Preliminary investigation into the threat of Bronze Birch Borer (BBB - *Agrilus anxius*) to Scotland

Project Final Report

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This work was commissioned by Scotland's Centre of Expertise for Plant Health Funded by Scottish Government through the Rural & Environment Science and Analytical Services (RESAS) Division under grant agreement No PHC2020/06

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Please cite this report as follows: K. Dainton, C. Pollard, F. Trotter, A. Paterson, M. Dunn, M. Marzano, A. Whiffin, T. Kendall & D. Williams (2023). Preliminary investigation into the threat of Bronze Birch Borer (BBB - Agrilus anxius) to Scotland: Project Final Report. PHC2020/06. Scotland's Centre of Expertise for Plant Health (PHC). DOI: 10.5281/zenodo.8255823

Available online at: planthealthcentre.scot/publications

Dissemination status: Unrestricted

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Acknowledgements: The authors would like to thank the Technical Services Unit (TSU) at Forest Research for their help setting up and assessing the field trials, Elibank Estate for permission to use their woodland for the trials, Claire Rutledge from Connecticut Agricultural Experiment Station and Amanda Roe and Véronique Martel from Natural Resources Canada for sharing their knowledge and experience of BBB in North America. We would also like to thank Pete Hollingsworth and Sonia Humphris from the Scottish Plant Health Centre for their advice and support througout the project.

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Content

1 Executive Summary

This report details findings and recommendations from a year-long project investigating the threat that bronze birch borer (BBB, *Agrilus anxius*) poses to Scotland. The project concentrated on three areas: the current and potential distribution of *Agrilus* species in Scotland, potential BBB entry pathways, and BBB surveillance methods.

Research Undertaken:
We reviewed and assessed existing data sources, including UK *Agrilus* records, information on the ecology of BBB in its native North American range and BBB surveillance methods. We also gathered new information and data. This included modelling UK birch (*Betula*) distribution, identifying potential BBB entry pathways, mapping those stakeholders relevant to the prevention, surveillance, eradication or management of BBB, assessing the risks associated with different pathways and testing a selection of monitoring methods. Throughout these processes we identified knowledge and data gaps, such as the lack of *Agrilus* records from Scotland and general under recording of these species in the UK.

Project impact:

- Provide a baseline understanding of the existing data and knowledge relating to native and non-native *Agrilus* species in the UK.
- Evidence existing awareness of BBB in Scotland and the UK more widely and highlight associated risks.
- Give recommendations to inform BBB contingency planning, future research priorities, and policy actions.

Conclusions and *recommendations* from this project:

Sub-project 1:

Ten *Agrilus* species (one not yet confirmed as established) are reported from the UK. Most of these species are restricted to a southern England distribution and there is only one historic *Agrilus* record from Scotland. Most species are reported to be under recorded in the UK, especially those that exist in areas outside south England. It is not known how knowledge of existing *Agrilus* species in the UK will impact the detection of invasive species such as BBB. *To better understand current Agrilus distributions in the UK future targeted surveillance is recommended in collaboration with beetle recording schemes, museum curators and individual recorders.*

Species distribution modelling results showed that birch trees (*Betula spp.*) are mainly found across East, West, and South Scotland, and South and South-East England up to elevations of 675m. The trading ports in Felixstowe, Harwich, Southampton, Portsmouth, and Shoreham are potential BBB entry points therefore birch in Norfolk and Hampshire, Surrey, West Sussex, East Sussex, and the Isle of Wight may be vulnerable to first infestation, were BBB to arrive in the UK. Despite limitations due to the inconsistent climate datasets used in species distribution models, these still offer the best method for estimating birch distribution. *Development of an improved species distribution model would involve the inclusion of impacts of land management and land use change as well as coexistence of birch species with other tree species.*

BBB is widespread across North America and, although the lifecycle is temperature-driven, this does not appear to limit distribution. Native North American birch species are resilient to BBB, unless stressed by climatic factors such as drought. Eurasian birch species, including UK species, are highly susceptible to BBB even when healthy. *International collaboration with*

BBB researchers to link the existing North American forecasting tool with GB species distribution models for more accurate investigation of pest host interaction and overall risk.

Sub-project 2:

The potential for BBB to survive the processes used to turn birch into pellets or chips for large scale biomass energy production use are low, and so pathways for BBB to enter Scotland via this pathway were not seen as plausible. However, sector scale forces could cause currently unused or marginal products, processes, or pathways, to become economically or politically attractive. *Developing realistic policy and economic scenarios for use in trade modelling could reveal potential tipping points for large scale changes in processed or unprocessed birch into the UK.*

There remains high uncertainty around the characteristics of small pathways of unprocessed birch into the UK from North America, for example as part of the craft trade. Knowledge, awareness, and behaviours of both producers and end consumers are likely to be key. *Investigations are required into the plausibility of this and other small shipment volume pathways for entry of BBB. Potential to conduct a paired experiment with North American researchers to monitor craft and ornamental birch items for emergence of insect pest species, particularly beetles.*

Sub-project 3:

The main surveillance methods used to monitor pest *Agrilus* species in North America are interception traps. Green and purple versions of two trap types (sticky prism traps and multifunnel traps) are the most commonly used for BBB and emerald ash borer (EAB, *Agrilus planipennis*). Successful captures of these species rely on the positioning of traps in open, sunny areas. Synthetic lures have been devised for some *Agrilus* species, but not BBB, which is thought to rely on volatiles emitted by damaged, weakened or susceptible birch trees for mate-finding. BBB captures are therefore significantly enhanced by placing traps in artificially damaged (girdled) birch trees. Traps tested in field trials in Scotland did not catch any native or non-native *Agrilus* species. Several feasibility considerations for using these traps were noted, including time and labour requirements, high levels of non-target captures and training needs. *Further testing and development of monitoring traps, in collaboration with North American researchers, is therefore recommended.*

2 Introduction

2.1 *Project rationale*

Considerable research has been undertaken to assess the threat that emerald ash borer (EAB, *Agrilus planipennis*), poses to Eurasian Ash (*Fraxinus* spp.). Although there has been less research on the related species, bronze birch borer (BBB, *A. anxius*), the latter is thought to pose a greater proportional threat to Scotland than EAB, due to both BBB's cold climate tolerance and the importance and abundance of birch across Scotland. Assessments of BBB risk has often been considered alongside that of EAB, as have management options (Evans et al. 2020), gaps therefore remain in the specific understanding of the threat posed by BBB. This project was undertaken to gather evidence to better assess the threat BBB poses to Scotland, to inform risk assessment, surveillance and contingency planning, and identify key risks and knowledge gaps.

2.2 *Agrilus beetles*

The beetle genus *Agrilus* (Coleoptera: Buprestidae) is one of the largest in the world, containing more than 3,000 described species (Kelnarova et al. 2019). They are distinguished from other Buprestidae by the combination of a subcylindrical body form and paired toothed tarsal claws (Duff 2020). The larvae of these shiny beetles feed exclusively (at least in Europe) on plants, including trees (Harde, 1984). Many of these species play a crucial role in breaking down and recycling plant nutrients. A small but significant number, such as bronze birch borer (*Agrilus anxius*, see Front cover) and emerald ash borer (*A. planipennis*), can damage and kill trees.

