- El Fakhouri et al. (2022): With an average of 4.25 larvae per row meter, 34.87% of pod damage was observed.
- Wakil et al. (2009), in an experimental plot, observed a larval density of 2.92 larvae/plant causing 26.24% of pods to be infested.

Crop loss with control (covering specific controls included in control costs section)

Tomato

- Hanafy & El-Sayed (2013): after Indoxacarb insecticide applications, 42.5% of plants were infested, compared to 87.5% in no control plots.
- Abbas et al. (2015): after Indoxacarb treatment, 4.86% yield loss observed. Compared to 23.41% in no control plots.
- Ghosh et al. (2010): after high dose application of spinosad, 2.2% of fruit were observed to be infested. 20.6% of fruit infested after lambda-cyhalothrin application. 31.6% of fruit infested after cypermethrin application. 78.6% of fruit infested in untreated control plots.
- Arrizubieta et al. (2016): after *Bacillus thuringiensis* (Bt) spray application, 17.3% of fruits were observed to be damaged, compared to 25.3% in untreated control plots.
- Rahman et al. (2014): after Bt application, 13.25% of fruits were infested, compared to 18.32% in untreated control plots. This resulted in an additional 5.96 tonnes/ha of yield over the untreated control plots.
- Singh et al. (2017): after Bt application, 19.13% of fruits damaged, compared to 36.08% in control plots. This resulted in an additional 2.75 tonnes/ha of yield over the untreated control plots.
- Patil et al. (2018): after *H. armigera* nucleopolyhedrovirus (HaNPV) application, 17.61% of fruits were damaged, compared to 30.25% in untreated control plots.
- Bhanuprakash et al. (2019): after HaNPV application, 27.16% of fruits were damaged, compared to 34.25% in untreated control plots.
- El-Heneidy et al. (2010): after releasing 40,000/0.5ha *Trichogramma* parasitoids four times (12-15 day intervals between releases), 1.5% of fruits were infested, compared to 5.5% in the untreated control sites.
- Hussain et al. (2015): in a 15 x 10m plot, releasing 600 *Trichogramma* parasitoids resulted in 10.18% of

	<p>fruits infested, compared to 43.56% in the untreated control.</p> <ul style="list-style-type: none"> For mating disruption: Burgio et al. (2020) found that fruit damage at harvest time, after deploying 100 pheromone dispensers/ha, averaged approximately 4%, compared to about 7.8% in the untreated control plots. <p>Maize</p> <ul style="list-style-type: none"> Cannot find relevant data on chemical or biological control in maize. <p>Cotton</p> <ul style="list-style-type: none"> Malinga & Laing (2022): same study as no control for cotton above – refer to that for difference in damage compared to no control. After Lambda-cyhalothrin application (120mL/ha) in 2018, an average of approximately 2.4 larvae per 12 plants, resulting in approximately 1.8 damaged bolls per 12 plants. The same application in 2017 resulted in an average of approximately 4.4 larvae per 12 plants, resulting in approximately 2 damaged bolls per 12 plants. Cannot find any additional data on the remaining insecticides for cotton. Malinga & Laing (2022) also tested biopesticide (Bt and HaNPV) efficacy. In 2017, post-Bt treatment larval density and damaged bolls were approximately 5.8 per 12 plants and 2 per 12 plants, respectively. In 2018, larval density and damaged bolls were approximately 3.3 per 12 plants and 2.3 per 12 plants, respectively. Refer to “crop loss no control” data for comparison with untreated control larval density and damage. The same study found that after HaNPV application (200mL/ha in water) in 2017, the larval density and damaged bolls were approximately 5.3 larvae per 12 plants and approximately 1.7 bolls per 12 plants, respectively. In 2018, the larval density and damaged bolls were approximately 2.8 per 12 plants and 2 per 12 plants, respectively. Refer to “crop loss no control” data for comparison with untreated control larval density and damage. <p>Soybeans</p> <ul style="list-style-type: none"> Perini et al. (2016): 14 days after indoxacarb insecticide treatment (60 g/ha), an average of 1.5 larvae/sq. meter was observed, compared to 2.8 larvae/sq. meter in the untreated control plots. Subsequent yield at harvest time from the indoxacarb plots was 2370kg/ha, compared to 2098/ha for the control. 14 days after spinosad insecticide treatment (33.6 g/ha), an average of 0.8 larvae/sq. meter was
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	<p>observed. Subsequent yield at harvest time from the spinosad plots was 2594kg/ha. 14 days after methoxyfenozide insecticide treatment (96 g/ha), an average of 1 larvae/sq. meter was observed. Subsequent yield at harvest time from the methoxyfenozide plots was 2200kg/ha. 14 days after lambda-cyhalothrin insecticide treatment (11.2 g/ha), an average of 0.8 larvae/sq. meter was observed. Subsequent yield at harvest time from the lambda-cyhalothrin plots was 2342kg/ha.</p> <ul style="list-style-type: none"> • Perini et al. (2016) also tested Bt application in soybeans using two different products. One was applied at a rate of 4.5×10^{11}g/ha, and 14 days after application, larval density was 0.3/sq. meter and yield was 2197kg/ha (see above on chemical applications for density and yield comparison for untreated control plots). Application of the second product (2.5×10^{13}g/ha) reduced larval density to 0/sq. meter after 14 days and the yield at harvest time was 2384kg/ha. • Naik et al. (2020): Bt application rate not given. Bt application reduced larval density from 2.25 larvae per plant prior to application to 0.6 per plant 7 days after application. 11.40% of pods were damaged at harvest time and yield was 3922kg/ha. The untreated control plots exhibited 29.17% pod damage and 2917kg/ha of yield. • Ismailov et al., 2022: Tested field application of four different HaNPV strains (5-10mL of viral subspecies/L). The mean damage to soybeans amongst these four applications was 1.8%, compared to 9.6% for the control. • Naik et al. (2020): 7 days after two HaNPV applications (500LE/ha), larval density decreased from 2.37/plant before the spray to 0.48/plant. At harvest time, 6.20% of pods were damaged, compared to 26.80% in the untreated control plots. Yield was 4996kg/ha, compared to 2917kg/ha in the untreated control plots. <p>Chickpeas</p> <ul style="list-style-type: none"> • Chitralekha et al. (2018): application of lambda cyhalothrin insecticide resulted in a reduction in larval density of 2.55 per row meter before spraying, to 1.61 per row meter after spraying. In the untreated control the pre- and post-spray densities were 2.99 and 4.85 per row meter, respectively. The lambda cyhalothrin treated plots exhibited 29.23% pod damage 1244.30kg/ha of yield, whereas the untreated controls exhibited 58.69% pod damage and 871.19kg/ha of yield.
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- Yogeeswarudu et al. (2014): indoxacarb reduced larval density by 100% after 7 days of spraying. This study did not assess crop loss/damage.
- Vikrant et al. (2018): application of 0.166l/ha of Spinosad resulted in mean reduction of 40.81% of larval population 10 days after spraying, and a harvest time yield of 2550kg/ha. The same application the following season resulted in a 75.55% reduction and a harvest time yield of 2680kg/ha. There was a 0% reduction of larval density in the control in both seasons, whereas the first season and second seasons resulted in a harvest time yield of 1350kg/ha and 1480kg/ha, respectively.
- Akbar et al. (2018): application of 100ml/acre of methoxyfenozide resulted in a reduction of larval density from 2 per plant before spraying, to 1 per plant 7 days after spraying (2.33 to 2.66 per plant in untreated control). Pod damage and yield were 11.60% and 1036.66kg/ha, respectively, compared to 19.14% and 593.34kg/ha, respectively, in the untreated control.
- Wakil et al. (2009b): application of Bt at 2kg/ha resulted in a larval density of approximately 1.3 per plant and a pod infestation of approximately 15% compared to approximately 2.4 per plant and pod infestation of approximately 25% in the untreated control plots.
- Chitralkha et al. (2018): Applied two spraying events of Bt at 750g/ha. In first season, mean larval population after the second spray was 1.37 larvae per row meter, compared to 4.54 per row meter for the control. This resulted in 32.40% of pods damaged in Bt plots, compared to 55.67% in untreated control plots.
- Vikrant et al. (2018): Applied Bt spray at 1kg/ha. In the first season, mean larval population 10 days after application of the second spray event was 1.70/plant, compared to 4.20/plant in the untreated control plots. At harvest time, yield from the Bt plots was 1810kg/ha, compared to 1350kg/ha from the untreated control plots.
- Vinkrant et al. (2018): Applied HaNPV at 250mL/ha. 10 days after second application event, the mean larval population density was 2.45/plant, compared to 4.20/plant for the control. At harvest time, yield from the HaNPV plots was 1520kg/ha, compared to 1350kg/ha from the untreated control plots.
- Kambrekar et al. (2009): Field-tested a number of HaNPV isolates that were initially obtained from field collections. The two most effective isolates resulted in

	<p>11.1 and 11.9% pod damage, and 744kg/ha and 737kg/ha of yield, respectively. The untreated control resulted in 32.7% pod damage and 333kg/ha of yield.</p> <ul style="list-style-type: none"> • Chitrlekha et al. (2018) and Vikrant et al. (2018) also have Bt and HaNPV. Wakil et al. (2009) (two different studies) also has <i>Trichogramma</i>. • HaNPV has reduced efficacy on chickpea because it produces compounds that causes inactivation of HaNPV on the leaf surface (Aminu et al., 2023). • Wakil et al. (2009a, b) observed that augmentatively released <i>Trichogramma</i> parasitoids were ineffective in controlling <i>H. armigera</i> in chickpea and reducing damage. An earlier study had shown that <i>Trichogramma</i> are ineffective on chickpea because they are not attracted to chickpea volatiles, and are repelled by trichomes and trichome exudates on the plant surface (Romeis et al., 1999). <p>Economic injury levels/thresholds</p> <ul style="list-style-type: none"> • Tomato: between 1.41 to 1.72 and between 2.11 to 2.58 larvae per row meter, during different growing seasons (Sousa et al., 2020). 1 larvae per plant to keep damage below 5% (Cameron et al., 2001). • Cotton: when plants are seedlings, up to the flowering stage, threshold is 2 larvae/meter. When plants are bearing up to 15% open bolls, threshold is 3 larvae/meter. When plants are bearing 15-40% open bolls, threshold is 5 larvae/meter (DAFF, 2016). • Soybean: during pod-fill, 2.31 larvae/sq. meter (Rogers & Brier, 2010a). For vegetative soybean, 8 larvae/sq. meter (Rogers & Brier, 2010b). • Chickpea: economic injury level of 1.20 and 0.95 larvae per row meter, from two different seasons. Economic threshold of 0.90 and 0.73 larvae per row meter from the two different seasons (Zahid et al., 2008). A different study calculated an economic injury level and economic threshold of 2.35 and 1.76 larvae per row meter, respectively (Singh et al., 2021). • Could not find any information on thresholds for maize.
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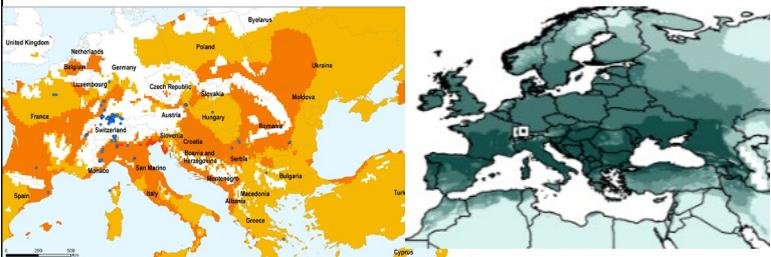
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6 APPENDIX 3

Damages and costs associated with *Halyomorpha halys* invasion and control, with consideration to the outlook for Europe

Background

Halyomorpha halys (Hemiptera: Pentatomidae) is a stink bug of north eastern Asian origin. It has invaded large areas across North America and Europe, but is still spreading. Nymphal stages and adults feed on fruit on a wide range of wild and cultivated plants. Feeding damages reduce fruit quality up to total loss. Adults overwinter in shelters (forest, buildings) from where they infest orchards in spring. Within a large range of its geographic distribution 1-2 generations per year occur.

