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Developing a European Toolbox to manage potential invasion by emerald ash borer (*Agrilus planipennis*) and bronze birch borer (*Agrilus anxius*), important pests of ash and birch

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The threats posed by the buprestid beetles emerald ash borer (*Agrilus planipennis* Fairmaire) and bronze birch borer (*Agrilus anxius* Gory) have been the subject of considerable research, primarily to develop methods for detection and management of the pests. PREPSYS, a Euphresco project, has worked with collaborators globally to assess the 'state of the art' for the two insect pests and to identify those measures that would best prepare Europe for potential invasion by the pests, especially emerald ash borer which is now in the western part of Russia and in eastern Ukraine. Building on an excellent exchange of knowledge and discussion at the OECD-sponsored international conference held in Vienna in October 2018, the concept of a European Toolbox to increase preparedness for dealing with the pests has been developed. This includes key components including surveillance, direct intervention, use of natural enemies and increased awareness of the problems associated with the pests. Collaboration is essential in delivering and refining the European Toolbox.

Introduction

Among the >3000 species in the genus *Agrilus* (Coleoptera: Buprestidae), several have reached pest status, often linked to the presence of already weakened trees (Evans *et al*., 2004; Kelnarova *et al*., 2019). Whilst representatives of the genus are global in range, it is the massive damage and tree mortality noted in North America arising from the establishment and spread of the Asian emerald ash borer (EAB), *Agrilus planipennis*, which has prompted concern in those countries where ash is a native or planted tree species. There are also concerns about the closely related bronze birch borer (BBB), *Agrilus anxius* which, although relatively innocuous on native birches in its natural North American range, has been shown to rapidly kill European birch (*Betula pendula*) (Muilenburg and Herms, 2012). Both EAB and BBB have been included in the new Regulation (EU) 2016/2031 of the European Parliament and of the Council establishing a list of priority pests which will be implemented in December 2019 (https://ec.europa.eu/info/law/better-regulation/initiatives/ares-2019-3625609_en).

Following its discovery in Michigan, USA, in 2002, EAB has spread over virtually the entire natural range of ash in North America and continues to spread, assisted considerably by human transportation of infested material (Herms and McCullough, 2014; McCullough, 2020). One of the defining characteristics of the North American invasion by this species of beetle is a lag period of several years before it was recognised as a damaging invasive pest (Siegert *et al*., 2014). In North America, estimates of its year of establishment suggest that it may have been present for a minimum of 12 years before it was discovered, by which time it had already spread throughout Michigan and into Ontario in Canada (Herms and McCullough, 2014).

In virtually, the same time frame as the invasion of EAB into North America, the beetle crossed the ecological barrier of the Ural Mountains, presumably through human assistance in trade, and established in the Moscow region of Russia (Baranchikov *et al*., 2008). Here, it also went unrecognised until 2002 and had already caused substantial mortality to ash, principally the widely planted exotic North American green ash, *Fraxinus pennsylvanica*. It continues to spread mainly in a westward direction and is now very close to the border of Belarus (Orlova-Bienkowskaja, 2014) and has recently been recorded in Ukraine (Drogvalenko *et al*., 2019; Orlova-Bienkowskaja *et al*., 2019), and confirmed by the Ukraine National Plant Protection Organisation in October 2019 (https://gd.eppo.int/reporting/article-6632). EFSA has also included the two beetle species in its pest prioritisation (https://www.efsa.europa.eu/en/efsajournal/pub/5731).

In both the North American and Russian situations, it is likely that the beetle was introduced through packaging wood or possibly live plants for planting (EPPO, 2013a). Onward spread, particularly in North America, has been principally through human transportation especially of firewood taken to camp grounds by holidaymakers (Daigle *et al*., 2018; Diss-Torrance *et al*., 2018). Analysis of the influence of transportation routes and volumes of suitable host material by Yemshanov *et al*. (2015, 2020) emphasised the key role of human transportation in the ongoing spread and development of new foci of infestation in North America. As indicated by Alexander (2020), the fact that EAB has reached and established in Boulder, Colorado is clear evidence that it can cross areas lacking contiguous presence of host trees.

Arising from the evidence base in North America and Russia, there are, unsurprisingly, real concerns in Europe about the likelihood of invasion by EAB and its potential impacts on the ash resources that are already impacted heavily by the fungus *Hymenoscyphus fraxineus* (Sansford, 2013). Under the Euphresco banner (www.euphresco.net) detailed assessment of the risks to Europe of EAB and the related bronze birch borer (BBB, *A. anxius*) have been carried out by the PREPSYS project (https://www.forestresearch.gov.uk/research/prepsys/). This project aims to gather knowledge on all aspects of the biology, spread, impact, and management of both EAB and BBB. As part of this process, an international conference, part sponsored by the OECD's Co-operative Research Programme on Biological Resource Management for Sustainable Agricultural Systems and by the UK government department DEFRA was held in Vienna in October 2018. Presentations from the conference are available on the BFW website (https://bfw.ac.at/emeraldashborer), and many of the speakers have contributed to this special issue of *Forestry: An International Journal of Forest* Research, which is devoted to emerald ash borer, and other *Agrilus* species.