2.3 *Project overview*

This project was split into three sub-projects that each addressed a separate aspect of BBB (*A. anxius*) risk and management. Sub-project 1 focused on the current UK distribution of native and established *Agrilus* species, plus the potential distribution of BBB were it to arrive in Scotland or elsewhere in the UK. Sub-project 2 investigated the possible pathways via which BBB might arrive in the UK, including identifying relevant stakeholders and assessing the risk levels associated with different pathways. Sub-project 3 tested the feasibility and efficacy of available BBB surveillance methods for use in Scotland. The aims, methods and results of each sub-project are detailed below.

3 Sub-Project 1: Current and potential Agrilus spp. distribution in Scotland

This sub-project is split into three strands based on the following aims:

- Gather information and distribution data on *Agrilus* species in the UK.
- Model and map the distribution of birch (*Betula pendula*, *B. pubescens*, *B. nana*) across Great Britain (GB) under current and future climate scenarios.
- Review BBB ecology and environmental requirements in North American range to inform future mapping of potential BBB distribution in GB.

3.1 UK Agrilus species

3.1.1 Methods

The scientific literature and biological records (including identification keys (Hackston, 2019; Duff, 2020), NBN atlas (2021), iRecord (2021)) were interrogated for information on *Agrilus* species in the UK. Entomological curators and individual beetle recorders were also contacted for specific knowledge of *Agrilus* species presence in Scotland.

3.1.2 Results

3.1.2.1 Agrilus species presence and distribution in the UK

Ten *Agrilus* species have been recorded in the UK, see Table 1 for details. Five of these are considered native (*A. biguttatus*, *A. viridis* (see Figure 1), *A. laticornis*, *A. angustulus*, *A. sinuatus*). Four of the other five (*A. cuprescens*, *A. cyanescens*, *A. olivicolor* and *A. sulcicollis*) have been added to the British list since the early 1990s, most likely facilitated by recent climate warming (Duff, 2020). The tenth species (*A. ater)* is known from a single record (Booth, 2018) and establishment has not yet been confirmed. The distribution of eight of these species is confined to England, with *A. biguttatus* and *A. angustulus* also recorded from Wales, although all species are thought to be under recorded (Duff, 2020). There are no recent reports in the published literature of any of the species being recorded from Scotland or the island of Ireland. See below for more information on historic *Agrilus* records from Scotland.

Figure 1 - Two colour variations of the native UK Agrilus species - Agrilus viridis (Hackston 2014)

Table 1 - The distribution and host species of the 10 Agrilus species recorded from the UK, adapted from published information in Hackston 2012; Duff 2020 and iRecord, 2021

Species	Larval host tree /plant	Known UK distribution	Arrival in UK
Agrilus biguttatus	Quercus (oak)	England, Wales. Local C and SE England, very local in C Wales. Spreading, scarce. More common in S and E England. Moving north (to Manchester and York) and west (into Wales). Associated with Acute Oak Decline (AOD).	Native
Agrilus viridis	Quercus Salix (willow)	England. Local in SE England, very local in C England. Scarce. Old records confused with *A. angustulus* and *A. laticornis*.	Native
Agrilus laticornis	Quercus	England. Local in NE, C and E England, scarce.	Native
Agrilus angustulus	Quercus	England, Wales. Local in C and SE England, very local in SW England and Wales, formerly NE England. Scarce, sometimes frequent. The commonest European species.	Native
Agrilus sinuatus	Crataegus (hawthorn) Pyrus (pear)	England. Local in C and S England. Scarce. Mainly SE England, some records further W and N to Nottingham.	Native
Agrilus cuprescens	Rubus (bramble) Rosa (rose) (Larvae produce galls)	England. Very local in SE England. Scarce. Spreading from SE London, where first recorded. Pest of cultivated roses in southern Europe.	2008 (Hodge, 2010)
Agrilus olivicolor	Carpinus (hornbeam) Fagus (beech) Corylus (hazel)	England. Very local in SE England. Rare.	2016 (Mendel, 2016; James, 2019)
Agrilus cyanescens	Lonicera (Honeysuckle) Polyphagous	England. Very local in C & SE England, spreading rapidly, scarce, sometimes frequent. Spreading through the south Midlands and around London (Bristol / Derby/ East Anglia / Cambridge / London)	2008 (Hodge, 2010)
Agrilus sulcicollis	Quercus Fagus	England. Very local in C & SE England. Frequent. First recorded in Hertfordshire, from where it has spread.	1992 (James, 1994, 2006)
Agrilus ater	Populus (poplar) Salix	England. One female recorded from Surrey.	2017 (Booth, 2018)

3.1.2.2 Agrilus species in Scotland

We undertook a thorough review of archive records, biological collections, and other published and unpublished sources during this project. This included contacting curators, recording scheme organisers, record centres and individual beetle recorders. This review found two historic records of *Agrilus viridis* in Scotland; one from the Solway District and one from Argyll (M'Gowan, 1919-1920; Levey, 1977). On further investigation, it was confirmed that the Solway record relates to specimens collected by Rev. William Little in June 1839, in the vicinity of Rae Hills, Annadale, Dumfriesshire (Curtis, 1840). The other record from Argyll could not be verified.

The specimens collected by Little were, at the time, considered an undescribed species, and named *A. littlei,* now considered a synonym of *A. viridis*. He collected some twenty specimens, and it appears that these were distributed among collectors, with examples held at both National Museums Scotland, Edinburgh and the Natural History Museum, London (M. Barclay, personal communication, 8 November 2021). There is still some confusion over the true synonymy of this species (Dobson *et al.* 2012). Information collected during this project confirmed that there are no other known *Agrilus* records from Scotland, with the exception of the records from Little (Dainton and Whiffin 2021). Anecdotal evidence, however, supports the theory that this localised population of *A. viridis*, and possibly others, may still exist albeit overlooked and unrecorded for over a century. Targeted surveys in suitable habitat, local to the original recording site, would help ascertain if this is the case.

3.1.3 Implications of existing Agrilus species distribution in the UK

In general, *Agrilus* species are considered under recorded in the UK, most probably due difficulties in capturing and monitoring adults in their tree canopy habitats. It is unclear whether the very limited known existence of *Agrilus* species in Scotland will help or hinder the detection of any invasive *Agrilus* species, such as BBB. On one hand the lack of existing species in Scotland means that few people are expecting to see or are searching for *Agrilus* and these species are therefore likely to go unnoticed. Alternatively, the novelty of finding an *Agrilus* beetle in Scotland may mean any records are more likely to be reported. If the risk of BBB arriving in Scotland were to increase, for example it was found elsewhere in Europe, it may be beneficial to raise awareness within the entomological community, particularly groups and individuals focused on Coleoptera (beetles).

Although the number of *Agrilus* species present in the UK has doubled in the last 30 years, the distribution of most species remains climatically restricted to the south of England. There is evidence, however, that some species are spreading north and west most likely driven by warming annual temperatures due to climate change (Duff 2020). It is therefore likely that *Agrilus* species will be found in Scotland in the future. Regardless, BBB is significantly more cold-tolerant than these species so is predicted to be readily able to colonise birch throughout the UK were it accidently introduced (EPPO, 2013).

As with many beetle genera there are difficulties distinguishing between *Agrilus* species, particularly at juvenile life stages (egg, larvae, pupae) but also the adult beetles. This could result in confusion between native and potential invasive species. Unlike emerald ash borer (EAB), which is a distinctive bright green, BBB is much more similar in appearance to some existing UK species. It is therefore recommended that any future *Agrilus* specimens collected from Scotland are retained, examined and identification verified before acquisition into the entomological collection at NMS. Molecular methods may also be used to help identify *Agrilus* species, for example using Kelnarova *et al*.'s (2019) DNA reference library for c.100 *Agrilus* species from the Northern Hemisphere (this includes *Agrilus planipennis* (EAB) and several of the *Agrilus* species already present in the UK, but not *A. anxius*).