<p>1. Potential distribution of pest</p> <ul style="list-style-type: none"> • Species distribution models <ul style="list-style-type: none"> ○ CLIMEX models ○ Other SDM models 	<p>Kriticos et al. 2017 & Zhu et al. 2012 should contain the relevant information</p> 
<p>2. Distribution of host crop plants (regarding potential overlap with pest)*</p> <ul style="list-style-type: none"> • Focus crop • Other primary host crop plants • Other host crop plants • Spatial extent of host crop plants in Europe • Relevant information on spatial extent within countries. 	<p>More than 300 host plants have been recorded (Kriticos et al. 2017). A list of major and other host plants is available here https://gd.eppo.int/taxon/HALYHA/hosts Due to its broad host range, it is unlikely that the species will be limited in its distribution by host availability</p> <p><i>For further information I focus on apple</i> A table on the area under apple production in Europe can be found here Statistics Eurostat (europa.eu) More detailed for regions here Statistics Eurostat (europa.eu)</p>
<p>3. Entry and exclusion</p> <ul style="list-style-type: none"> • Likelihood of entry and establishment <ul style="list-style-type: none"> ○ Invasion pathways? ○ No exclusionary measures ○ Exclusionary measures ○ How costs of exclusionary measures effects probability of entry and establishment 	<p><i>H. halys</i> is already present in large parts of Europe. EPPO provides regularly updated distribution records here https://gd.eppo.int/taxon/HALYHA/distribution</p> <p>Invasion pathways long distance: All life-stages can be associated with agricultural goods, in particular overwintering aggregations of adults pose a high risk (Garipey et al. 2014), those can be transported by human movement across large distances.</p> <p>Exclusion: Phytosanitary measures at entry points – however, those are not done within the EU. <i>Jamieson et al. (2022) and the NZ RA document give a detailed analysis of potential invasion pathways into (the not yet invaded) New Zealand – not all data that they use are easily available for Europe.</i></p> <p>Invasion pathways short distance: Adults fly into orchards from overwintering sites and neighboring crops, nymphs are able to crawl considerable distances (see 5.).</p>

	<p>Exclusion: Nets are able to prevent the entry of bugs into the orchard. Costs are 12'000 (hail-net already present) or 20-35'000 Euro (incl. substructure)/ha + 25.8 manhours additional workload/year (for Germany, Eberhardt 2021). Nets would provide additional benefit by prevention of other pests.</p>
<p>4. Detection of incursions</p> <ul style="list-style-type: none"> • Time of incursion detection • Expenditure on detection (and how it relates to time of detection) • How does time of detection effect costs? 	<p><i>Maybe we need to discuss our scenario here</i> <i>Are we talking here about an introduction scenario? As mentioned previously within EU plant products are not checked – maybe Norway, UK or are we talking only about in-field detection?</i></p>
<p>5. Establishment and spread (dispersal)</p> <ul style="list-style-type: none"> • Suitable areas for establishment** <ul style="list-style-type: none"> ○ SDM models ○ Host distribution • Probability of established colony growth <ul style="list-style-type: none"> ○ Host plant density ○ Radial increase velocity (new propagules) <ul style="list-style-type: none"> ▪ Intrinsic growth rate ▪ Diffusion constant (km²/unit time) ○ Allee effect severity 	<p>Suitable areas for establishment are given in 1. Host plant density is unlikely to be a limiting factor for spread due to the polyphagy of <i>H. halys</i> (see 2.).</p> <p>Population increase Developmental times Lower development threshold around 11-15°C (Kriticos 2017 and references within). Degree-day requirements for <i>H. halys</i> 537.6°C/d above 14°C egg-adult + 147.6°C/d for pre-oviposition period (Nielsen et al. 2008). 588.24°C/d above 12.4°C egg-adult (Haye et al. 2014) -> Number of generations per year usually 1-2 Egg-adult development takes 76.7-81.2d at 20°C; 41.9-44.92 at 25°C and ~33.5d at 30°C (Haye et al. 2014; Nielsen et al. 2008). If the 2nd generation cannot complete its development numbers in the following year are reduced (Haye, personal. com.) <i>By matching this information with climate data from Europe it should be possible to assess the average number of generations in each location but I don't know currently how to do it</i></p> <p>Replacement rate Overwintering mortality among diapausing adults is highly variable, with reports from Europe ranging between 39% (Haye et al, 2014) and 89% (Costi et al, 2017). This may be attributable in some part to uni vs. bivoltine phenology and resultant differences in accumulated body mass prior to overwintering (NZ RA). A full life-table under Swiss condition is given in Haye et al. (2014.) 1 Female lays on average 79 eggs, under semi-natural conditions, total mortality of Swiss <i>H. halys</i> populations was 86.7 % with a net reproductive rate of 5.69. Under (<i>unrealistic</i>) optimal laboratory conditions: net reproductive rate= 60; generation time = 57 (Nielsen et al. 2008)</p>

	<p>Spread parameters Foraging BMSB have been reported to fly an average of 2.7km, with about 13% of the population capable of flying >5km (Lee and Leskey, 2015). Experimental results have demonstrated that BMSB may fly as far as 75km or 117km in a single flight (Wiman et al. 2015; Lee and Leskey 2015), (from NZ RA). The proportion of BMSB individuals undertaking dispersal flights increases with increasing temperature (Lee and Leskey, 2015). <i>It is important to note that the species is known for long distance travel as hitchhiker (see 3.)</i></p>
<p>6. Market data</p> <ul style="list-style-type: none"> • Domestically produced quantities • Domestically consumed • Traded 	<p><i>To be filled by the economists ☺</i></p>
<p>7. Direct damages and their costs***</p> <ul style="list-style-type: none"> • Crop production (physical production/ value of production) • Crop loss per unit area/pest density (no-control, control scenario) • Higher labor costs for sorting etc. • Temperature thresholds for damage expression/seasonal effects etc. • Other factors on damage severity 	<p>Crop production (<i>all data collected for apple</i>) For physical production and value of production see FAOSTAT</p> <p>Crop loss Direct damage to fruits is first (hardly) visible as a tiny discolored dot at the stylet insertion point, which is not considered economic injury per se. These injuries can progress into much more apparent including shallow, often discolored deformations on the fruit surface and, in the flesh, discrete areas of brown necrosis (Bergh et al. 2019). One has to distinguish between fruit losses due to fruit abortion (<i>rarely measured</i>), completely unmarketable fruits and fruits that achieve a lower price. Fresh fruit vs processing fruit, for the latter neither internal nor external feeding injury are considered problematic (Bergh et al. 2019).</p> <p>Crop loss no control NZIER 2017: Yield loss assumptions in NZ 47% Zhang et al. 2007: Organic orchard in Beijing (Original reference unavailable and in Chinese) 23.4-30.8% fruit damage depending on variety. Leskey et al. 2020: West Virginia: year 1: 21.67-25.95%; mean numbers of nymphs/adults trapped concurrently: 2/3.4 year 2: 31.82-41.67%; mean numbers of nymphs/adults trapped concurrently: 2.8/8 Short et al. 2017: West Virginia: year 1: ~42%; year 2: ~68%; (mean numbers of concurrently trapped beetles also given) Candian et al. 2018: Italy: 7.1-9.0% depending on variety Joseph et al. 2015: Virginia: year 1: 48.9%; year 2: 68%</p>

	<p>Unterthurner and Ladurner (2021) organic: year 1: 9.8-22% depending on location and center/border of orchard, year 2 7.6-10.3%</p> <p>Crop loss with management</p> <p>NZIER 2017: Yield loss assumptions with reactive management in NZ 40%; with preventive insecticide management 24%</p> <p>Joseph et al. 2014: Commercial orchards in Eastern US (most were treated with insecticide programs specifically targeting <i>H. halys</i>). Between 39.3% (upper canopy, border zone, year2) and 14.2% (intermediate zone lower canopy, year 1) fruits with injury sites. <i>Some uncertainty whether internal and external damages should be added or not (different methodologies in different orchards) so I stick to external injuries, noting that numbers could be somewhat higher.</i> Overall average 22.5%</p> <p>Bergh et al. 2021: mean weekly captures of adults and nymphs linked to external damage in apple – <i>data are given as figures from which one could estimate the values or ask authors for the raw data. A very rough estimation of the weak linear relationship gives</i> 1 captured individual/trap (weekly, 1 pheromone pyramid trap/ha; maximum trapping distance 1.67 ha according to Kirkpatrick et al. 2017) = 5.5% damage; or 1 Adult = 10.4 %; overall recorded mean damage 17% (managed orchards).</p> <p>Stäheli (2022): Switzerland estimated by farmers in a year with strong incidence: 2.5%</p> <p>Leskey et al. 2020: West Virginia year 1: 6.67-36.67% perimeter trees and 8.95-18.46% in interior trees according to management strategy; mean numbers of nymphs/adults trapped concurrently: ~0.2/~0.7 (slight differences according to treatment)</p> <p>Year 2: 0.83-26.67% perimeter trees and 3.25-11.36% in interior trees according to management strategy; mean numbers of nymphs/adults trapped concurrently: ~0.2/~0.7</p> <p>Short et al. 2017: West Virginia: year 1: ~10% with threshold (bugs in pheromone traps) based spraying Year 2: ~10-15% (mean numbers of concurrently trapped beetles also given)</p> <p>Candian et al. 2018: Italy: 5.5-7.4% according to variety in insecticide treated; 4.3-5.8% in netted orchard</p> <p>Unterthurner and Ladurner (2021): year 1: 0-10.1% depending on location and center/border of orchard, year 2 0-1.4%</p> <p>Additional labor cost harvest</p>
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	<p>Decreased harvest performance in man hours because fruits have to be selected. 10% in apple (Stäheli 2022).</p> <p>Temperature thresholds for damage Optimal feeding activity between 16°C and 17 °C and no feeding at 26.5°C - 29.5°C (Wiman et al. 2014, 2015)</p> <p>Seasonal effects Highest population peak and highest damage are detected from July on (Bariselli 2016). Apple cultivars that mature late in the growing season face the most prolonged risk from <i>H. halys</i> (Joseph 2014). Apple cultivars harvested between about mid-summer and early October require protection from <i>H. halys</i> through at least three to four weeks preceding harvest (Bergh et al. 2019). Injury to apple was relatively inconsequential until after mid-June (Leskey et al. 2012). <i>It is important to note that H. halys damage cannot be distinguished from damage by other stink bugs that may co-occur in the orchards. However, many sources state that the damage has increase tremendously with appearance of H. halys and therefore they are confident that it can be attributed to this pest.</i></p>
<p>8. Indirect damages and their costs</p> <ul style="list-style-type: none"> • Vectoring diseases • Effects on beneficials • Export restrictions and lower export prices 	<p>Vectoring diseases In addition to the physical damage <i>H. halys</i> inflicts on fruit, it also known to vector a phytoplasma disease of Paulownia tomentosa in Asia (Hoebeke and Carter 2003) and can vector other phytoplasmas (Jones and Lambdin 2009; Paltrinieri et al. 2016). <i>However, those aspects seem to have not been further investigated or quantified, nor do they seem to play a role in apple orchards so far</i></p> <p>Effects on beneficials Invasion of <i>H. halys</i> resulted in up to an approximately fourfold increase in insecticide use (Leskey et al. 2012), including broad-spectrum insecticides in the postbloom period that have increased the incidence of secondary pest outbreaks (J.C.B., unpublished data) (in Joseph et al. 2014) similar Blaauw et al., 2016</p> <p>Export restrictions and lower export prices Import limits /obligatory treatments for consignments to Australia and NZ (https://www.agriculture.gov.au/biosecurity-trade/import/before/brown-marmorated-stink-bugs/prepare-import) Lower horticultural export prices due to concerns over increased chemical use have been considered in a NZ cost assessment (NZIER 2017)</p>