Learning from experiences in North America and Russia

EAB invasion appears to be characterised by rapid spread and associated massive mortality of susceptible ash species, usually those on which the beetle has not co-evolved. Thus, the list of trees attacked in both North America and Russia is dominated by ash species native to North America and which have been planted as exotics in other countries, including Russia. McCullough (2020) summarised the considerable literature on relative susceptibilities of both North American and European ash species and showed that green ash and black ash (*Fraxinus nigra*) were the most likely to be killed, with greater variability for white ash (*Fraxinus americana*) and relative resistance by blue ash (*Fraxinus quadrangulata*). In preparing Europe for potential invasion by EAB, the experiences in North America and Russia, where some mortality of European ash, *Fraxinus excelsior,* has been observed, indicated that this species is at risk especially if large population increases of the beetle on exotic green ash are located in the same locality (Pureswaran and Poland, 2009; Orlova-Bienkowskaja, 2014).

In addition to the presence of highly susceptible ash species in North America and, as exotic plantings, in the invaded part of Russia, population increases of EAB can also be linked to the absence of the usual spectrum of natural enemies that would normally restrict population growth. In its native range in Asia, EAB is not regarded as a serious pest, partially due to tolerance to attacks by native ash species and partially as a result of activities of a spectrum of natural enemies (Wang *et al*., 2010). Although some activity by generalist natural enemies has been noted in North America, this is generally too late to prevent large increases in EAB populations (Duan *et al*., 2014). Consequently, much effort has been put into exploration for, importation, rearing and release of natural enemies from the native ranges of EAB in Asia (Liu *et al*., 2003).

Pathways for local and long distance dispersal

Data on host ranges suggest that preparation for invasion of Europe by EAB should be based on the assumption that infestation on both native and exotic, principally North American, ash is likely. Since the beetle is spreading west from the Moscow area and is now in Ukraine and close to the border of Belarus, the expectation is that either natural or human-assisted dispersal will result in infestation in Europe in the near future. At a minimum, the westward spread of EAB in Russia is at least 40 km per year (Straw *et al*., 2013; Orlova-Bienkowskaja, 2014), mainly along major transport routes with ash planted alongside. With regard to the main pathways by which EAB could reach Europe from any of its native or invaded ranges, the principal means identified in the EPPO Pest Risk Analysis (EPPO, 2013a) are summarised in Table 1.

Under EU Directive 2000/29/EC, most of the above pathways are highly regulated or not allowed and represent the 'front line' in preventing importation of EAB into the EU. As with all processes to minimise risks of pest movement along pathways, there is high dependence on compliance which is usually assessed by inspections of trade movements and on surveys to ensure absence of the named pests. Thus, in developing a European Toolbox to prepare for invasion by EAB, the first component is preparedness through recognition of and management of key pathways to reduce the likelihood of movement of the pest along those pathways. An important, but difficult, part of managing pathways is enhanced surveillance to determine whether a pest has succeeded in transferring from a pathway end point to host trees in the country of arrival.

Surveillance to assess for possible introduction and establishment of EAB in Europe

Over the years since EAB was first detected in Michigan in 2002, there has been extensive research into the most effective methods to survey for and, where appropriate, quantify attacks by EAB. McCullough (2020) and Yemshanov *et al*. (2020) provide both background to developments in North America and advances in surveillance methodology that provide a strong basis for building a surveillance component for a European Toolbox.

Methods for detection of EAB activity in an area vary with both the purpose of detection (initial detection, rate of spread or quantitative assessment) and with deployment of, usually, limited resources to carry out surveillance. From a European perspective, where the initial position is that the pest is not known to be present, emphasis is on early detection of an inevitably small pioneer population of the pest. Much can, therefore, be learned from experiences in North America.

Table 1 Principal pathways for movement of EAB (EPPO, 2013a).