3.2 Modelling and mapping of birch distribution

To better understand the risk that BBB poses to UK birch we wanted to map UK birch (*Betula* spp.) distribution. Maps produced by data recording schemes, such as BSBI (Botanical Society of Britain & Ireland (bsbi.org)), and NBN (NBN Atlas - UK's largest collection of biodiversity information), already show that birch is widespread across the UK (Figure 2). However, although some of these records are checked for accuracy and verified, limitations exist regarding the reliability of unverified data records. Additionally, BSBI and NBN records do not consider the environmental ranges that optimise or limit birch growth and therefore also impact species distribution. We therefore used species distribution modelling (SDM) to predict areas of birch dominance. One advantage of using SDM is that it considers the current environmental ranges of birch by integrating important climate and soil variables into the modelling of birch distribution and determining which of these variables are the most significant in predicting birch distribution. Future climate predictions can also be integrated into SDM to map potential changes in birch distribution over time.

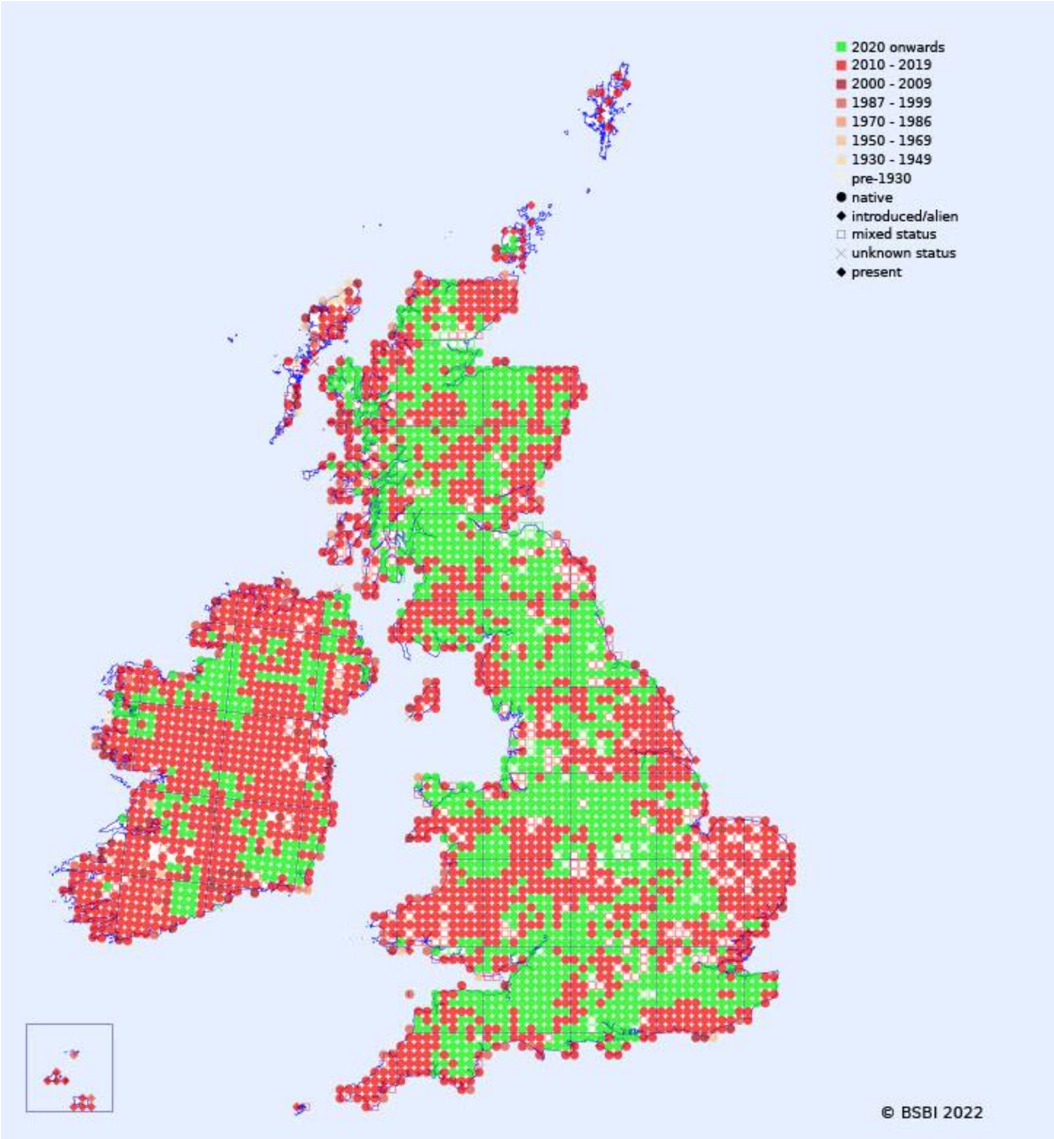

Figure 2 - UK distribution of birch (Betula species) from Botanical Society of Britain and Ireland (BSBI) Source, BSBI, 2022

Using SDM to estimate the risk of BBB infestations to birch across GB woodlands is reliant on access to accurate and reliable birch occurrence data. For this project we used national forest inventory (NFI) data, which is only available for publicly owned land. Fortunately, species distribution models (SDMs) exist that can predict birch distribution across large spatial scales with samples of occurrence data and climate and soil data. Such models are used to infer the distribution of a single species, or to predict species composition when the models are run for multiple species across the same spatial area (Araújo and Guisan 2006). Here we present the progress made in predicting optimum areas of birch distribution across GB for the purpose of determining areas at risk of BBB infestation in case of invasion into British woodlands. We first present the methodology used for the modelling process. We then present the results and discuss limitations of the modelling approach.

3.2.1 Methods to map birch distribution

We used the biomod2 modelling approach, which consists of an ensemble of SDMs (Thuiller et al. 2016). These SDMs use recorded tree species occurrences together with climate and soil variables to predict birch distribution. Birch is a widely spread genus across Great Britain, therefore broad areas may be affected by BBB infestations. However, the SDM enabled us to identify areas of >60% birch abundance as matched to the public forest estate inventories, following an approach by Ray et al. (2021) who modelled oak distribution with >60% oak presence data in NFI sub-compartments (Ray et al., 2021). The threshold 60% was chosen in the modelling approach as it proved to reliably predict oak distribution across Great Britain. The modelling approach thus considers areas with high birch abundance because of the environmental predictors used in the model and excludes areas with lower birch abundance. BBB can infest pockets of birch of any size but areas where birch abundance is higher are more likely to be particularly at-risk of BBB infestation and be prone to greater landscape scale effects of infestation. BBB can attack all UK birch species; therefore, we included occurrence data for all recorded birch species in GB from the public forest estate inventories. These were:

- Silver birch (*Betula pendula*)
- Downy birch (*B. pubescens*)
- Dwarf birch (*B. nana*)

We used climate and soil variables from the latest Ecological Site Classification version 4 (ESC v4) from Forest Research:

- Climatic moisture deficit (CMD)
- Accumulated temperature (AT)
- Topographic wetness index (TWI)
- Digital elevation model (DEM)
- Wind exposure (DAMS)
- Soil moisture regime (SMR)
- Soil nutrient regime (SNR)

The climatic moisture deficit (CMD) represents the mean monthly difference between potential evapotranspiration and precipitation for the climatic period 1961 – 1990. Accumulated temperature (AT) is the sum of temperatures above 5°C per day and covers 1961 – 1990. The topographic wetness index (TWI) expresses the balance between water supply and local drainage, which are controlled by landscape terrain. The digital elevation model (DEM) models the elevation of the landscape. Wind exposure (DAMS) presents the average windspeed and frequency of wind regimes, and is based on location, elevation, and topography. The soil moisture regime (SMR) and soil nutrient regime (SNR) represent average soil moisture and soil nutrients at a given site, respectively. These environmental variables were found to be significant in predicting tree species distributions on the public forest estate inventories (Ray et al. 2021) across GB to model oak distribution in the private sector. We thus used the study by Ray et al. (2021) as a guide to model predicted optimum birch distribution.