9. Control costs of invaded areas

- Cost of detection in invaded unit of area
- Unit of area where pest detected (can this be used to infer pest density?)
- Cost of control measures in area
 - Increased pesticide/netting etc. costs
 - Higher labor costs to monitor and treat

Current detection methods

Aggregation pheromones: three types of commercially produced BMSB traps available, brand of trap has an associated lure. These lures may be purchased independently of the traps and several trap and lure combinations are possible.

AgBio pyramid trap (*price only available on request*)
Trécé sticky trap (lure 5pc/33.63USD, to be replaced every 12wk; traps 1-2USD)

Rescue funnel trap (~20 USD)

Preliminary data from Tracy Leskey on trap efficacy using a lure containing 5 mg pheromone and 50 mg MDT indicated that traps lure BMSB within a 3.5ha radius and offer 21% recapture within 10m of the trap declining to 2% at 60m. (NZ RA 2019).

Pyramid trap: maximum trapping distance 1.67 ha (Kirkpatrick et al. 2017)

Chemical control

Needs some more discussion with the partners, what is actually used and in which amounts etc.

Pyrethroids and neonicotinoids are effective in containing *H. halys* but the short residual activity of many compounds makes necessary to repeat the treatments every 7-10 days (Blaauw et al., 2015; 2016).

Trap-based threshold-triggered insecticide applications, perimeter spray applications, or perimeter AK (attract-and-kill trees) can reduce pesticide quantity (Leskey et al. 2020).

Country	Indication	Authorized substances*
Switzerland	Heteroptera	Spinosad, Flonicamid <i>Emergency license: Acetamiprid</i>
Austria	<i>H. halys</i>	Acetamiprid, Pyrethrine, <i>Emergency license: Cypermethrin</i>
Italy	<i>H. halys</i>	Pyrethrine, Acetamiprid, Etofenprox, tau-fluvalinate, Tebufenozide, Flupyradifurone
France	Heteroptera	Lambda cyhalothrine, Deltamethrine, tau-fluvalinate, Etofenprox
Germany	Heteroptera	Lambda cyhalothrine, Deltamethrine, Dazomet, Pyrethrine, Abamectin, Magnesium- aluminiumphosphide, Phosphan, gamma cyhalothrin

It is important to note that many of the insecticides used in the US are not allowed in Europe or European countries

*Some of the modelling papers have this information. Including CLIMEX paper

**Often covered already in 1.

*** See Carrasco et al. (2012) WCR paper for equations for cost taking into account damages based on pest density.

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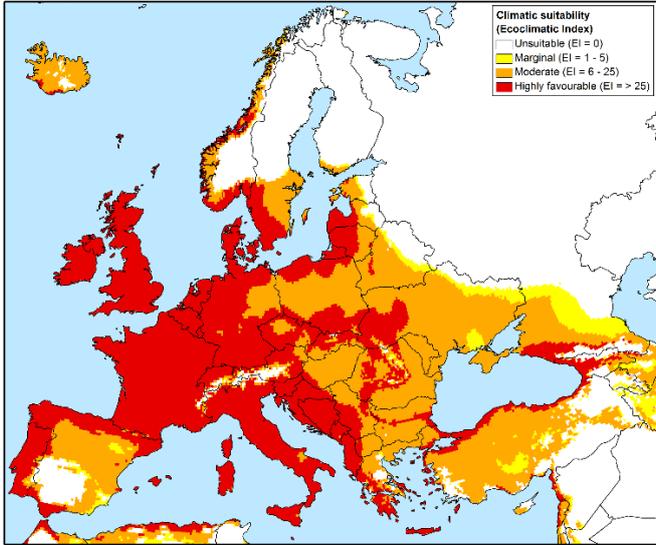
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7 APPENDIX 4

Damages and costs associated with *Phytophthora ramorum* invasion and control, with a focus on Europe

<p>Potential distribution of pest</p> <ul style="list-style-type: none"> • Species distribution models <ul style="list-style-type: none"> ○ CLIMEX models ○ Other SDM models 	<p>A CLIMEX model (Ireland et al., 2013) was developed to infer the potential global distribution of <i>P. ramorum</i>. The model combined phenological data for the three main <i>P. ramorum</i> genotypes at the time, as there was insufficient data to treat each lineage independently. The EU2 lineage, which exhibits a different pathogenicity and threat in Europe to the earlier introduced and much more widespread EU1 lineage, was also not included in parameterisation because at the time it was newly discovered (Van Poucke et al., 2012). A study found that when grown at different temperatures, the growth curves for the EU1 and EU2 lineages were very similar, as were the lower limit and optimal range. However, the upper limiting temperature limit is higher for EU2 (27 °C vs 29 °C) (Harris et al., 2020). This may not have a major effect on potential distribution in Europe, as Ireland et al. (2013) showed that the main limiting factors (i.e. in European Russia, Swiss Alps, northern Europe) were cold stress and moisture availability.</p>  <p>The model predicts that almost all of Europe is highly suitable for the establishment of <i>P. ramorum</i>. It is already widespread throughout Europe (27 countries) (EPPO, 2023), but the model suggests room for further spread into countries where it is currently not known to occur.</p>

<p>Distribution of host plants (regarding potential overlap with pest)</p> <ul style="list-style-type: none"> • Differences between <i>P. ramorum</i> lineages. 	<p><i>P. ramorum</i> exhibits a very wide host range, with the European pest risk analysis listing 133 species (though with differing levels of certainty and susceptibility) (Sansford et al., 2009). Host plant availability would therefore not limit its potential distribution.</p>
<p>Entry and exclusion</p> <ul style="list-style-type: none"> • Likelihood of entry and establishment <ul style="list-style-type: none"> ○ Invasion pathways? ○ No exclusionary measures ○ Exclusionary measures ○ How costs of exclusionary measures effects probability of entry and establishment 	<p><i>P. ramorum</i> is already widespread in Europe, but there are still climatically favourable areas where it is not currently known to occur (EPPO, 2023; Ireland et al., 2023). Invasion from sources within Europe are therefore now likely to be more important than from the US or native origin (VKM, 2023).</p> <p>Invasion pathways</p> <ul style="list-style-type: none"> • Grünwald et al. (2012) explains that population genetic analysis suggests that imported nursery plants that were infected with <i>P. ramorum</i> was the initial pathway of invasion to the US. The nursery trade appears to be the main source of long-distance spread/invasion (Jung et al. 2016, 2021). • The updated pest risk assessment for Norway (VKM, 2023) provides a list of the eight most important entry pathways, and categorisation of likelihood of entry for each of these (see Table 2 and section 2.2 in general for other useful details). For example, the most important pathway is considered to be the planting of infested, often symptomless, nursery stock, either introduced or produced inside the countries. Ornamental nurseries across Europe show very high infestation rates with <i>P. ramorum</i> (Jung et al. 2016). Of these <i>P. ramorum</i> is almost ubiquitously associated with <i>Rhododendron</i>, which is the most transmissive host plant contributing to the spread of the pathogen throughout Europe (Vercauteren et al., 2013; Jung et al., 2016; VKM, 2023). VKM (2023) stipulates that of the 319 border interceptions of <i>P. ramorum</i> involving plants for planting, potted plants, or cuttings, 231 of these were infected <i>Rhododendron</i>. This risk assessment also reports the relative tonnage of <i>Rhododendron</i> imported to Norway by the five EU countries that constitute the majority of imports (Figure 6). <p>Exclusionary measures</p> <p>The regulatory status of <i>P. ramorum</i> in Europe is somewhat complicated by the already widespread presence of EU lineages, and absence of the 2 NA</p>