1. Wood with or without bark of recorded hosts of EAB (*Fraxinus* spp., *Juglans mandshurica*, *Juglans ailanthifolia*, *Pterocarya rhoifolia*, *Ulmus davidiana*) from where the pest occurs. The main traded commodities for this category are round wood, wood with bark (including debarked wood), bark-free wood, and firewood. Analysis of these pathway commodities by EPPO indicated that there is some trade of sawn wood from North America and Russia and of firewood from Russia to Europe.
2. Plants for planting of recorded hosts of EAB originating from where the pest occurs. EPPO notes minor volumes of trade of *Fraxinus* plants for planting from Canada, USA, and China although data were not comprehensive.
3. Waste wood originating from where the pest occurs. There is trade in waste wood from Russia to some European countries (notably Finland, and at lower volumes Denmark and Germany). However, the trade does not usually differentiate softwood from hardwood and thus it is not possible to determine the proportion that could be ash. If ash is present, it would represent a high risk pathway.
4. Hardwood wood chips originating from where the pest occurs. There is trade in hardwood chips from some countries where the pest occurs. Turkey is a major importer of wood chips from both Canada and USA. Finland is a major importer of hardwood chips from Russia. Processing to create wood chips will tend to kill most life stages present but not to negligible levels (McCullough *et al*., 2007).
5. Wood packaging material (including dunnage) containing known hosts of EAB. There are no precise data on the composition of wood packaging material but if ISPM15 compliance is high, this should be a low risk pathway (IPPC, 2019). However, non-compliance would increase the risk significantly.
6. Bark and objects made of bark of known hosts of EAB. Volumes moving on this EU-regulated pathway are unknown and it is lower risk than attached bark.
7. Furniture and other objects made of untreated wood of known hosts of EAB originating from where the pest occurs. Since furniture has visual and functional value, this is likely to be a low risk pathway unless it is 'rustic' furniture where bark is a feature or wood is covered by other materials. There are no data on movements along this pathway.
8. Natural spread. Evidence for movement along main rail and road routes from Russia westwards indicates that spread of up to 40 km per year takes place (Orlova-Bienkowskaja and Bienkowski, 2018; Straw *et al*., 2013), although this is likely to be partially due to the hitchhiking pathway (see below). Observations in North America suggest that when infestations grow, the rate of spread also grows, reaching an average of >40 km per year (Siegert *et al*., 2014).
9. Cut branches of known hosts of EAB originating from where the pest occurs. There is no evidence of trade and this pathway is intrinsically likely to present low risk.
10. Hitchhiking. In both North America (Buck and Marshall, 2008) and Russia (Straw *et al*., 2013), movement by hitchhiking of adult EAB on vehicles has been cited as a pathway. This is closely linked to natural movement and is likely to be significant for local dispersal and initial establishment of new foci of infestation along transport routes.

One of the attributes of EAB that is exploited in developing monitoring systems is the propensity of adult beetles to be attracted to stressed trees (Herms and McCullough, 2014). Of particular interest in developing surveillance for early detection is the finding that stressed trees are colonised preferentially at very low beetle densities. For example, at both very low and at high densities of EAB in an area, *F. pennsylvanica* trees stressed by girdling (removing the bark from a band around the trunk) captured significantly more adult beetles than healthy trees or those exposed to the stressor methyl jasmonate (Tluczek *et al*., 2011). Mercader *et al.* (2013) extended this finding by comparing girdled ash trees and Manuka oil-baited purple three-sided sticky traps. They showed that captures on girdled trees were significantly more effective at detecting very low (<5 larvae per tree) EAB densities than deployment of baited traps. There is a trade-off between the effort needed to girdle a tree compared with deploying a trap in the tree canopy, but the authors showed that this is outweighed by the much higher detection capacity when EAB densities are low. This would be the expected situation in Europe where initial invasion is likely to be characterised by low attack rates per tree. Girdling appears to be most effective in trees greater than 10 cm DBH which Mercader *et al.* (2013) pointed out could, through resource constraints, be a factor limiting the number of trees than can be utilised for monitoring in a given area. One potential method, that could be particularly beneficial in Europe, would be to use girdled potted ash trees as sentinel monitoring systems, a method that was used with some success in Maryland during the initial invasion by EAB (Sargent *et al*., 2010). Such a sentinel tree approach could also utilise the availability of trees in arboreta and botanic gardens ideally under the auspices of the International Plant Sentinel Network (Barham *et al*., 2016). Recent research by Silk *et al*. (2020) indicates that tree girdling is also an effective strategy for detection of BBB infestations in birch trees.

Alternative, complementary, monitoring systems have also been developed in North America and tend to be more effective once a population has established in an area, when it is important to determine both the density and geographical extent of the infestation. Early work on both the design and colour of traps indicated that green or purple traps are effective in attracting adult beetles, in both cases baited with volatile chemicals attractive to EAB, including Manuka or Phoebe oils or, particularly, (3Z)-hexenol (DeGroot *et al*., 2008, Crook and Mastro, 2010). Combining the EAB pheromone (3Z)-lactone and the host volatile (3Z)-hexenol increases trap catches and detection rates initially reported by Silk *et al*. (2011) and further developed by Ryall *et al*. (2012, 2013). Deployment of baited traps is a relatively low-cost process but requires regular checking and is generally non-quantitative and may result in substantial by-catch of non-target organisms (Skvarla and Holland, 2011). Francese *et al.* (2013)

carried out detailed studies of different trap designs, both for shape and for colour, and concluded that green multi-funnel traps with Teflon coating were the most effective for EAB. Green and purple sticky traps are also widely used.