We used the public forest estate inventory of birch species to train and test the biomod2 algorithms, separately for each of 14 national forest inventory (NFI) regions. The model was used to predict the likelihood of birch woodland from the broadleaved tree categories of the indicative forest type (IFT) layer prepared by the NFI. More detailed information can be found in the appendix of this report, and in Ray et al. (2021).

3.2.2 Modelling results

Results show that moisture deficit, accumulated temperature, elevation, and soil nutrient regime are significant environmental variables to predict birch distribution across Great Britain, while wind exposure also plays a significant role in North-West England (NFI 1), North-East England (NFI 2), North Scotland (NFI 9), North-East Scotland (NFI 10) and East Scotland (NFI 11). Evaluation of the results using true-skills-statistics (TSS) showed very promising results where the mean TSS across all ensemble models was 0.86 (equivalent to a correlation coefficient R2 = 0.86). This means that 86% of the predicted broadleaved woodland patches in the IFT were correctly identified from a cross-validation evaluation of the model. Further checking of birch stand predictions with the locations of the NFI sample squares in which birch was recorded showed 72% of the modelled data matched the NFI birch sample square locations.

Birch is predicted to be most dominant up to elevations of 675m in the lower Highlands, in West Scotland, South Scotland, and East Scotland. Especially the counties Ayrshire, Wigtownshire, Kirkcudbrightshire, Fife, Perthshire, Aberdeenshire, Banffshire, Elginshire, Nairnshire, Ross and Cromatry, Sutherland, and Invernesshire are inhabited by birch, while Caithness in the North is predicted to have less birch (Figure 3). While the Atlas of British Flora (https://bsbi.org/maps) includes records of birch across the Outer Hebrides, the species distribution modelling results predict a lack of birch dominance there and across Orkney and Shetland.

Other areas in GB that the SDM predicts to have a high abundance of birch include the uplands of Northern Wales, and the following English counties: Cumbria, Lancashire, Yorkshire, Gloucestershire, Lincolnshire Norfolk, Hampshire, Surrey, West Sussex, East Sussex, and the Isle of Wight. Birch in Norfolk and Hampshire, Surrey, West Sussex, East Sussex, and the Isle of Wight may be at higher risk of BBB infestation due to proximity to potential BBB entry points at the trading ports of Kings Lynn, Felixstowe, Harwich, Southampton, Portsmouth, and Shoreham. Nearby birch would be particularly vulnerable to infestation if the beetle enters the UK via one of these ports. The birch prediction layer across GB (Figure 3) is available on request to the authors of this report as a GeoTiff raster file or an image png file.

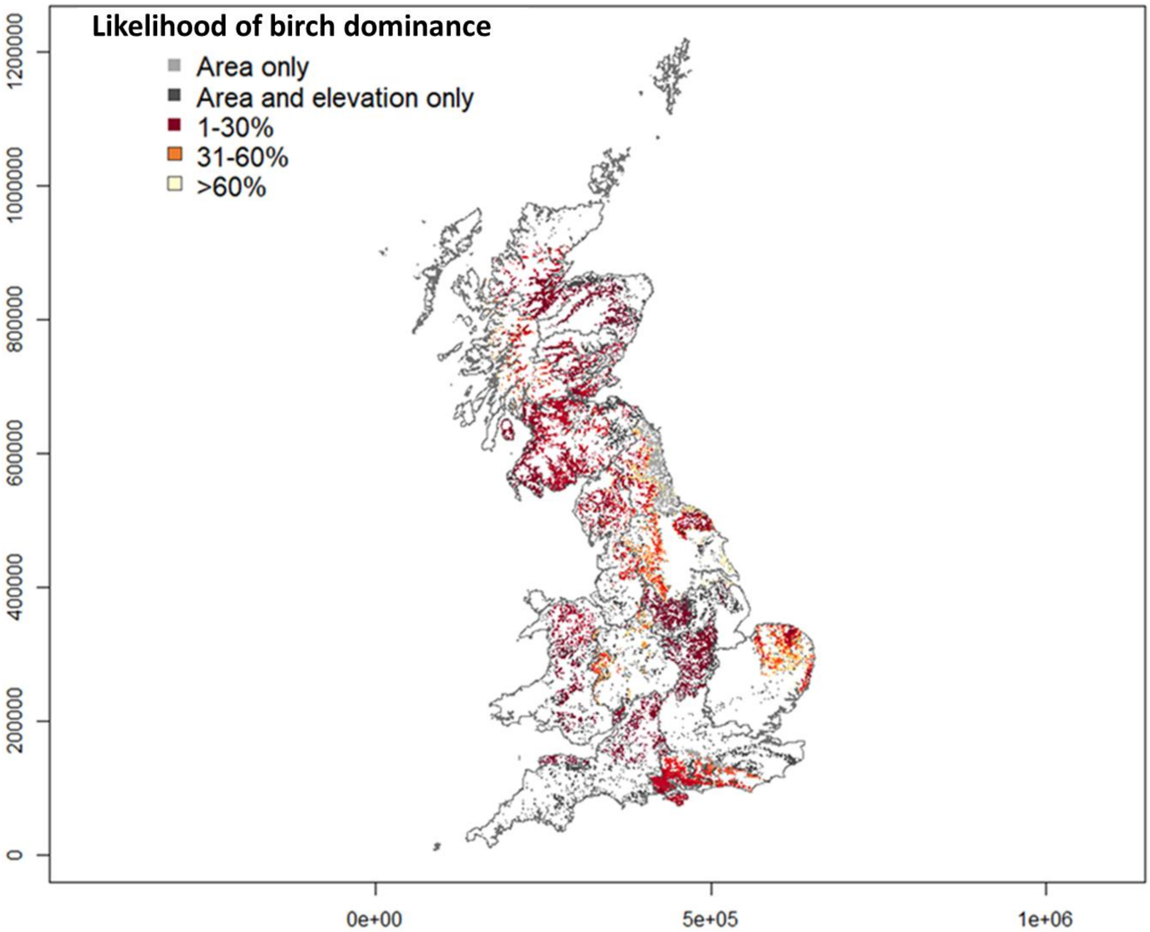

Figure 3 - Predicted areas of birch dominance (based on presence per NFI sample square), modelled across all 14 National Forest Inventory (NFI) regions and filtered by estimated NFI birch area (light grey), elevation ranges (dark grey), and overlap between area. The likelihood of birch dominating an area is estimated in percentage: red pixels indicate areas where birch will dominate landscapes with a 1 – 30% likelihood, followed by a likelihood of 31 – 60% (orange); and > 60% (yellow).