	<p>lineages (named after the continent where first discovered) and the 8 Asian lineages from Japan and Vietnam (Jung et al., 2021).</p> <ul style="list-style-type: none"> • EU lineages of <i>P. ramorum</i> are now officially a regulated non-quarantine pest. Some requirements remain surrounding the transport of symptomatic nursery stock, the transport of nursery stock in areas of known <i>P. ramorum</i> occurrence, and the destruction of infected (and surrounding) nursery plants that are known to be major transmissive host plants (EU, 2021; EU, 2022). However, we were not able to obtain data specifically related to the cost of these measures. • Non-EU lineages of <i>P. ramorum</i> are not known to occur in Europe and are regulated as a quarantine pest. There are consequently prohibitions on the importation of certain plant species, known to be susceptible to these lineages, from Canada, Japan, UK, US, and Vietnam. Phytosanitary certificates are required for importation of these plants from other areas (EU, 2021). This is the only scenario where exclusionary measures are relevant. • Sansford et al. (2009) summarises a UK impact assessment from DEFRA in 2008 (I cannot find how to access this directly) that estimates costs of damage and management over 20 years if the pest were to arrive and spread, under two scenarios (EU minimum requirements, or increased activity). Some of these estimates could be relevant to the current regulatory statuses described above for EU and non-EU lineages. <ul style="list-style-type: none"> ○ Cost of diagnostic tests (which would be used on symptomatic plants): EU minimum requirements £161,000 in first year. Increased phytosanitary activity £779,000 per year. ○ Cost of government inspections: EU minimum requirements £615,000 in first year. Increased phytosanitary activity £2.27 million per year. ○ Cost of administrative burden negligible (e.g. maintaining records of phytosanitary certificates for imports < £100 per year).
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<p>Detection of incursions</p> <ul style="list-style-type: none"> • Time of incursion detection • Expenditure on detection (and how it relates to time of detection) 	<p>Time of detection – assumption?</p> <p>Cost of incursion detection (non-EU lineages)</p> <ul style="list-style-type: none"> • Cost of diagnostic tests and cost of government inspections, described above, also relevant here. <p>Cost of field detection (EU lineages)</p> <p>The Norwegian updated risk assessment (VKM, 2023) described the typical procedure for detecting <i>P. ramorum</i> in Europe. This would likely still apply with the current regulatory status of EU lineages (as described above).</p> <ul style="list-style-type: none"> • Inspection of known susceptible host plants (e.g. <i>Rhododendron</i>) at import sites and/or nurseries (estimate inspection costs from those given for Britain above?). • Plants that show <i>Phytophthora</i> infection symptoms are tested with the Pocket Diagnostic field detection kit for <i>Phytophthora</i> (€451.62 for 50 tests) (Pocket Diagnostic, 2023). • If symptomatic plant parts test positive for <i>Phytophthora</i>, samples are taken to the laboratory and identification of <i>P. ramorum</i> made from morphological traits of isolated culture or by molecular methods (estimate from diagnostic costs from those given for Britain above?).
<p>Establishment and spread (dispersal)</p> <ul style="list-style-type: none"> • Suitable areas for establishment <ul style="list-style-type: none"> ○ SDM models ○ Host distribution • Probability of established colony growth <ul style="list-style-type: none"> ○ Host plant density ○ Radial increase velocity (new propagules) <ul style="list-style-type: none"> ▪ Intrinsic growth rate ▪ Diffusion constant (km²/unit time) ○ Allee effect severity/no Allee effect 	<p>Suitable areas for establishment</p> <p>Refer to sections for CLIMEX models and host distribution above.</p> <p>Colony growth</p> <p>Host plant density</p> <p>Difficult to put numbers on this. Could assume that nurseries are high density, but for establishment, natural spread to, and within, the surrounding environment (or parks where the plants are eventually planted) is key.</p> <p>Intrinsic growth rate</p> <ul style="list-style-type: none"> • Elliot et al. (2011) present the growth rates of the NA1, NA2, and EU1 lineages at minimum, optimal, and upper temperature limits (NA lineages absent from Europe and officially considered quarantine pest, unlike the EU lineages, so may be important to differentiate). I have attached the table for this data at the end of this document (Table 1, before reference list). Colony growth rates are calculated in mm/day. • O’Hanlon et al. (2017a) also presents growth rates at different temperatures for the same lineages, but with the addition of the EU2 lineage (also infects a forestry plant species (larch) in

	<p>Europe, which EU1 had jumped to before EU2 discovery – more detail later). The table of growth rates in mm/day is attached at the end of this document (Table 2).</p> <ul style="list-style-type: none"> • Jung et al. (2021) present data for growth of all 12 lineages at the optimum of 20 °C and at the upper temperature limit of 28 °C which are given at the end of this document (Figures 1-2). • It is important to consider this data within the context of the biology of oomycetes. Although colony growth is a necessary pre-requisite for establishment and spread, it is limited to velocity of spread on a single infected host plant. <p>Diffusion constant</p> <p>Natural dispersal</p> <ul style="list-style-type: none"> • Experiment with central infected <i>Rhododendron</i> plant with circles of plants around it either in direct contact, 5 cm, or 30 cm from the infected plant. Surrounding plants collected after 7 days and monitored for infection. Only plants in direct contact developed infection (25% and 69% after 7 days in two separate trials). No aerial spread (Heungens et al., 2009). • Pastalka et al. (2017) also revealed very limited capacity for aerial dispersal over a five year experiment in a quarantine research nursery. • Can disperse up to 10 meters from rain splash during rain events that last 1-6 days (Davidson et al., 2005). Same study also assessed stream water that runs through the source location and found <i>P. ramorum</i> 6km downstream from source. • Rizzo et al. (2005) – aerial study of infested forest area in Oregon showed about half of the new infections each year occurred within 100m of trees that died from infection the previous year. • Chastagner et al. (2008) – two year study at Christmas tree plantation bordering infected host plants found that most of the infected Christmas trees occurred within 4.4m of source trees. <p>Natural dispersal at larger spatial-scales</p> <ul style="list-style-type: none"> • This is important when <i>P. ramorum</i> nursery infections spill-over into adjacent wild or plantation systems (that may have high host-density), where spread can potentially continue over larger spatial scales. • Maschetetti et al. (2008) – used microsatellite analysis to estimate that rare strong wind (with
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rain) events can cause medium-long range dispersal of 1500-10,000m.

- Meentemeyer et al. (2011) – presents a spread model over a 40-year period (1990-2030) in a spatially heterogenous (in terms of host-availability) landscape in California, where the pathogen kills oak and tanoak. Model predicts a ten-fold increase in disease spread between 2010 and 2030 (to 8,000km of land area in 2030). Eliminating influence of long-distance dispersal made little difference to this prediction due to the substantial number of isolated infestations caused by multiple previous long-distance dispersal events. This paper may be useful for you to look into in more detail (model structure, etc.).
- Curry county (Oregon) – spreading between 0.8 – 7.2km per year, with control measures (COMTF, 2023).
- In the UK, where *P. ramorum* has jumped from nursery plants to infecting larch (*Larix* spp.) plantations and forests, it was reported that in May 2010, an estimated 2,400 hectares were affected (Webber et al., 2010). By 2017, about 20,000 hectares were affected (Harris et al., 2018). Pathogen had quarantine status during this time, so management of spread via felling of infected trees and host plants within a buffer zone would have been occurring.

Human-mediated dispersal

- The nursery trade, specifically the movement of infected plants intended for planting, is the most important pathway of dispersal for *P. ramorum*. Its rapid spread throughout Europe was facilitated by this, though it was detected in low frequencies (under 5% of nurseries) before 2009 (Sansford et al., 2009). In the Europe-wide nursery survey of Jung et al. (2016) ca 35 % of the tested 333 ornamental nurseries were found infested with *P. ramorum*. However, it is very difficult to find numbers on spread/unit time in this context as this relates to trade networks, which theoretically allows spread to occur anywhere within that network (perhaps not very limited spatially unless control measures are in place – see below point).
- Xu et al. (2009) – spatio-temporal analysis of *P. ramorum* spread between nurseries and garden centres in England and Wales found a maximum

	<p>spread of 60km between 2003-2004. This is with control measures in place.</p> <p>SODmap project may be useful – can view distribution data in California on Google Earth.</p>
<p>Control costs of invaded areas</p> <ul style="list-style-type: none"> • Cost of detection in invaded unit of area • Unit of area where pest detected (can this be used to infer pest density?) • Cost of control measures in area • See Carrasco et al. (2012) WCR paper for equations for cost taking into account damages based on pest density. 	<p>Sansford et al. (2009) covers estimated control costs in the UK (citing a DEFRA impact assessment that is no longer available). However, estimates were provided for two scenarios that both follow at least the minimum requirements of the EU quarantine status of <i>P. ramorum</i> at the time. This also does not include <i>P. ramorum</i> in larch plantations.</p> <p>Cost of detection</p> <ul style="list-style-type: none"> • Provided towards the end of ‘entry and exclusion’ section. <p>Unit area where pest detected</p> <ul style="list-style-type: none"> • Assumption? <p>Cost of control measures</p> <ul style="list-style-type: none"> • Estimations for Great Britain (for EU minimum requirements scenario at the time) that cost of staff and plant health inspection provision, and the implementation of requirements resulting from inspections, would be £1.7 million after 20 years for the nursery industry (Sansford et al., 2009). • For the scenario with increased phytosanitary measures over the EU minimum requirements, this estimate increases to £2.2 million after 20 years (Sansford et al., 2009). • For public gardens in Great Britain, it was estimated that under the EU minimum requirements scenario, cost of clearance would amount to £13.7 million after 20 years (Sansford et al., 2009). • For the scenario with increased phytosanitary measures over the EU minimum requirements this estimate decreases to £4.4 million after 20 years due to gardens eventually being cleared of the pathogen after nine years (with control costs being zero after this) (Sansford et al., 2009). • Cost of clearance of <i>Rhododendron ponticum</i> (as a control strategy) in UK woodlands and public gardens was estimated at £7,000 and £10,000 per hectare, respectively (Forest Research, 2007). • UK data were used to make similar estimates for Europe. Between 2004 and 2006, €972,000 was spent on official inspections for nurseries and €3,500,000 for parks (Forest Research, 2007).

	<ul style="list-style-type: none"> • Five year government funded programme initiated for England and Wales totaling £25,000,000 for awareness campaign, research, containment and eradication measures related to nurseries, woodlands and heath land. In addition, a further £500,000 and £100,000 for England and Wales, respectively, was provided for <i>Rhododendron</i> clearance work in 2009 (Williams et al., 2010). • Control costs associated with infected nursery plants has been substantially surpassed by those associated with the control of <i>P. ramorum</i> in larch forests in the UK since 2010. Between 2010 and 2019, around 25,000 hectares of larch had either been removed, or scheduled to be removed, in the UK (Harris et al., 2021). By 2022, it is estimated that 35,000 hectares of larch had been removed at a cost of around €215 million (PurPest proposal). • There are some similar calculations and estimates for the US, but perhaps this is not relevant? (Hall & Albers, 2009; Kovacs et al., 2011; Brasier et al., 2022).
<p>Damages and their costs</p> <ul style="list-style-type: none"> • Cost of damage per unit area invaded (again, does unit area infer density?) <ul style="list-style-type: none"> ○ Nurseries ○ Gardens ○ Forests • Damage thresholds 	<p>Market data for nursery production in EU countries – EUROSTAT (2020).</p> <ul style="list-style-type: none"> • Under EU minimum requirements scenario, estimated loss to the nursery trade industry (due to plant loss) for Great Britain was £2.2 million over 20 years. This begins at £54,000 per year, but increases to £163,000 per year from year four onwards due to increasing disease spread (Sansford et al., 2009). • For the increased phytosanitary measures scenario, estimated loss to the nursery trade industry for Great Britain was £400,000 over 20 years. • Public value at risk in England and Wales is estimated to be £578 million for heritage gardens, £386 million in heathland, and £482 million in woodland (total £1.446 billion) (Drake & Jones, 2017). • Kovacs et al. (2011) estimated that between 2010 and 2020, the cost of loss of damaged oak trees (on developed land) would be USD\$7.5 million, and \$135 million in property value losses. This does not represent losses of commercial products, but rather of the removal and replacement of damaged trees. For more detail, Table 1 in this

	<p>study provides the area size assessed for each county assessed, and Table 6 provides costs for each county. This study may be worth looking into in more detail because it uses a spread/economic costs model.</p> <ul style="list-style-type: none"> • Kliejunas (2010) reports that losses of at least \$100 million per year in stumpage value (lost harvest), out of a total stumpage value of USD\$1.68 billion in the state, could occur if eradication was not successful (2008 estimate). • Cost of plants destroyed due to <i>P. ramorum</i> in Washington State nurseries: between 2004 and 2005, 17,266 plants were destroyed at 32 nurseries, which had an estimated collective worth of USD\$423,043. The cost per nursery was \$13,220 over the two year period (Dart & Chastagner, 2007). • Cost to the US and Canada <i>Rhododendron</i> export trade is estimated at around \$USD 5 million (Brasier et al., 2022). • Over \$USD 30 billion of commercial timber production threatened by <i>P. ramorum</i> in the US (Brasier et al., 2022). • Could not find relevant information on damage/action thresholds applied. For a pathogen that produces different levels of inoculum depending on the foliar host species (sporulation potential) (Davidson et al., 2008; Harris & Webber, 2016), it may be more pertinent to consider thresholds in relation to the level of infection required for different host species to become infectious to nearby hosts. However, I could not find any specific thresholds relating to this in the literature. Rollins et al. (2015) found that in irrigation water, an inoculum threshold of 51 zoospores/ml was required to infect <i>Rhododendron</i> leaves, suggesting that nurseries and regulatory agencies could use this understanding to consider risk associated with using <i>P. ramorum</i> infested irrigation water (this is not a damage threshold though).
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Table 1. Elliot et al. (2011).