When more quantitative data on EAB attack rates are required, the branch sampling procedure developed by Ryall (2015) has proved effective in North America. This method involves removal of two branches per tree followed by peeling of the basal 50 cm to reveal any life stages of the beetle. It has a known detection rate (74 per cent) for low-density asymptomatic infestations but is time-consuming and has not been verified for larger diameter (>40 cm) trees. It is included in the EFSA Survey Guidelines for EAB outlined by Schrader (2020) and which will be formally published in 2019.

A novel approach to detection in both woodland situations and where wood is being imported or stored is the use of sniffer dogs trained to detect either EAB or BBB. In North America, the Emerald Ash Borer Detection Feasibility Study (https://wd4c.org/emeraldashborer.html) in Minnesota demonstrated that WD4C dogs were able to distinguish ash from other tree species and, within ash samples, to detect those that were infested by EAB. Feasibility studies are also being carried out in Austria by Hoyer-Tomiczek (https://bfw.ac.at/rz/bfwcms.web?dok=10131) building on success in detection of Asian longhorn beetle (Hoyer-Tomiczek *et al*., 2016), with initial promising results in detecting EAB larvae and frass (Hoyer-Tomiczek and Hoch, 2020).

There is, therefore, a range of techniques available for both early detection and more quantitative detection of increasing populations of EAB to be included in the European Toolbox. However, where to deploy these resources when no initial detections of EAB have been made remains a difficulty since either a grid-based or a random sampling placement implies very large effort to have a high probability of detecting low density initial incursions of the pest (Venette *et al*., 2002; Coulston *et al*., 2008). Thus, development of an optimal surveillance approach for Europe is required so that scarce resources can be deployed at locations where there is the highest likelihood of the pest arriving and potentially establishing. Apart from improvements in technology and placement of resources, there is an urgent need to raise awareness of the risks posed particularly by EAB but also to BBB (Marzano *et al*., 2016).

Optimal surveillance; where to deploy monitoring systems to detect an invasion front

The importance of recognising and evaluating pathways for movement of EAB from source to sink has already been emphasised. Whilst examination of entities moving along pathways offers one method of assessing potential incursions of EAB, this is severely constrained by high volumes of movement of goods on many of the recognised pathways, combined with low inspection rates. Development of an optimal surveillance approach requires a more structured assessment of the components of pathway movements, taking account of where they originate, the nature of the products moving, and particularly, where the pathway end points (both spatially and temporally) lie in relation to proximity to suitable host trees for EAB. Yemshanov *et al*. (2015) developed models for EAB in North America that assessed movements along known pathways (particularly firewood movement to campsites) and distinguished between propagule pressure (PP) and maximum expected coverage problem (MECP). PP is a probabilistic measure of the expected number of pest adults arriving at a previously uninvaded location from an infested source area. MECP maximizes the expected number of pathway origins included in the whole survey system and is included if at least one of the pathways ends in a surveyed destination. In their analysis, Yemshanov *et al*. (2015) looked at a wide range of model scenarios and demonstrated that PP models were more applicable when knowledge of pathways and of population distributions is poor. For potential invasion of new areas along trade pathways (i.e. the situation in Europe), the MECP model approach can be used to allocate surveillance linked to particular tracked pathways (e.g. through customs declarations) and their end points. It can account for variation in survival of the pest along the pathways from different sources, particularly if resource limitations mean that only a small proportion of initially invaded sites can be surveyed. More recently, this approach has been extended and applied to EAB invasion of Winnipeg in Canada where there is spread from known areas, combining human-assisted and natural spread (Yemshanov *et al*., 2020). In this modelling approach, minimising worst-case damage from failed detection can be achieved by surveying more sites with suitable host trees at farther distances from the known infested area. This would minimise the risk of significant damage if the pest was not detected quickly in an area with large availability of host trees.

From a European perspective, the MECP approach offers an opportunity to assess the scale of movements along the identified pathways, accounting for where the pathways originate in relation to known ranges of EAB. This will require detailed analysis of pathway dynamics and modelling the arrival points relative to the proximity of host trees. Hence, using an optimal surveillance approach should be a key component of a European Toolbox for EAB, which would enable advice to be provided to regional plant protection agencies to allocate survey effort in a more targeted manner.

Management of EAB populations in a European context

Awareness of the risks posed by EAB and BBB to European ash and birch woodlands requires a European-wide approach that extends beyond the EU member states. Petter (2020) described the approach of EPPO (European and Mediterranean Plant Protection Organisation) in preparing for potential invasion by EAB and BBB. Since EPPO covers a much larger area than the EU, it is well placed to develop methodology and provide guidance on all aspects of prevention, surveillance, and management of a wide range of pests, including EAB. For EAB in particular, EPPO has provided procedures for official control of EAB once initial infestations have been found (EPPO, 2013b).