3.2.3 Limitations of species distribution models (SDM)

We have used SDM to create a map of the predicted GB distribution of native birch species (*Betula pendula, B. pubescens, B. nana*), based on the environmental predictors that drive their distribution. Using this approach enables the estimation of likely occurrence of birch across the entire country, thereby overcoming the problem of lack of occurrence data on private land and limited data only available via the NFI. However, because of the lack of data, there is always a given level of uncertainty in the predicted occurrence of birch, expressed in the 86% and 72% accuracy of our predicted birch distribution, respectively. Predictions from models are based on inference from environment and samples of recorded occurrence. Because environmental variables vary, and it is impossible to record every individual birch tree, uncertainties need to be considered when using these modelling results in BBB risk assessments. This uncertainty is supported by the fact that the modelling of birch is entirely based on environmental predictors but does not include human impacts such as land use methods and change (e.g., what silvicultural practices impact growth of birch), or the impact of coexistence with other tree species or disturbances. Thus, while we can model birch distribution across GB with relatively high confidence expressed by the good TSS results and correlation between predicted distribution and NFI sample square locations, other variables may also influence birch distribution (and with that BBB infestations).

3.3 Bronze birch borer ecology in native North American range

3.3.1 Background

Due to time constraints, it was beyond the scope of this project to extend the species distribution modelling to include potential BBB distribution in Scotland and the UK. Instead, we have gathered information on BBB ecology and the climate, habitat, and environmental variables driving species distributions across its native range in North America. The intention being that this information, and the potential BBB entry pathways identified in sub-project 2, could be used to inform BBB distribution modelling in Scotland in the future.

3.3.2 Overview

The bronze birch borer (BBB, Figure 4) is native to North America where it breeds in birch trees (*Betula* spp.) causing periodic damage and mortality, sometimes on a massive scale. For example, BBB killed 105 million drought-stressed birch trees in the 1980's (Muilenburg and Herms 2012). Although BBB has been found to attack many different birch species, tree susceptibly varies between species. The native North American birch species that have co-evolved with BBB are much more resilient to the beetle than non-native birch species (Nielsen, Muilenburg, and Herms 2011). North American birch species rarely succumb unless predisposed by stress and outbreaks of BBB are associated with widescale stress events, such as drought (Muilenburg and Herms 2012). Eurasian birch species, however, are highly susceptible to BBB even when healthy, which has proved a limiting factor to planting these species in N. America.

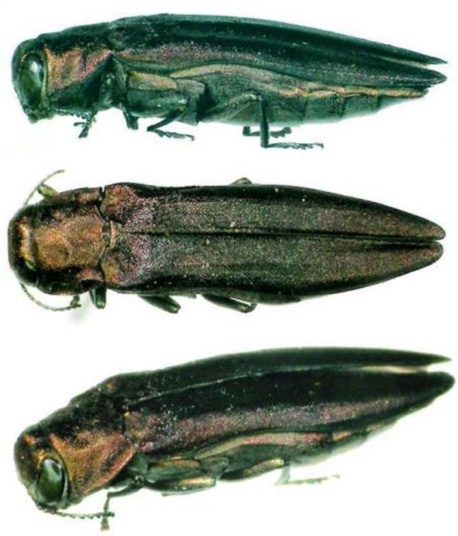

Figure 4 - Bronze birch borer, Agrilus anxius (Parsons 2008)

3.3.3 BBB lifecycle and ecology

The lifecycle and ecology of BBB have been comprehensively reviewed by Barter (1957) and Muilenburg and Herms (2012) and are summarised in the Forestry Commission Contingency Plan for BBB (Forestry Commission 2016). We have extracted key information on BBB ecology from these documents and other sources and summarised it in Table 2. We have also identified knowledge and data gaps relevant to a UK context.

Table 2 - Information on the lifecycle stages of Bronze birch borer (A. anxius) in its native North American range (based on information extracted from Barter (1957); Muilenburg and Herms (2012); Forestry Commission (2016)

Life cycle stage	Information
Total	The BBB life cycle takes 12-24 months and is driven by temperature and tree host condition. BBB completes it life cycle more quickly in warmer climates and on stressed, more susceptible hosts. Survival rates are also higher in these conditions. **Knowledge gaps:** It is possible that the BBB lifecycle could extend beyond 2 years in colder northern climates. Other invasive beetle pests (e.g. Asian longhorn beetle (Straw et al. 2016)) were found to have a longer life-cycle (3 years) in the cooler UK maritime climate, than in warmer areas of central and southern Europe (1 or 2 years). It is not known if BBB would be similarly affected.
Egg	Each female beetle lays c.25 (max. 75) eggs, in batches of 1-14 eggs on / in bark crevices, preferably in sunshine.
Larva	Larvae hatch c.14 days after oviposition. They feed on phloem / xylem of birch trees for 1 or 2 seasons, creating galleries 25cm – 127 cm long (shorter on more resilient trees, longer on more susceptible trees). Larvae undergo five growth stages (instars), all of which can overwinter. It is the larval feeding damage that causes tree decline and mortality, which occurs once the larvae have girdled the tree. Larger, healthier and more resilient birch tree species take longer to girdle than smaller, weakened and more susceptible species. Larger beetle populations also girdle trees faster.
Prepupa	Prepupal larvae (fifth instars) require a period of cold / freezing temperatures before pupation can occur. **Knowledge gaps:** Length and temperature requirements for cold period have not been quantified. Anecdotal evidence suggests chilling BBB lab cultures at 2-4°C for a couple of months is sufficient. The southerly expansion of BBB in North America indicates that this low temperature requirement is unlikely to be a limiting factor in the UK. Further investigation is required.
Pupa	Pupal cells are constructed by fifth instars in the xylem or thick bark prior to overwintering. Pupation is triggered by cold temperatures (see above).
Pupation	Pupation occurs in spring-summer (April-June) and takes 2-3 weeks.
Adult emergence	Adults emerge from trunks and branches in late Spring and Summer, creating distinctive D-shaped holes. Emergence is triggered by temperature and occurs over a period of 6-12 weeks, peaking 2-4 weeks after first emergence. **Knowledge gaps:** Some information exists on the degree days required for emergence, but would need to be correlated to UK climate.
Adult maturation feeding	Adults must feed on foliage to achieve reproductive maturity. They feed on several broadleaf species including birch, willow (Salix), and poplar (Populus) for c.5-25 days. This defoliation has a negligible effect on the trees. This life cycle stage presents an opportunity to target and kill adults feeding on leaves using systemic insecticides (as used for EAB control). **Knowledge gaps:** the acceptability of using systemic insecticides against BBB in the UK is not known but is likely to be low due to native birch foliar feeding species. If this method were to be used, matching application timing to adult emergence (using surveillance methods) would be crucial.
Adults	Adult beetles live 5 to 7 weeks with feeding, but only survive c.5 days without feeding.
Mating	No sex or aggregation pheromones have been detected and it is presumed adult beetles rely on host volatiles to locate mates. Females only need to mate once (although they will mate multiple times). Female fecundity varies depending on the host plant species that they fed on during maturation feeding. **Knowledge gaps:** female fecundity following foliar feeding on UK species is not known.

3.3.4 Environmental drivers of BBB outbreaks

Bronze birch borer (BBB) attacks all species of birch (*Betula*) and infests tree stems and branches of all sizes above 1 cm diameter. Tree species and tree condition are the main drivers of BBB outbreaks in North America, where it has been associated with dying birch since at least 1925 (Barter 1957). It is, however, considered a secondary pest on native North American birch species, which display high resilience levels when healthy. These birch species become much more susceptible following stress events, particularly high temperature and drought periods. As such, low-level, localised populations of BBB are often found on individual or small groups of birch trees in poor health, with wide-scale BBB outbreaks only occurring following mass birch dieback events. During this project, discussions with researchers in the USA and Canada revealed that in many regions it is difficult to find large enough populations of BBB to carry out experimental laboratory research (C. Rutledge, personal communication, 15 March 2022). Despite sometimes existing in these low levels, BBB are highly skilled in detecting and seeking suitable host trees (i.e., damaged or stressed birch) and can move readily to utilise this resource. However, even when they are healthy Eurasian birch species planted in North America (mostly as ornamental or amenity trees in urban and garden settings), are significantly more susceptible to BBB attack and death than native North American species.