Species (# of isolates)	Lesion	2°C	20°C	28°C
<i>P. ramorum</i> NA1 wt (6)	149.91 (± 12.20) b	0.91 (± 0.27) b	2.67 (± 0.04) a	2.28 (± 0.44) b
<i>P. ramorum</i> NA1 nwt (4)	45.42 (± 6.81) a	0.07 (± 0.16) a	3.13 (± 0.27) b	1.83 (± 0.13) a
<i>P. ramorum</i> NA2 (6)	205.15 (± 9.85) c	0.87 (± 0.05) b	2.14 (± 0.08) a	2.28 (± 0.09) b
<i>P. ramorum</i> EU1 (7)	199.58 (± 10.52) c	0.78 (± 0.06) b	2.73 (± 0.05) ab	2.32 (± 0.08) b
<i>P. foliorum</i> (1)	75.33 (± 11.53)	0.76 (± 0.07)	5.16 (± 0.07)	5.89 (± 0.16)
<i>P. lateralis</i> (1)	33.48 (± 2.76)	0.14 (± 0.04)	3.51 (± 0.03)	2.74 (± 0.10)
<i>P. hibernalis</i> (1)	107.48 (± 16.42)	1.23 (± 0.11)	3.18 (± 0.10)	0.00 (± 0.00)

Standard error is provided in parentheses. Column means with the same letter are not significantly different at $p = 0.05$ (ANOVA, Hochberg's GT2 method). Other *Phytophthora* species are shown for comparison but were excluded from statistical analysis.
wt, wild type morphology; nwt, non-wild type morphology.

Table 2. O'Hanlon et al. (2017).

Lineage	4 °C ($F_{3,892} = 7.5$, $P < 0.001$)	10 °C ($F_{3,893} = 35.3$, $P < 0.001$)	15 °C ($F_{3,889} = 38.6$, $P < 0.001$)	20 °C ($F_{3,881} = 23.7$, $P < 0.001$)	25 °C ($F_{3,886} = 11.9$, $P < 0.001$)
EU1 ($n = 116$)	1.4 ± 0.5 (2.5)	3.5 ± 0.5 (3.1)	4.9 ± 0.8 (4.0)	5.9 ± 0.8 (4.0)	5.0 ± 1 (6.9)
EU2 ($n = 40$)	1.5 ± 0.6 (2.9)	3.8 ± 0.7 (5.0)	5.3 ± 0.9 (5.3)	6.1 ± 1.0 (9.1)	5.3 ± 0.6 (4.2)
NA1 ($n = 8$)	1.2 ± 0.5 (2.0)	2.9 ± 0.5 (2.4)	4.0 ± 0.4 (1.6)	4.9 ± 0.5 (3.3)	4.5 ± 0.5 (2.5)
NA2 ($n = 2$)	1.5 ± 0.6 (1.7)	3.6 ± 1.1 (2.7)	5.0 ± 1.5 (4.3)	6.0 ± 1.8 (4.7)	5.2 ± 1.4 (3.4)

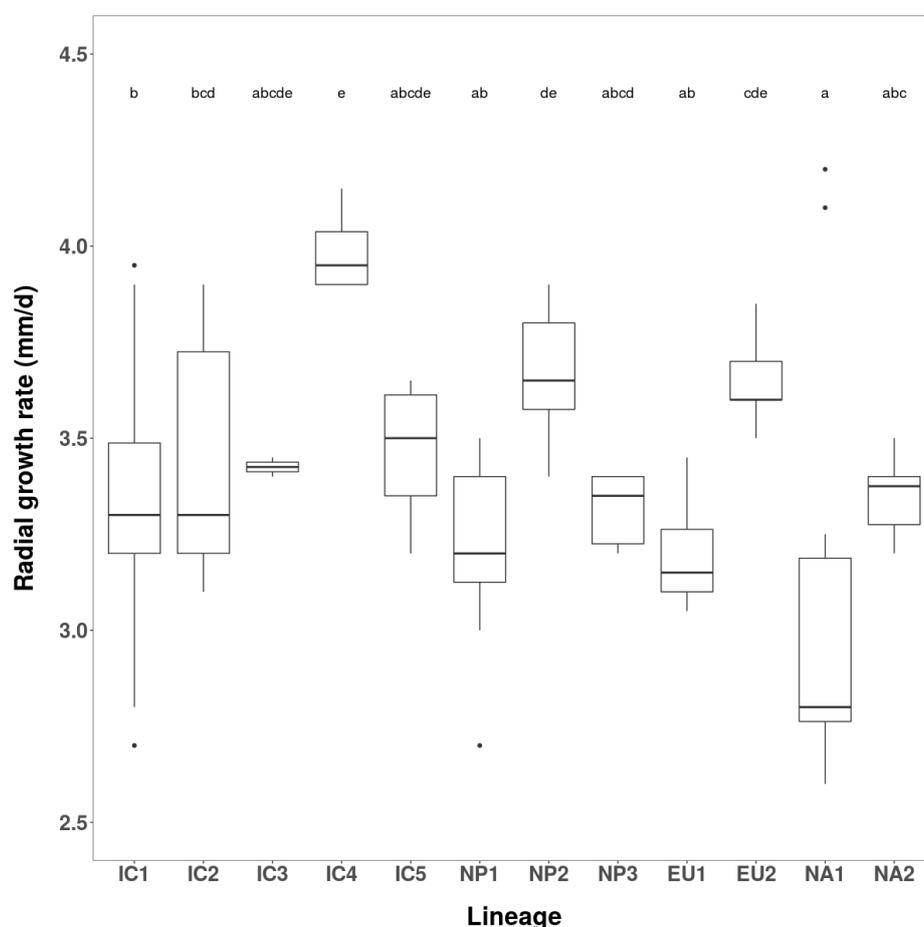


Figure 1 (Jung et al., 2021). Box and whiskers diagram showing daily radial growth rates of the eight Asian lineages (IC1-IC5; NP1-NP3), the two European lineages (EU1, EU2) and the two North American lineages (NA1, NA2) of *Phytophthora ramorum* at 20 °C on carrot agar (CA). Different letters indicate statistical differences at significance level $\alpha = 0.05$.

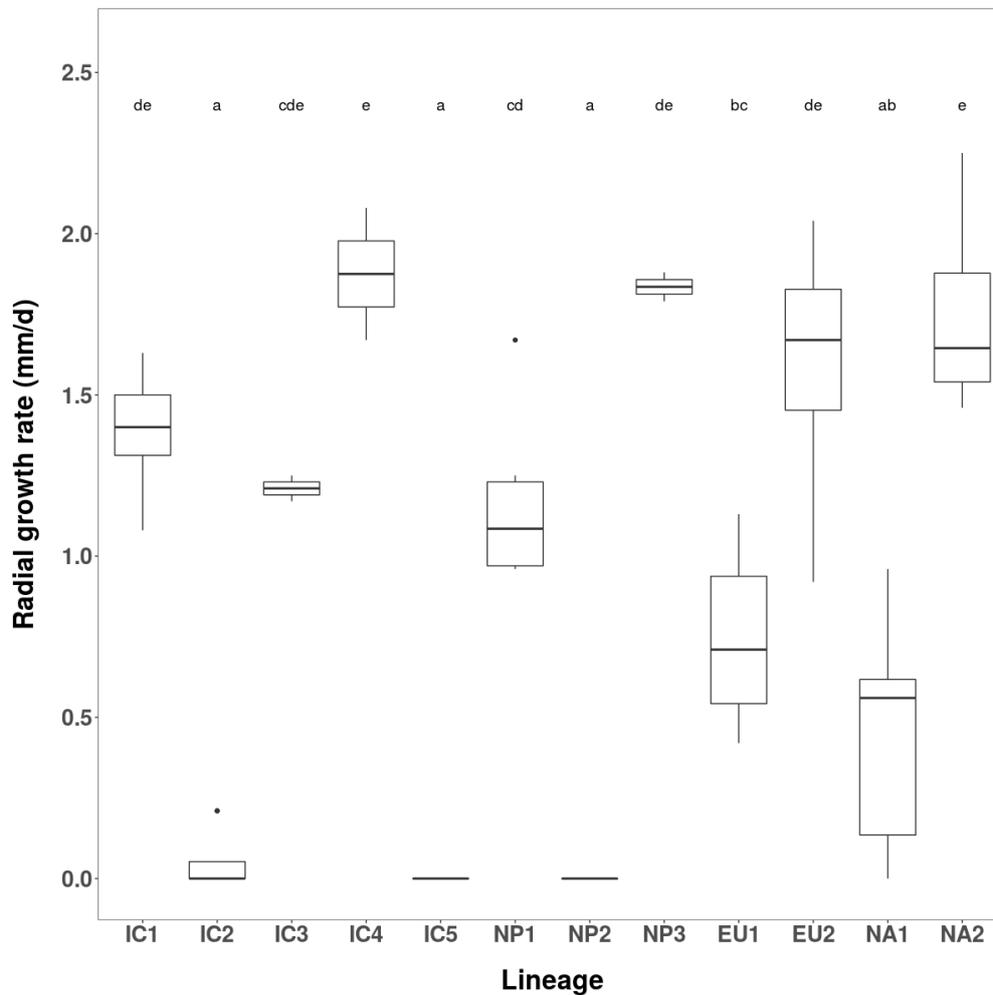


Figure 2 (Jung et al., 2021). Box and whiskers diagram showing daily radial growth rates of the eight Asian lineages (IC1-IC5; NP1-NP3), the two European lineages (EU1, EU2) and the two North American lineages (NA1, NA2) of *Phytophthora ramorum* in a gene x environment stress test at 28 °C on 2% V8-agar (V82A). Different letters indicate statistical differences at significance level $\alpha = 0.05$.