Since survey resources are inevitably limited, a risk and statistics-based surveillance approach is essential to maximise the likelihood of early detection and also to provide confidence that infestations are not being missed. EFSA is preparing survey guidelines for risk-based surveillance of EAB, including open access to the statistical tools RiBESS+ (https://shiny-efsa.openanalytics.eu/app/ribess) and SAMPELATOR (https://shiny-efsa.openanalytics.eu/app/sampelator), which can be used for survey design.

If early detection of EAB establishment is achieved, the scale of the infestation must be assessed urgently. Application of the most sensitive survey techniques would be required initially to assess presence, with the aim of high certainty that false negatives are not being included in the initial infested area and to begin quantification of the scale of attacks at the tree level. Taking account of the known relatively low rate of natural spread by EAB, detailed tree by tree inspection during sanitation felling to approximately 1 km radius from known infested trees is the recommended approach for Europe (EPPO, 2013b). Any new infestations found during the delimiting survey will extend the survey area and associated felling by a further 1 km radius. These measures are accompanied by the setting up of a regulated area at least 20 km wide to include surveys and prohibition of movement of host material. If these measures fail to eradicate the pest then the regulated area is extended to at least 100 km in which suppression and prohibition of movement are applied to contain the pest and prevent further spread. Experiences in both Canada and the USA indicate that it is difficult to contain EAB through quarantine, despite very high investment in outreach and publicity to raise awareness of the pest (Diss-Torrance *et al*., 2018). Surveys are also difficult to coordinate in urban areas where identification of ownership, access to sites, and determination of who is responsible for both the survey and any consequent management action can be impediments to concerted action.

In the expectation that eradication is unlikely, bearing in mind the long period between establishment and detection experienced in North America and Russia, measures to reduce population growth and contain the pest are likely to be given priority in Europe. The Toolbox will, therefore, require a range of approaches that will be employed collectively to contain the pest to the minimum possible area with minimum possible damage to host trees.

Sanitation felling

Conceptually, the EPPO and EFSA strategies for initial survey and management of EAB are similar and require surveillance to be concentrated on high risk sites with a maximum expected local spread of up to 1.5 km. EPPO guidance for management includes sanitation felling of all host trees within a radius or band of 1 km around known infested trees. This requires resources to survey the affected area, including inventory of potential host trees and assessment of whether trees being felled are already infested by EAB. Difficulties arise when the attacks are in heavily populated urban locations, which is the case in most of the infested areas of North America. Here, the aim of the felling is only partially to reduce EAB activity and more to reduce risks to people from dead standing trees that could shed branches or fall entirely. With many cities having large inventories of trees, often dominated by ash, resources must be made available or diverted to ensure a balance between survey, reporting (in part through awareness campaigns), and action to manage both infested and non-infested trees (Alexander *et al*., 2020).

Regardless of whether the identified infested trees are in urban or rural locations, felling has to be accompanied by destruction of any life stages that may be present in the trees. In general, this is achieved through chipping or burning any of the trees that might have live beetle stages present (generally the cambium and outer wood). Ownership and responsibility for action can make it difficult to coordinate felling programmes, particularly since speed is essential in order to prevent beetle emergence and further infestations. In some cases in North America, some of the felled trees are converted to products, thus providing some recompense to partially offset the costs of felling (Alexander *et al*., 2020).

Insecticide treatment

In the years since EAB was first detected in Michigan, there has been substantial effort to identify the most effective direct intervention strategies to augment sanitation felling (Herms and McCullough, 2014). In the USA, from the range of insecticides tested, it would appear that trunk injection using emamectin benzoate is an efficient and cost-effective option to reduce the rate of tree mortality, although it has relatively little influence on total EAB population size (McCullough *et al*., 2018). Azadirachtin has been the insecticide of choice in Canada but emamectin benzoate has recently been registered there to increase the options. Apart from the 2–3 years of protection for the individual treated tree, recent research has indicated that protection of a cohort of trees in a local area can be achieved by treating only a proportion (as low as 1 per cent) of trees systematically across the area (Mercader *et al*., 2015, 2016; McCullough *et al*., 2018). This area-wise approach offers potential for minimising direct intervention and also appears to enhance the activities of natural enemies, particularly woodpecker predation (McCullough *et al*., 2018).

There are, of course, potential negative aspects in deployment of a relatively broad-spectrum insecticide such as emamectin benzoate, including the risks of effects on non-target organisms on ash and possible risks to honey bees and from run-off to water courses arising from falling leaves containing the insecticide. Studies of trunk-injected pesticides for EAB and other pests have indicated very limited potential impacts on non-target organisms either directly on the tree (Duan *et al*., 2018) or indirectly through pollen or decomposing leaves (Burkhard *et al*., 2015). General advice on use of insecticides, especially emamectin benzoate applied by trunk injection, is widely available in North America (Hahn *et al*., 2011; Herms *et al*., 2019) and includes assessment of both efficacy and non-target risks.