3.3.5 Factors limiting BBB populations in native range

Tree resilience is the most important factor limiting BBB populations in North America, primarily due to low larval survival in healthy native birch (Barter 1957). Parasitoids and predators also provide a level of natural population control across BBB's North American range. The latter has a limited impact on BBB populations compared to tree host susceptibility.

3.3.6 Threat BBB poses to the UK, including Scotland

The two predominant birch species in the UK, silver birch (*Betula pendula*) and downy birch (*B. pubescens*) have been found to be very susceptible to BBB where they encounter this beetle in North America (Nielsen et al. 2011). Although the susceptibility of dwarf birch (*B. nana*) is unknown, it is likely that BBB would also attack this species which has a more restricted UK distribution. Given the very wide distribution of BBB across the USA and Canada (Figure 5) it is unlikely that other drivers, such as climate, would be a limiting factor to the spread of BBB were it to be introduced to the UK. The life cycle of BBB is, however, regulated by temperature. To what extent the speed of population growth and distribution spread would therefore be impacted by average, minimum and maximum annual UK temperatures, is not known. Several reviews (EPPO 2011; Muilenburg and Herms 2012) have, however, concluded that BBB would have a very high probability of establishment were it introduced into the UK or Europe, and would pose a significant threat to Eurasian birch, including that growing in Scotland, resulting in high mortality of birch, and major economic impacts (EPPO 2011).

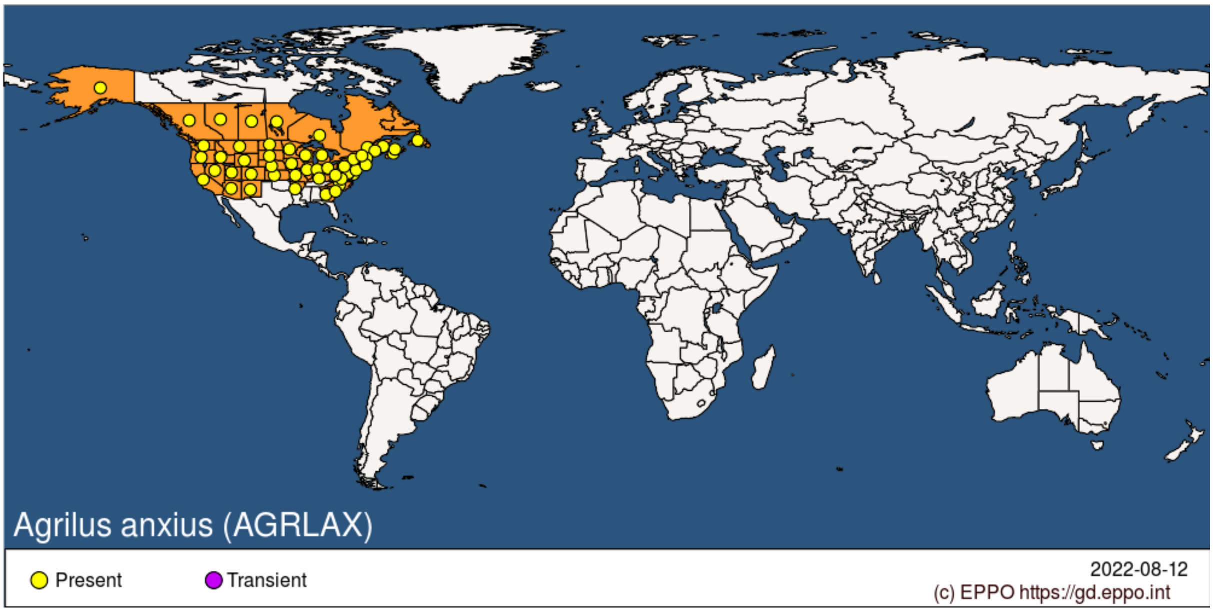

Figure 5 - Distribution of Bronze birch borer, Agrilus anxius (EPPO 2022)

BBB has the potential to cause significant economic and ecological damage to UK birch woodlands. Native birch species are of high ecological value because of their functions in storing carbon and regulating hydrological cycles, re-establishing woodlands as pioneer trees, and providing habitat for animals, including many insects (Gimingham 1984; Lee et al. 2015). Individual birch trees are also an important and aesthetic feature in the Scottish landscape. Furthermore, birch wood is a popular choice of household fuel (in the form of wood and pellets) and crafting material. Infestation of BBB could jeopardise these functions of birch, and lead to expensive costs for control and recovery of birch woodlands.

To better understand the potential UK distribution of BBB, further species distribution modelling is recommended. A BBB forecast mapping tool (Bronze birch borer Forecast | USA National Phenology Network (usanpn.org)) has been developed to predict adult emergence in North America and is used to target control methods. It may be possible to collaborate with the reseachers that developed this tool to create a UK model based on the same BBB parameters. Preventing the arrival of this beetle pest remains paramount to protecting birch trees in the UK, including Scotland, as such, potential pathways to entry and associated risks are considered in sub-project 2 below.

4 Sub-Project 2: Key roles and data gaps in assessing BBB risk pathways

4.1 Aims

- Map existing evidence of trade pathways and associated stakeholders, which could act as a route of BBB entry to Scotland
- Identify data gaps concerning trade-enabled routes of entry
- Outline potential planning steps for reducing the risk of BBB entry via trade pathways

4.2 Methods

4.2.1 Stakeholder mapping

Stakeholder mapping began using the potential pathways identified in previous research and plans (e.g. Evans, Marzano, and Williams 2021; Forestry Commission 2016). We discussed potential pathways (and associated stakeholders) with Forest Research experts in entomology and wood supply. As live birch species for planting cannot currently be imported from North America, a decision was made to concentrate on biomass as the major potential pathway of infested birch into the UK. Pathways and maps relating to biomass were created through web-based searches, with consultation from those experts mentioned above. A stakeholder list (individual, group, business, or organisation) was then compiled using previous research, online databases, web-based searches, policy documents, and grey literature.

4.2.2 Risk workshop

Having identified target stakeholder types during mapping (4.2.1), we conducted five context-setting interviews with key informants from plant health policy, plant health research, natural resource management, and the biomass energy production sector. Interviews took place online between November 2021 and February 2022. The aim of the context-setting interviews was to build understanding around potential pathways identified during mapping, which would feed into design (structure and content) of the risk workshop. Context-setting interviews discussed the following topics: biomass stakeholder maps (4.2.1), potential geographical sources of introduction (USA, Canada, Europe), potential method of introduction (imported birch for biomass energy production - pellets, chips, logs), BBB detection, and key stakeholder behaviours required for increased biosecurity. Key informants were also asked to suggest potential attendees for the risk workshop.