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8 APPENDIX 5

Damages and costs associated with *Bursaphelenchus xylophilus* invasion and control, with consideration to the outlook for Europe

Background

The pinewood nematode (PWN) *Bursaphelenchus xylophilus* (Nematoda: Aphelenchoididae;) is native to North America. It invaded Asia more than 100 years ago and more recently Europe. It is transmitted by different native Cerambycid beetles of the genus *Monochamus*. The nematode is the causative agent of pine wilt disease (PWD) in the affected areas. The critical mechanism for PWD expression is still unknown, although it is assumed that PWNs and bacteria induce a plant defense response that ultimately hinders water transport in the plant and leads to wilting (Mamiya 1983). Expression of the disease is linked to climate; it is less rapid in cooler climates and no expression at all occurs below a certain temperature threshold (Gruffud et al. 2016)

1. Potential distribution of pest

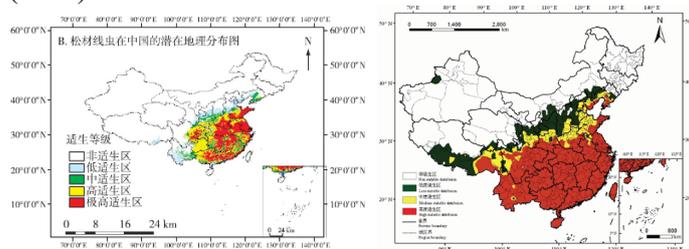
- Species distribution models
 - CLIMEX models
 - Other SDM models

Multiple actors are involved in the expression of the disease:

a) PWN

For Europe, PWN is likely to establish throughout the distribution range of suitable hosts; Coniferous plants are present in all EPPO countries (Evans et al. 2009).

Han et al. (2015) present a MaxEnt model for China (left, colors refer to no, low, medium, high and very high suitability). A Climex model (right), including a climate change scenario is provided by He et al (2012).



b) The vector

For PWN in Europe, the only known vector is *M. galloprovincialis* (Sousa et al. 2001), but also can potentially be vectored by other *Monochamus* species existing in Europe, like *M. sutor*, *M. saltuarius*, *M. sartor* and *M. impluviatus* (Russia, Finland). A recent PRA for Europe does not consider vector presence as a limiting factor for PWD, as vectors are native and widespread in all countries except in Great Britain (Baker et al. 2019). The beetles are associated with different coniferous trees (Hellrigl 1971).

Nevertheless, SDMs from other countries may report relevant climate parameters. E.g. Estay et al. (2014) compiled a MaxEnt model for Chile, that was based among others on the European species *M. galloprovincialis*, *M. sutor* and *M. saltuarius*.

It is possible that further, non-native vectors may become introduced and add to the vectoring of the species. (See PRA for non-EU *Monochamus* spp. by Bragard et al. 2018)

c) Disease expression (Pine wilt disease, PWD)

Monochamus adults carrying nematodes can be present in an area without necessarily causing PWD (Gruffud et al. 2016). Disease

expression in trees infected with the nematode depends on temperature, soil (drought restricts water uptake by tree, increasing disease expression) and environmental conditions (moisture) and can either appear rapidly or with latency of one or several years (Zhao et al. 2008; Gruffud et al. 2016). Gruffud et al. (2016) developed a process-based model to determine the influence of climate on the expression of PWD. (The model was further applied to Germany, including a climate change scenario, Gruffud et al. 2019). In the model, the infestation level of the tree with nematodes determines expression of wilt and the initial infestation of nematodes increases or decreases according to the temperature and moisture conditions. The output map shows in black PWD predicted, in grey PWD possible and in white PWD not predicted.

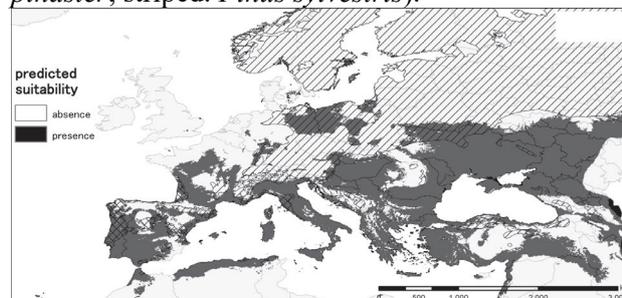


A simplified model version shows:

- wilt for 99 % of locations with $MST \geq 20^{\circ}C$.
- no wilt for 100 % of locations with $MST < 19.31^{\circ}C$.
- some wilt (under certain conditions) for 83 % of locations with $19.31^{\circ}C \leq MST < 20^{\circ}C$.

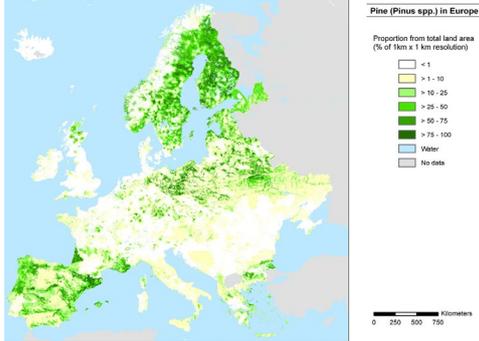
MST= mean summer temperature (averaged over June, July and August. A common model assumption is that trees die from PWD if temperatures are higher than $20^{\circ}C$ for at least 8 weeks (Soliman et al. 2012; Sathyapala 2004).

A worldwide MaxEnt model including a climate change scenario is presented by Ikegami and Jenkins (2019), it includes a detailed analysis of Europe (current scenario shown, crossed areas: *Pinus pinaster*, striped: *Pinus sylvestris*).



Hirata et al. (2017) present another worldwide, detailed model of PWD under climate change.

Several MaxEnt models were developed for Asia (Tang et al. 2021; Lee et al. 2021; Hao et al. 2022; Ouyang et al. 2022), as well other models (Gao et al. 2019; Matsushashi et al. 2020; Liu and Zhang 2022; Yoon et al. 2023) some of the model parameters may be useful for a model on European regions.

<p>2. Distribution of host crop plants (regarding potential overlap with pest)*</p> <ul style="list-style-type: none"> • Focus crop • Other primary host crop plants • Other host crop plants • Spatial extent of host crop plants in Europe • Relevant information on spatial extent within countries. 	<p>PWN prefers <i>Pinus</i> species, but is also able to attack other Coniferae. Susceptibility of <i>Pinus</i> species to PWN differs, with the European species <i>P. mugo</i>, <i>P. nigra</i>, <i>P. pinaster</i> and <i>P. sylvestris</i> being considered susceptible and <i>P. halepensis</i> being classified as intermediately suitable (ANSES 2018). Other conifer species are non-susceptible either because they are not suitable for vector maturation feeding, vector reproduction or nematode infection. A full list is provided in ANSES (2018). The European Forestry Institute (https://efi.int/) provides maps and underlying GIS data at a 1x1 km resolution for</p> <ol style="list-style-type: none"> a) Forest % share of land area (Schuck et al. 2002) b) Dominant tree species separating <i>P. pinaster</i> and <i>P. sylvestris</i> and <i>Pinus</i> spp. (Brus et al. 2012). c) Wood production in m³/ha (Verkerk et al. 2015) <p>Distribution data for all tree species incl. <i>P. mugo</i> and <i>P. nigra</i> are also provided by Caudullo et al. (2017). Tröltzsch et al. (2009) provide at 1x1 km resolution data of % land cover for <i>Pinus</i> spp. in Europe.</p> 
<p>3. Entry and exclusion</p> <ul style="list-style-type: none"> • Likelihood of entry and establishment <ul style="list-style-type: none"> ○ Invasion pathways? ○ No exclusionary measures ○ Exclusionary measures ○ How costs of exclusionary measures effects probability of entry and establishment 	<p>PWN has already established in continental Portugal and Madeira (Mota et al. 1999, Valadas et al. 2012). The initial introduction probably occurred from an Asian population (Mallez et al. 2021: Japan; Douma et al. 2017: China). In Spain it is present with few occurrences (EPPO 2023). Evans et al. (2009) list in order of priority, probable entry ways of PWN and its vectors:</p> <ol style="list-style-type: none"> 1) untreated coniferous wood packaging materials (but the implementation of ISPM No 15 reduces this risk to an acceptable level), 2) round wood and sawn wood of host species, 3) plants for planting (except seeds) of host species (including bonsai plants), 4) particle and waste wood of host species, 5) cut branches (including Christmas trees) of host species, 6) isolated bark (including Christmas trees) of host species <p>EU mandates treatment by heat or fumigation of coniferous wood (other than packaging, which is covered by ISPM 15 (IPPC 2019) and chips/sawdust) imported from areas with PWN (EU 2019). Douma et al. (2017) developed a pathway model for PWN via round and sawn wood from China based on data from Eurostat as well as PWN transfer efficiency, host cover, vector activity and other. According to the model from 2000-2012 84.2 PWN propagules</p>

	<p>transferred to hosts in EU countries, of those 62% in areas where PWN would stay asymptomatic. The numbers increased by ca. 1 PWN/year due to increasing trade. Highest exposure was predicted for Sweden, Belgium, Spain, Czech Republic and Italy. Ports and factories make up 98% of the exposure sources. The model could/should be applied also to other potential sources such as North America.</p> <p>Robinet et al. (2011) simulated separate introductions at 200 European ports and determined potential of spread of PWD from those points. Based on the spread simulations, the most important ports to monitor are those in Romania, Bulgaria, Croatia, Ukraine, Italy, Greece, Hungary, Slovakia and Slovenia.</p> <p>PWN was detected in about 40 batches of wood-based commodities entering into or circulating through France from 2000 to 2019, representing a little less than 0.7% of the total samples analyzed (Mariette et al. 2023). In China about 1% of inspected commodities were found infested (Gu et al. 2006).</p>
<p>4. Detection of incursions</p> <ul style="list-style-type: none"> • Time of incursion detection • Expenditure on detection (and how it relates to time of detection) • How does time of detection effect costs? 	<p>EU legislation mandates emergency measures to prevent the spread of PWN including annual monitoring of wood samples and checks for signs of the nematode and its vector beetles (European Council 2012).</p> <p>In warm areas where PWD is likely to develop, surveys should focus on the pine species which are most likely to show symptoms and the time of year when symptoms are likely to develop (EPPO 2018). It is important to note that infected pines take 4–6 weeks to develop symptoms (Futai 2013).</p> <p>Samples can then be analyzed for presence of PWN by different methods either from the living tree (Zhao et al. 2009), cut wood discs (Nakabayashi et al. 2018), wood packaging material (Bonifácio et al. 2014), or bark (Cardoso et al., 2012).</p> <p>In colder climates PWD may appear with latency of months to years (Gruffud et al. 2016), which makes those areas particularly problematic for detection (EPPO 2018). PWN can even live in a pine tree for at least 11 years without evoking symptoms (Bergdahl and Halik 2004). In conditions that do not lead to symptoms expression, sampling of vector beetles and inspection of trees and wood debris showing signs of <i>Monochamus</i> activity should be performed (EPPO 2018). Wood samples are mostly taken at areas close to ports and industrial sites, to ensure the highest probability to find the nematode (Jordbruksverket 2012; Hannunen and Tuomola 2020).</p> <p>Expenditure on detection</p> <p>In Europe 16'000-21'000 samples were taken annually during 2014-2016 (European Commission 2018). Costs in Finland were 100'000 EUR/year for ca. 400 samples/year (Hannunen and Tuomola 2020). In Norway ca. 420 samples are taken annually, representing 0.02% of the estimated number of suitable objects with <i>Monochamus</i> marks in the total sampling area of the detection survey (Bergseng et al. 2012; Okland et al. 2010). In Sweden 3,146 samples were taken between 2000–2007 (Jordbruksverket 2008). In France initially around 400 samples were taken, those numbers were increased to 800 in the last ten years, complemented by samples from wood trade and <i>Monochamus</i> beetles trapped with pheromone traps (Mariette et</p>