In a European context, emamectin benzoate is approved for particular uses (various edible food crops) and, currently, would not be formally approved if EAB was discovered in European ash trees. However, experimental use approvals have been employed to test the use of the active ingredient for some forest pests, including oak processionary moth (*Thaumetopoea processionea*) and horse chestnut leafminer (*Cameraria ohridella*) (Burkhard *et al*., 2015). Based on the effective development of this active ingredient for use in integrated pest management strategies in North America, there is considerable value in ensuring that emamectin benzoate is included in the European Toolbox and has approval for use against EAB and BBB.

Biological control

As with many invasive pests, one of the factors that can lead to greater impacts in invaded regions is the absence of the usual spectrum of natural enemies that would tend to keep the pests at balanced low levels in their native ranges (Drake, 2003; Olson and Rieske, 2019). Knowledge of the roles of natural enemies in the native range of EAB has provided a basis to consider classical biological control through introduction and release of several parasitoids from China (Liu *et al*., 2003; Bauer *et al*., 2015). Following assessment of potential impacts on non-target hosts, four species of parasitoid have been licensed for release in the USA and Canada (Bauer *et al*., 2015). Three species are larval parasitoids; *Spathius agrili* and *Tetrastichus planipennisi* (both Hymenoptera: Eulophidae) from China and *Spathius galinae* from Russia. The fourth species is an egg parasitoid; *Oobius agrili* (Hymenoptera: Encyrtidae) from China (Bauer *et al*., 2015). Although there are very encouraging signs that released parasitoids have established and are reducing the scale of infestations, the need to climate-match the species to different areas occupied by EAB has become apparent (Duan *et al*., 2018). Thus, *O. agrili* and *T. planipennisi* have established throughout their release ranges and are spreading naturally, whereas *S. agrili* has established only to the south of the 40th parallel and no further releases are planned north of this latitude. By contrast, early results suggest that *S. galinae* is better adapted to northerly latitudes and has established and is showing promise in the North-eastern United States following releases in 2016 and 2017 (Duan *et al*., 2019). Monitoring suggests successful establishment of *S. galinae* and up to a 20-fold increase in density from 2016 to 2018.

Recent observations of natural enemy impacts on EAB in the European part of Russia have provided evidence that the native European parasitoid *Spathius polonicus* is attacking and having an increasing impact on the pest in the invaded range (Orlova-Bienkowskaja and Belokobylskij, 2014). This finding is encouraging since *S. polonicus* has a relatively wide distribution in Europe having been recorded in Belarus, Czech Republic, Germany, Poland, South European Russia, Spain, Switzerland, The Netherlands, Ukraine, and Yugoslavia (van Achterberg, 2019). As suggested by Orlova-Bienkowskaja (2014), it seems likely that *S. polonicus* has spread eastwards to exploit the increasing host availability presented by EAB in western Russia. The recent report of EAB in Ukraine (Orlova-Bienkowskaja *et al*., 2019; https://gd.eppo.int/reporting/article-6632), where the pest is spreading west provides a further zone of encounter for *S. polonicus*.

In addition to the evidence of classical biological control from rearing and release of exotic natural enemies in North America, impacts of generalist natural enemies on EAB populations have also been recorded. For example, woodpecker activity is prevalent in high infestation areas of EAB attack in North America and evidence of their feeding is a further indicator of pest presence (Koenig and Liebhold, 2017). Generalist natural enemies that switch prey to reflect increases in potential resources can, therefore, add to the total impact on EAB and BBB population dynamics. However, since they are generalists, they are also likely to switch to more abundant resources when EAB/BBB populations decline, which may be of minor significance if the overall populations are below damaging thresholds. Recent studies reported by McCullough (2020) suggest that use of trunk injections of emamectin benzoate have no significant effects on natural enemy populations, thus offering valuable potential for integrated pest management of EAB.

With regard to the European Toolbox for management of EAB, emphasis should be on maximising the potential of the native *S. polonicus*, including consideration of rearing and release to augment natural populations, along with early assessment of importation, rearing, and release of exotic parasitoids from China and the eastern part of Russia. The long lead-in for host-range assessment of exotic natural enemies for potential release in the EU requires investment at an early stage and collaboration with researchers and the authorities in North America to exploit their increasing experience of these potentially valuable control agents.

Awareness campaigns

One of the major planks of management of EAB invasion in North America has been the use of awareness campaigns to provide information on the increasing threat from the pest and to attempt to reduce spread arising from poor biosecurity (Novoa *et al*., 2017). In the early days after discovery of EAB in Michigan in 2002, much effort was put into educating stakeholders about the risks of moving infested material, with particular emphasis on transportation of firewood whilst travelling to campsites (Dis-s-Torrance *et al*., 2018). Studies of camper attitudes to threats from EAB indicated that awareness rose rapidly from 2006 to 2008 then levelled off. The balance between general awareness of EAB (impact and tree loss) changed over time to be more focussed on how moving firewood increased the likelihood of new infestations. An interesting finding was that awareness of the risks of moving firewood during camping trips eventually translated to increased awareness of threats in moving firewood for domestic consumption.