The risk workshop took place online on 2nd March 2022, coordinated by Forest Research. The aim of the risk workshop was to bring together knowledgeable stakeholders to discuss current evidence and data gaps for understanding risks associated with sources of potential introduction of bronze birch borer to Scotland. Participants were researchers and stakeholders (n=12) from governments, natural resource management organisations, and the UK biomass sector. The workshop was split into two parts; the first half set the scene with presentations from UK and USA researchers, and the second half used a six-stage pest introduction pathway to structure discussions around likelihood of BBB entry, data gaps, and relevant stakeholder behaviours. These discussions form the data for analysis. The six-stage risk pathway (Dandy et al. 2017) was presented to participants in breakout groups in sequence, alongside a scenario and suggested discussion questions (Table 3). Participants were then brought back together for a general discussion, including a poll which asked, “Which is the most important stage [along the six-stage pathway] for addressing the risk of BBB?” Workshops were recorded verbatim and transcribed by a professional transcription company. Transcripts were used to identify key themes on potential BBB pathways.

Table 3 - BBB risk workshop discussion structure

Risk pathway stage	BBB scenario	Discussion questions
1. Pre-introduction	Birch is harvested in North America from an area with BBB. Birch is processed for export to the UK biomass sector and BBB survives processing	Is this plausible? What would need to happen? Is it likely that BBB would go undetected? Are there any other likely scenarios at this stage?
2. Introduction	Infested birch arrives is undetected at a port in the UK and then distributed throughout the UK to multiple sites	Is this plausible? What would need to happen? How likely is it for BBB to go undetected at the ports and then be distributed through the UK? Are there any other ways infested birch would come into the UK?
3. Release	While shipments of imported birch are stored prior to use, BBB escapes into the local environment and survives	Is this plausible? What would need to happen? Is it likely that a shipment of imported birch would be stored long enough for BBB to escape into the wider environment?
4. Establishment	BBB breeds and becomes established	Is this plausible? How long would BBB have to go undetected until it becomes established?
5. Spread	Infested wood is harvested locally and moved around the country for processing and use, spreading BBB widely	Is this plausible? What would need to happen? Is there an industry in the UK that supports the harvesting of local birch? How would natural spread / hitchhiking interact with this scenario?
6. Mitigation / Containment	BBB is detected in woodlands throughout the UK and polices are put in place to contain the spread and stop future infestation	Is this plausible? What would need to happen? Is it likely we could contain BBB if it became established in the UK? Who (stakeholders) we need to be involved along a pathway?

4.3 Results

4.3.1 Key stakeholders along the risk pathway

Pathways of entry for BBB are centred on birch and birch product imports. Nine stakeholder types were identified, five of which directly handle birch or birch products when moving into or around the UK: Birch sources, Ports (exit and entry), Processing/storage, Retailers, and End users. Three stakeholder groups do not move birch themselves but are associated with birch movement or with plant health in the UK: Advisors & influencers, Policy & regulation, and Monitoring & detection. The final stakeholder group was termed Other. A total of 1529 stakeholders (individual, group, business, or organisation) were identified over the nine stakeholder categories (Table 4). Retailers made up by far the largest group identified, due to the open access UK government Biomass Suppliers List (BSL Suppliers List (biomass-suppliers-list.service.gov.uk)) which is used to keep track of biomass suppliers eligible for specific UK government incentives (e.g. Renewable Heat Incentive). The Biomass Suppliers List is clearly useful for identifying retailers in the sector, but it should be assumed that future changes in energy policy may result in changes to those eligible to be included on the list or list obsolescence, via lack of updating or total removal.

Different stakeholder groups and their likely association with different stages in the proposed risk pathway are shown in Table 4, and a schematic of the flow of birch imported into the UK, from source to end users is shown in Figure 6.

Table 4 - Stakeholders identified by group and introduction stage

Stakeholder group	**Handle birch directly**	**Number of stakeholders identified**	**Proposed stage of risk pathway**
Source of birch material	Yes	5	1, 2
Ports (exit and entry)	Yes	31	1 - 3
Processing / refinement of product	Yes	49	2, 3, 5
Retailer	Yes	1134	2, 3, 5
End users	Yes	228	2, 3, 5
Advisors & influencers	No	61	2 - 6
Policy & regulation	No	5	2 - 6
Monitoring & detection	No	14	2 - 6
Other	NA	2	NA

Risk pathway stages: 1 Pre-introduction; 2 Introduction; 3 Release; 4 Establishment; 5 Spread; 6 Mitigation / containment

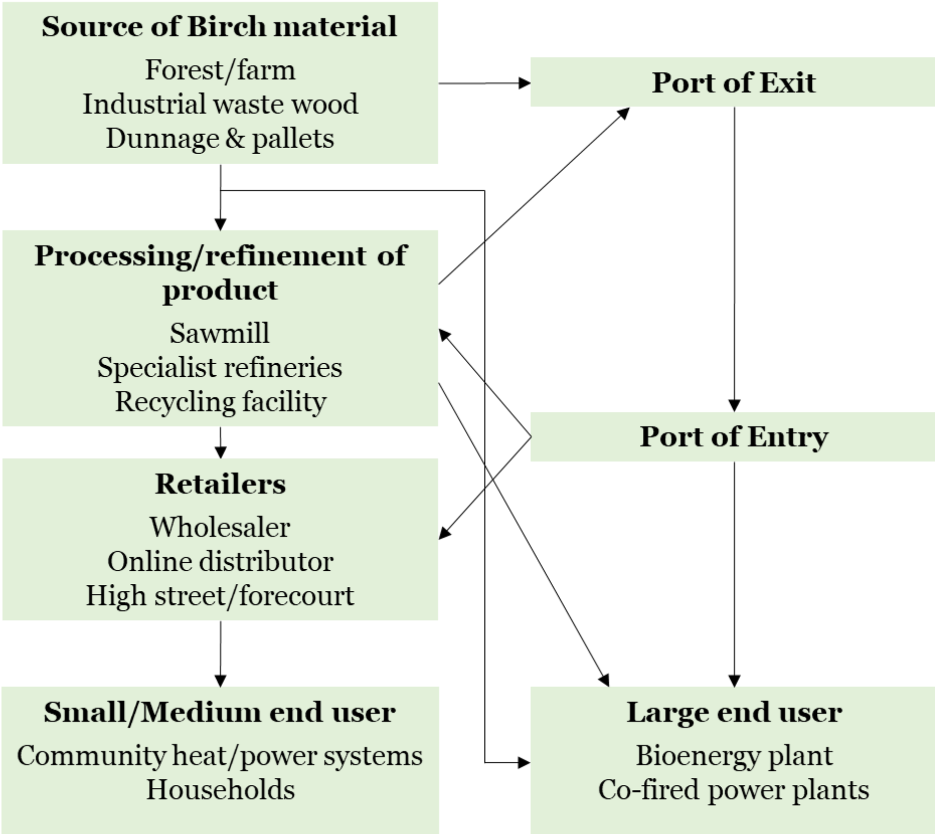

Figure 6 - Flow of imported birch from source to end user

4.3.2 Key topics identified from the workshop

During the risk workshop, we asked participants to vote which risk pathway stages were the most important for addressing the risk of BBB (they could vote for more than one stage). Stages 1 (Pre-introduction) and 2 (Introduction) received the highest number of votes (eight votes each), followed by stage 3 (Release, 2 votes) and stage 4 (Establishment, 1 vote). Stages 5 (Spread) and 6 (Mitigation / containment) received no votes. Discussion revealed that pre-introduction and introduction (stages 1 and 2) were seen as the most important stages on the risk pathway for focussing efforts. Interventions at later stages were seen as more difficult due to i) the ability of a small founder population of BBB to breed and go unnoticed over a long period of time and ii) the difficulty of eradication once established. The following two sections will detail discussions surrounding stage 1 and stage 2 (identified as of greatest importance), respectively. The subsequent stages (stages 3 to 6) which are more associated with domestic or internal parts of the risk pathway, were identified as of lower importance so were not discussed in as much detail. Further work on these stages is required to better understand the internal risk pathways for BBB. A third section discusses the importance of these early stages of introduction.