	<p>al. 2023). In Austria 168 samples were taken in 2021 (Hinterstoisser and Brandstetter 2023). In Portugal, more than 10 000 samples are collected each year for the detection of PWN and 2000 traps are installed for the capture of <i>Monochamus</i>, representing a 1'150'000 EUR/year cost. Collection of samples is followed by diagnostic. Conventionally, this is done by Baermann funnel extraction method and observation of morphological nematode characters (Lee et al. 2021). Many other diagnostic methods have been developed, some of them could be used for onsite detection (reviewed in Lee et al. 2021). For example, RT-PCR and conventional PCR are used for diagnostics in France (Mariette et al. 2023). More recently, detection of infested trees using hyperspectral imaging has been developed, utilizing the fact that damage symptoms usually become visible at the tree crown first (Iordache et al. 2020, Yu et al. 2021), however this method is not widely implemented yet, although encouraged in EPPO standard PM9/1 (6) (EPPO 2018).</p> <p>Sensitivity Hannunen and Tuomola (2020) calculated for the Finnish scenario the test sensitivity at below 0.15 in 18 out of 19 years with a corresponding probability of 97.5. Okland et al. (2010) estimate an average 14.3 years until detection in Norway. With 60'000 samples per year, the probability of detecting the infestation within the first year is 0.17 and within the fourth year about 0.8. Baker et al. (2019) estimate an average 120 month until detection in Europe by expert elicitation (Q1: 84, Q2: 120, Q3: 170) with no distinction between the symptomatic and asymptomatic zones.</p>
<p>5. Establishment and spread (dispersal)</p> <ul style="list-style-type: none"> • Suitable areas for establishment* <ul style="list-style-type: none"> ○ SDM models ○ Host distribution • Probability of established colony growth <ul style="list-style-type: none"> ○ Host plant density ○ Radial increase velocity (new propagules) <ul style="list-style-type: none"> ▪ Intrinsic growth rate ▪ Diffusion constant (km²/unit time) 	<p>See above for SDM models, host distribution and host plant density.</p> <p>Tree-infestation and spread occur via multiple ways:</p> <p>a) Infestation via pathogenic life cycle When beetles feed (largely maturation feeding within the first 15 days after emergence but also later) on healthy, susceptible trees nematodes may enter the tree via feeding scars. Few (10s to low hundreds) specimens transmitted to a host tree are sufficient to enable a PWN population to establish in that tree. (Evans et al. 2009). They spread rapidly (150 cm/d) and multiply within the tree. The time to double for a PWN population (under lab conditions) independent of origin or diet, was 13–17 d at 20 °C and 6–7d at 25–31 °C (Pimentel et al. 2018). Likewise, a generation times of 12d at 15°C, 6d at 20°C and 3d at 30°C, with a temperature threshold for development: 9.5°C or 10°C was found (Evans et al. 1996/2009; Futai 1980). Wang et al. (2005) calculated a rate of population increase of 0.83, 0.65, 0.34, 0.42 for different strains, with virulent strains increasing faster than avirulent ones. Similarly, Pimentel et al. (2022)</p>

<p>○ Allee severity effect</p>	<p>found population doubling times mostly between 4.6 and 13.9, again linked to virulence. Trees then die more or less rapidly from the infestation. As dying trees may harbor millions of nematodes and are attractive to <i>Monochamus</i> females for oviposition, they provide a source of infestation in the next beetle generation that emerges from those trees (Baker et al. 2019).</p> <p>b) Infestation via saprophytic life cycle Where PWN does not lead to PWD, dead wood can become infested by oviposition of <i>Monochamus</i>. Spread can occur within the <i>Monochamus</i> population and to further dead wood objects. <i>Monochamus</i> can also infest living trees via maturation feeding but further spread from those trees is not expected (Bergseng et al. 2012).</p> <p>c) Spread via movement of vectors (local) <i>Monochamus</i> beetles are generally poor fliers (Akbulut and Stamps 2012). The larger proportion of beetles remains within short distance, however, when no suitable breeding sites are available, beetles fly longer distances (Okland et al. 2010). David et al. (2014) found a mean distance of 16 km flown over the lifetime (ca. 100 d) of <i>M. galloprovincialis</i> with a maximum flight distance of 62.7 km in flight mill experiments (more details are given in Table 1 of the publication). In mark and recapture experiments lifetime adult dispersal was 107–122 m on average, maximum 464 m (95% confidence limits: 121–2365 m); the population density in this study was 96 to 474 adults ha⁻¹ (Torres-Vila et al. 2015). Slightly larger ranges were found for the Asian <i>M. alternatus</i> (Kobayashi et al. 1984). Fitted dispersal kernels under a continuous forest cover locate the median of dispersers at 233–532 m, while 99% of the dispersing <i>M. galloprovincialis</i> would not disperse further than 2344–3496 m; distance records were 5 km (Etxebeste et al. 2016). In fragmented landscapes distance records were 8.3 and 13.6 km (Gallego et al. 2012; Mas et al. 2013). In a model combining flight mill with mark and recapture data, the lifetime flight distance was 63 km on average and the mean dispersal distance was of ca. 13 km. At the end of the maturation period, when most nematodes have been already transmitted to host pines via shoot feeding, about 80% of the insects were located at more than 500 m from the emergence point (Robinet et al. 2019).</p> <p>Nematode load of <i>M. galloprovincialis</i> averaged 2000-2300 (Naves et al. 2006). <i>Monochamus</i> may have a semi-, uni- or bivoltine life cycle in Europe (Firmino et al. 2017). <i>M. galloprovincialis</i> in Portugal flies from May through October,</p>
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but phoresy by *B. xylophilus* only occurs within a short period in early summer. Nematodes within their hosts show a gregarious frequency (Firmino et al. 2017). About 75% of beetles emerging from an infested tree are infested by nematodes (Okland et al. 2010). Infestation rates per beetle via maturation feed lie between 0.25 and 2 (Bergseng et al. 2012). Females lay eggs within the range of 37–87 during their lifespan (Hellrigl 1971; Naves et al. 2006). Within-log generation survivorship of *M. galloprovincialis* was 53% (Linit 1989, 1990). Net reproductive rate for *M. alternatus* was 8.76–10.7 (Robinet et al. 2009; Togashi and Shigesada 2006)

In Japan the nematode spreads at a mean expansion rate of 6 km/year exclusively with the aid of beetle (*M. alternatus*) flight (Togashi and Shigesada 2006). Another Japanese study found a 4.2 km per year range expansion of the invasion front (Takasu 2000). According to frequencies of pairwise distance, the most likely distance of the highest infestation probability after one year in Korea is around 1.2 km from the disease source. When simulating spread, asymptomatic carrier trees played an important role in disease occurrence (van Nguyen et al. 2017). There was an almost exponential increase in the cumulative areas of PWD-damaged forests from 1982 to 2020 in China (Wang et al. 2022). Nematode spread by the beetle in China was estimated 7.5 km/ year (Robinet et al. 2009).

The number of carried nematodes and reproductive potential of the Portuguese population of *M. galloprovincialis* seems to be reduced compared with the American *M. carolinensis* and Asian *M. alternatus* and consequently the rate of spread of PWD might be slightly lower (Akbulut and Stamps 2012). A model predicts gradual spread of PWN with an average rate of 0.83% of the total current Iberian pine forest area infected yearly corresponding to 43,763 ha per year in the period 2020–2050; susceptibility of different pine tree species to the PWN was a strong determinant of PWN expansion (De la Fuente and Saura 2021).

Baker et al. (2019) estimate an average 5 km/year spread rate of PWN in Europe by expert elicitation (Q1: 2 km, Q2: 5 km, Q3: 7 km).

d) Human-assisted spread (regional)

Long-distance transportation of infested pine logs is likely the primary cause for the regional spread of the pinewood nematode (Togashi and Shigesada 2006). Infested sites located further away than the estimated spread by beetle movement represented more than 90% of observations in a study in China and the mean long-distance spread was 111–339 km. Railways, river ports, and lakes had significant effects on the spread

	<p>pattern. Human population density levels explained 87% of the variation in the invasion probability (Robinet et al. 2009).</p> <p>Allee effect Beetles have to interact with pine trees twice, once for maturation feeding and once for oviposition. Below a minimum pine density and/or a minimum beetle density the disease fails to invade. The incubation period after which a tree contacted by a first beetle becomes ready for beetle oviposition by later beetles is crucial for the emergence of this Allee effect (Takasu 2009). Also, the expansion rate decreases to zero due to the Allee effect when a large proportion of beetles are engaged in long-distance dispersal (Togashi and Shigesada 2006). Yoshimura et al. (1999), Gordillo and Kim (2012) and Osada et al. (2018) give detailed mathematical relationships for beetle and pine density and eradication rate on the development of population growth due to the Allee effect.</p>
<p>6. Market data</p> <ul style="list-style-type: none"> • Domestically produced quantities • Domestically consumed • Traded 	<p><i>To be filled by the economists</i></p>
<p>7. Direct damages and their costs**</p> <ul style="list-style-type: none"> • Crop production (physical production/ value of production) • Crop loss per unit area/pest density (no-control, control scenario) • Higher labor costs for sorting etc. • Temperature thresholds for damage expression/seasonal effects etc. • Other factors on damage severity 	<p>Crop production Eurostat (2011) gives data for forestry, standing stocks, products and trade according to country, but not separated by tree species. The EFISCEN Inventory database: https://efi.int/knowledge/models/efiscen/inventory gives national forest inventories of 32 European countries according to region, owner class, structure, site class and tree species. (The level of detail between different countries may vary). Portugal, where PWD is already present, depends heavily on pine tree production (12% of its industrial GDP and 3.2% of the GDP, 10% of foreign trade, 5% of national employment (Gordillo and Kim 2012).</p> <p>Crop loss Direct damage only occurs under suitable climates (see above), thus substantial direct crop losses are expected in Portugal, Spain, Southern France and Northwest Italy (Soliman et al. 2012) and on susceptible tree species (see above), either native or introduced for forestry industry. Further, pine mortality is spatially aggregated; warm, dry locations with higher evapotranspiration present high values, while in areas of extensive pine occupancy in a diverse landscape mortality decreases (Calvao et al. 2019). Forest habitat and beetle pressure in the surrounding landscape are good predictors of</p>

pine mortality in *P. massoniana* forests in China (Yu et al. 2023).