Despite the multitude of awareness campaigns at federal and state levels, spread of EAB across North America continued, culminating in the finding of EAB in Boulder, Colorado, which could only have arisen through human transportation (Alexander *et al*., 2020). In Denver, which has no evidence of EAB attack but is close to Boulder, a massive awareness campaign is ongoing to provide prior information of the threats posed by EAB through a wide range of media, exemplified by the ‘Be a Smart Ash’ campaign (https://beasmartash.org/). An important part of the campaign in Boulder was the initiative shown by the municipal authorities in learning from experiences in cities in the east that had already experienced the issues arising from EAB attack. This translated into contingency planning and high preparedness, which led to early detection of EAB and rapid deployment of survey, selective felling, and use of emamectin benzoate by trunk injections (Alexander *et al*., 2020).

Perceptions of the pest and its management have been assessed in relation to European preparedness for the pest (Marzano *et al*., 2020). The authors analysed EAB strategies and stakeholder responses in the twin cities of Minneapolis and St Paul which, although geographically adjacent, adopted different approaches to the pest, with both using reactive and pre-emptive felling but Minneapolis avoiding use of insecticide. From these and other studies, management decisions have to balance the demonstrated benefits of chemical insecticides against the strong negative perception linked to their widespread use. This is likely to be even more polarised in Europe where there is a wide perception of insecticides being ‘bad’ for the environment along with lack of trust in regulators linked to low understanding of the toxicology and associated risks (Bearth *et al*., 2019).