There is scarce information on **density depended losses**. In 1978 65% of the 56,000 ha of pine forests in Ibaraki prefecture in Japan were affected by PWD, accounting to a timber loss of 742,000 m³ or loss of 10% of the total volume of growing stock within a year (Mamiya 1988). In 1979 25% of the 2.6*10⁶ ha pine forest in Japan were damaged corresponding to 0.65*10⁶ ha or 2.43*10⁶ m³ timber loss or 312*10⁶ m³ timber loss. In 1999, those figures were 28% of the 2.1*10⁶ ha pine forest in Japan were damaged corresponding to 0.58*10⁶ ha or 0.72*10⁶ m³ timber loss or 356*10⁶ m³ timber loss (Mamiya 2004).

Losses are rather given as **annual losses in m³ or trees**.

In Japan, the annual loss of pines caused by pine wilt reached a maximum value of 2,430,000 m³ in 1979 (Mamiya 1988), and then decreased to 663,500 to 835,200 m³ in the period 2000–2005 (Togashi and Shigesada 2006). Annual loss of pine coverage has been 500'000 m³ annually from 2004-2014 (Kim et al. 2020; *actually, the number in the text is 50 mio., but the figure shows only 600'000, which seems more realistic considering two previous references*).

In Korea, the number of pine trees felled by PWD increased from 500'000 to 1.74 million between 2010 and 2015 and then decreased sharply to 500'000 and less in 2016-2019 (Kim et al. 2020).

In the initial infestation area within a 400ha forest in Portugal in the first year 4'226 dead pines were felled. Following careful management, the yearly number of dead maritime pine trees decreased by two-thirds in the second year (1'364), and again by half in the third year (644), representing a mean of less than two dead pines per hectare. Today annual mortality is below 500 pines, not all of it is related to PWD (Sousa et al. 2011).

Soliman et al. (2012) model the cumulative value of lost forestry stock without regular control measures in the 2008-2030 period to 22 billion Euro, representing 3.2-4% of the total value of susceptible trees in the EU. Annual cost is expected to stabilize at 300-800 million Euros after 2016. Trees were assigned percent mortality rates between 40 and 100% according to their age and susceptibility for PWD. Out of 24'594 million m³ forest trees in Europe, susceptible trees available for wood production represented 13'665 million m³ in the model. PWD is expressed in 696'764 out of 3'856'062 km² cells. Detailed data for the affected countries are given. Including price changes the estimated reduction in social welfare in 2030 is estimated at 218 million Euro.

Baker et al. (2019) estimate by expert elicitation an average 25% yield loss on *Pinus* plantations in the rapid wilt expression

	<p>zone of Europe (Q1: 17%, Q2: 25%, Q3: 35%) and 1.7% in the northern zone (Q1: 0.9%, Q2: 1.7%, Q3: 2.5%).</p> <p>While Evans et al. (2009) and Baker et al. (2019) consider direct loss from premature harvest (i.e. reduction in potential volume but trees retain value), Soliman et al. (2012) consider infested trees as worthless. Indeed, presence of PWN symptoms translated into a decrease in wood quality such as the 4–13% decrease in the main mechanical parameters, yet presence of the PWN did not change the technological classification of the wood (Rodrigues et al. 2010).</p> <p>Likewise PWN-infected <i>P. pinaster</i> wood is considered suitable for use as a raw material for wood-processing and energy industries and, particularly, for pellet production (Reva et al. 2012).</p> <p>When contingency measures apply, additional labor costs arise from the destruction of high-risk materials, such as wood and branches with a diameter below 20 cm that must be locally destroyed or removed from the stand (by shredding to wood sections with less than 3 cm, as this is the minimum size to low survival of <i>M. galloprovincialis</i> (Sousa et al. 2011).</p>
<p>8. Indirect damages and their costs</p> <ul style="list-style-type: none"> • Vectoring diseases • Effects on beneficials • Export restrictions and lower export prices 	<p>The presence of PWN, irrespective of symptoms can have important impacts on international trade (Evans et al. 2009). Countries with no PWN occurrence can impose temporary or permanent import bans (Dwinell 1997). Heat treatment or fumigation of wood packaging is already international standard (IPPC 2019). Heat treatment or fumigation of other wood-based products is often required such as in the EU (EU 2019).</p> <p>In countries where export of wood-based products that are not heat-treated, such as fuelwood and roundwood, is modest, national markets may be found and thus economic impacts are limited (Bergseng et al. 2012).</p> <p>Further costs may arise from possible changes of tree species to be grown and other costs (Evans et al. 2009).</p>
<p>9. Control costs of invaded areas</p> <ul style="list-style-type: none"> • Cost of detection in invaded unit of area • Unit of area where pest detected (can this be used to infer pest density?) • Cost of control measures in area <ul style="list-style-type: none"> ○ Increased pesticide/netting etc. costs ○ Higher labor costs to monitor and treat 	<p>Detection and monitoring</p> <p>Detection and monitoring is done by i) visual inspection of trees, ii) sampling of dead wood and iii) analyzing trapped <i>Monochamus</i> beetles (IPPC 2016). For i-ii see 4.</p> <p>Monitoring:</p> <p>The male produced aggregation pheromone 2-(undecyloxy)-ethanol (monochamol) from several <i>Monochamus</i> species (incl. <i>M. galloprovincialis</i> and <i>M. sutor</i>) can be used for beetle monitoring (Pajares et al. 2010). The pheromone should be complemented by bark beetle kairomones ipsenol and methylbutenol (Schenk et al. 2019; Alvarez et al. 2016). Further inclusion of α-pinene may enhance trap capture to some extent, but it also increases capture of non-target species, including natural enemies and thus should only be considered when</p>

maximizing the removal of vectors is considered a priority (i.e. PWD foci under eradication) (Alvarez et al. 2016).

The pheromone-kairomone blend is presented in Teflon coated cross-vane or multi-funnel traps (Schenk et al. 2019). The effective sampling area using a funnel-trap with the commercial lure is estimated 0.57-0.76 ha corresponding to a seasonal sampling range of 426-645m (Etxebeste et al. 2016). Nunes et al. (2021) estimate that with 9 traps spread over 180 ha, (=1/20 ha) it would be possible to locate the source of an outbreak with an accuracy of 86m, i.e. to restrict the search area for infected trees to an area of about 2.5 ha.

Traps should be monitored every 1-3 weeks (depending on collection method) and the persistence of the volatile blend is 40-45 d (Schenk et al. 2019; SEDQ 2020). Daily release rates are given in Boone et al. (2015). Timing of trapping activity should match flight season of *Monochamus* (Schenk et al. 2019). Trapped beetles are subsequently tested for nematode presence (see above), which can be time-consuming and/or costly as well (funnel extraction, morphological identification, PCR). Only mature insects (10–14 days of shoot feeding after emergence) can be lured into the traps (Alvarez et al. 2016).

Commercial suppliers for the lure (with and without a-pinene) can be found online but no prices are indicated:

<https://sedq.es/en/producto/galloprotect-pack/>

<https://solida.quebec/produit/monochamol-ipfenol-pouch-product-no-40sy3409/?lang=en>

Another pheromone product is sold for around 20 EUR, but it is not clear what it contains and it has been deemed less efficient than the one mentioned above (Foit et al 2019):

<https://www.witasek.com/pheromone-fallen/pheromone-lockstoffe/138/gallopro-pinowit-baeckerbock-zwoelfzaehniger/europaeischer-kiefernborckenkaefer-rothaariger-kiefernba>

<https://www.witasek.com/pheromone-fallen/pheromone-lockstoffe/138/gallopro-pinowit-baeckerbock-zwoelfzaehniger/europaeischer-kiefernborckenkaefer-rothaariger-kiefernba>

Multi-funnel traps can be purchased for 20 Euro- 85 USD

<https://www.witasek.com/shop/en/pheromone-traps-attractants/beetle-traps/423/witatrapp-multi-funnel-trap>

<https://www.forestrydistributing.com/lindgren-funnel-insect-traps-synergy-semiochemicals>

Cross-vane traps for around 30 Euro

<https://www.witasek.com/shop/en/pheromone-traps-attractants/beetle-traps/425/witaprall-cross-vane-panel-trap>

<https://www.forestrydistributing.com/cross-vane-panel-insect-trap>

Cost of control measures

Prevention

EU and IPPC mandate the treatment of traded coniferous wood, wood products and packaging. Treatment is either done by heat or by fumigation with methyl bromide (widely banned) or sulphuryl fluoride (Arcos et al. 2015). Detailed protocols regarding dosages and durations are given in ISPM 15 (IPPC 2019), treatment costs for

a palette after ISPM15 are estimated as 1.5 USD (Strutt et al. 2013). Wider economic implications of the standard are discussed in Strutt et al. (2013).

Debarking of stored logs is a further means to reduce risk of *Monochamus* and PWN infection (Dwinell 1997).

Further, EU regulations require an eradication zone of 500 m around any infected tree, which means to fell, remove and dispose of all susceptible plants within (Robinet et al. 2020). The effectiveness of this measure is questioned due to the much larger dispersal ranges of the vectors (Robinet et al. 2020). The mobilization of the necessary workforce, in particular machinery for forest operations, to conduct the extraordinary harvest, is costly and may pose a logistical challenge (Bergseng et al. 2012). These authors estimate the cost of eradication measures, which require a 3km eradication zone and a 17km observation zone in Norway, and costs from reduced income due to loss in timber production projected for the next 50 years to be 0.2-0.25 billion Euro (depending on the discount rate). Further costs will arise from reduced recreation and biodiversity (Bergseng et al. 2012).

Chemical control

In Japan in 1986 annual budget of PWN control was 50 million USD: 55% aerial spraying, 8% ground spraying, rest: residue removal or salvage of dead trees (Mamiya 2004).

However, aerial spraying is banned in the EU (Zweetsloot et al. 2018) and was never a viable option in Portugal, because pine forests are close to human settlements and protected natural areas (Sousa et al. 2011). Likewise, Baker et al. (2019) do not expect a rise in pesticide use due to introduction and spread of PWN as no effective treatments with plant protection products (PPPs) are currently available to control this pathogen.

Current control measures in the EU require the delimitation of eradication and buffer zones, eradication measures and contingency measures if eradication fails (European council 2012).

In Portugal, the most important control strategy is elimination of symptomatic trees in late autumn, winter and early spring, while the insect vector is found inside the tree. Trees with decline and wilt symptoms are visually identified and marked, felled and removed from the stand. Usually neglected material must be thoroughly collected and shredded to wood sections smaller than 3cm (minimum size for survival of *M. galloprovincialis*) or transported for processing into materials such as pellets, which creates additional costs (Sousa et al. 2011). In addition, *Monochamus* populations can be reduced by placement of traps from late spring to early autumn (Sousa et al. 2011).

	Other methods may be used in the future to control established populations, such as prescribed burning (Chen et al. 2020), biocontrol (Pires et al. 2022), the planting of resistant pine species (Dwinell 1997), induction of pine resistance (Jeon et al. 2022; Kim et al. 2019) or selection for PWN tolerance (Menéndez-Gutiérrez et al. 2018). Various studies address mathematical scenarios of near optimal control (e.g. Xu et al. 2023).
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*Some of the modelling papers have this information. Including CLIMEX paper

** See Carrasco et al. (2012) WCR paper for equations for cost taking into account damages based on pest density.

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