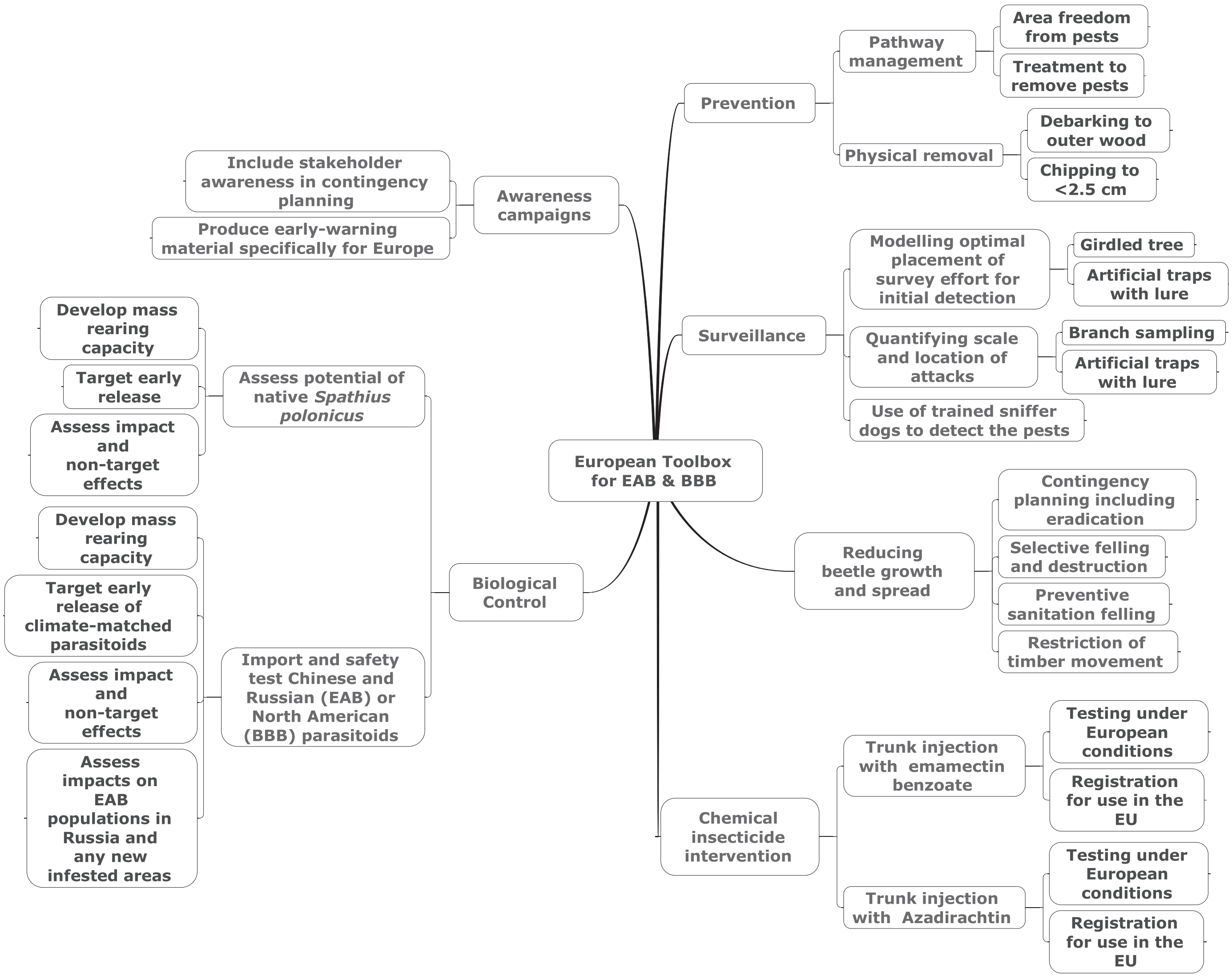

Figure 1 Schematic representation of a potential European Toolbox to prepare for and manage infestations by EAB and BBB.

Although EAB is not yet present in Europe, perceptions of its impact have been assessed through image-based choice experiments using visitor questionnaires to sites in the recreation areas in the Vienna floodplain (Arnberger, 2020). Visitors were presented with photo-realistic scenarios of different impacts on the existing ash resources, including simulation of EAB attack and tree mortality. Whilst most visitors had not heard about EAB, their visual preferences were for larger trees and acceptance of selective removal of impacted trees but not for widespread felling with re-planting using young trees, although this varied across different visitor types. Other factors, such as bicycle trails, presence of dogs, and degree of 'naturalness', were also relatively important with an overall desire for large, healthy trees.

In Europe, there is already awareness of loss of ash trees as a result of infection from the fungus *H. fraxineus* which has spread rapidly from the east (Timmermann *et al*., 2011). In the United Kingdom, where the disease was first recorded in 2012 but had been there since at least 2006, there is considerable effort to both increase awareness of the problem and also to encourage public involvement in reporting new findings as the disease spreads (e.g. through Tree Alert https://www.forestresearch.gov.uk/tools-and-resources/tree-alert/). Assessment of public attitudes and awareness of the disease is linked to potential future management of the dwindling ash resource, including efforts to identify and breed resistant trees (Dandy *et al*., 2017, Jepson and Arakelyan, 2017). Public feedback suggested the need for greater emphasis on breeding disease-tolerant trees, with younger contributors and gardeners being more likely to accept genetic manipulation in the process. As yet, there is no detailed assessment of how the UK public would react to EAB in addition to *H. fraxineus* (Marzano, 2020).

Stakeholder engagement is, therefore, likely to be an important component in the European Toolbox for EAB and will require careful handling in preparing for an additional important mortality factor to add to the existing ash dieback fungus.

Understanding the interaction between EAB and the pathogen H. fraxineus

The decline in ash following the arrival and spread of *H. fraxineus* has resulted in large resources of dying or dead trees across the natural and planted range of ash in Europe (Timmermann *et al*., 2011). Since one of the key factors in attack of ash by EAB is tree stress, the question arises whether the increased abundance of weakened and dying trees caused by the fungus would provide preferential breeding resources for the beetle. Although relatively little direct observation has been made of this potential ecological interaction between the two tree mortality agents, there is evidence that they now overlap in the European part of Russia (Musolin *et al*., 2017). The authors recorded the presence of both agents on trees but did not quantify the relative contributions to tree mortality, although they indicated that epicormic shoots that arise after beetle attack are particularly susceptible to the fungus and the combined effects of the two agents would increase overall tree mortality.

As EAB continues to spread west, it will increasingly encounter trees affected by ash dieback and the implications of the interaction will need to be accounted for in developing surveillance and response strategies for the beetle. The need to study this evolving interaction is clear and has been advocated by Ravn *et al*. (2020). At this stage, there is relatively little information on whether or how the two agents will interact with each other and there is an immediate need to determine whether trees affected by the fungus will prove more susceptible to EAB than healthy trees. This has implications for designing surveillance and early detection systems as an integral part of the European Toolbox.

Conclusions

As our knowledge of the interaction of EAB with its host trees increases, more components become available to add to the European Toolbox in preparation for the inevitable invasion of Europe by this pest. These tools derive mainly from knowledge gained in dealing with EAB in North America and, more recently, in Russia. Clearly, less is known about the potential threat and possible management of BBB, but many of the tools will be applicable should this pest also establish in Europe.

Some of the main components of a potential Toolbox have been described in this review and are summarised in Figure 1.

The close proximity of known EAB infestations to Europe demand immediate action to raise the level of preparedness and it is essential that concerted action is taken as soon as possible to act once the pest is located. Collaboration at all levels from researcher through to policy makers is a critical component in developing the Toolbox and this should continue to ensure delivery of a working system for Europe.

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