4.3.2.1 Unprocessed birch wood poses the greatest risk of introduction

Stage 1 is the pre-introduction stage of the BBB risk pathway. This stage consists of stakeholders involved with the sourcing, processing and exporting of birch products to UK. Discussions in the workshop about current methods of importation of birch identified three possible routes of introduction from North America (NA). Route one was through the exportation of birch pellets (mostly) and chips (less so) from NA, which are debarked and highly processed. Route two was through the arrival of birch firewood from Baltic countries to the UK in the form of kiln-dried logs. Bark may still be attached but kiln-drying should kill any BBB. However, BBB is not currently present in the Baltic countries, so route two would first require introduction from NA to Baltic countries before movement into UK. Route three highlighted a potential risk pathway that was not previously identified. This route focussed on untreated / unprocessed birch products entering the UK through online craft retailers or marketplaces via mail service providers. Birch was also noted to enter as dunnage or pallets, which would present a risk if not heat treated. Contamination of processed birch by unprocessed birch could also present a risk, for example sawmill sweepings making it into a shipment of processed wood. Unprocessed birch entering the UK was seen as posing the greatest threat of introductions although it was noted that BBB in its prepupae stage might have the potential to survive some heat treatment. Discussions around stage 1 indicated that although it was assumed that BBB would not survive the processing of birch, there was a need to better understand the pest biology in order to shed more light on potential weak points along the risk pathway during which BBB could potentially survive.

4.3.2.2 Small unregulated birch imports and birch storage

Stage 2 of the BBB pathway is pest introduction which includes stakeholders involved across the entire risk pathway (Table 4, Figure 6). Previous discussions from stage 1 indicated that a plausible route of introduction would be through online retailers, facilitating the importation of unprocessed birch logs arriving in the UK via mail / courier companies. Workshop participants noted that birch logs with the bark attached from NA are often sold as a commodity through online retailers or brought back as a souvenir directly to the UK in personal baggage. These means of introduction are particularly risky because birch products would enter the country without going through the proper phytosanitary checks. If unprocessed logs (as craft items or any other reason) were to enter the UK without undergoing the proper checks, a major concern would be the dilution effect, where one consignment of infested birch wood, be that an ornamental log from an online retailer or an infested piece of firewood, would then be split via distribution to many sites around the country, potentially spreading BBB quickly. Another key point regarding the risk of unprocessed wood was the speed of processing once imported. Wood would need to stored close to a birch source, for BBB to be able to feed and become established. Participants noted that quickly processed birch would present a lower risk than birch stored for extended periods. However, information surrounding how long an imported shipment of birch wood can sit in storage before being processed and or distributed is still widely unknown and unmonitored, posing another potential risk.

4.3.2.3 Importance of early stages in a pest introduction pathway

Participants emphasised that a proactive approach is necessary when it comes to preparing for the potential introduction of BBB into the UK as once BBB is introduced, it is very hard to detect. It was considered that establishment of BBB would likely occur over a 10-year period with two-to-three-year breeding cycles before the symptoms appeared and any visible damage to the tree became apparent. It was also noted that a founder population could be very small and survive, making it even more difficult to detect any BBB establishment in the UK. The adult beetles need a food source close to the site of emergence prior to breeding, and participants discussed how ‘scrubby’ birch is widespread in Scotland and could represent weakened trees more susceptible to infestation. It was predicated that once BBB was established, measures to eradicate the pest could be just as detrimental to the long-term health of native birch population, as the damage from the beetle itself. One participant summarised that once BBB became established, it would be ‘game over’ in terms of control. Participants noted that until more research is conducted to understand how BBB biology would affect its ability to establish and spread throughout the UK, lessons should be learnt from Emerald Ash Borer (EAB) research, such as: that only a small founding population might be required; the presence of a highly susceptible host could be key; and tree symptoms of infestation (canopy thinning leading to death) may take a number of years. If BBB were to make it past stages 1 and 2 of the pathway, participants noted that birch movement would need to be monitored throughout the UK. Participants suggested adopting further citizen science approaches to involve both knowledgeable amateurs and the general public in the monitoring, trapping and identifying of BBB, for example via the Observatree tree health platform. They also noted the need to improve trapping and monitoring technologies and make use of the existing research from North America, including the use of tree girdling. Using targeted surveillance methods at sites of entry such as ports as well as implementing a more general UK-wide monitoring programme could help track BBB distribution and movement.

4.3.3 Data gaps

Gaps in data and knowledge were identified during stakeholder mapping and also highlighted during the workshop:

Alternative sources of birch
- What are the characteristics (including volumes) of logs entering GB with bark attached through micro-sellers (e.g. online crafting trade)?

Potential impact of policy or market changes
- How might changes in the economics of biomass supply chain (production, transport) impact economic incentives to import?
- How might net zero / reduction in fossil fuel use change policy incentives to import?

How birch might be used in the future
- For example, could imported or domestic birch have a role in bioethanol production?
- How could changes in use, change the movement of birch?
- Could an increase in domestic birch use mean more to lose due to an outbreak?

Movement (volume and pathways) of birch within the UK
- How much birch is harvested and sold locally for firewood?
- What are the movements of live birch plants in the UK plant trade?

Knowledge / awareness of the general public regarding pests arriving on logs
- Do end users know or care where birch comes from?
- How would increasing knowledge impact behaviours?
- How effective would citizen science be for monitoring?

Knowledge on biology of BBB
- How better to study characteristics of BBB, as it is hard to locate in native range (although EAB could be used as a proxy)?
- What elements of wood processing (e.g. temperature, dehydration) can be survived by BBB and how?

4.4 Discussion

Our key informant interviews and risk workshop focussed primarily on wood movements in the biomass energy sector (pellets, chips, logs), although other pathways (live trees, art and craft sector) were also discussed. Results suggest that the threat of BBB entering the UK from North America through the biomass sector is currently unlikely. Due to the highly processed nature of birch in the form of pellets which undergo heat treatment and compression, the likelihood of a prepupae BBB surviving this process is seen as very low and workshop discussions around the risk pathway scenarios agreed that the threat of introduction from this highly processed wood is low and that the processed biomass supply chain is relatively secure. However, changes in policy surrounding the use of biomass as fuel in Scotland or the UK or changes in costs of production, processing and shipping of birch may result in risks increasing or decreasing. For example global events (such as EU exit or the war in Ukraine) may impact trade routes and result in birch biomass being imported from different countries, potentially with less rigorous biosecurity measures in place.

Three routes that unprocessed wood might arrive in the UK were noted: 1) online craft retailers who ship birch logs with the bark directly to the UK through mail couriers; 2) undetected spread of BBB to Baltic states, which then export infested wood with bark to the UK; and 3) dunnage or pallets made from birch used in the transportation of goods. There is considerable uncertainty surrounding the volume and frequency (and therefore, associated BBB introduction risk) of unprocessed birch entering through each of these three routes. All routes share minimal processing (through design or error) and would require circumstances favourable to BBB upon arrival. Favourable circumstances for BBB were identified as a period of storage prior to use, long enough for release of BBB and a plentiful supply of food (birch trees) near the site of release. Widespread 'scrubby' birch which is not managed for amenity, forestry, conservation, ornament, or other objectives, whilst growing close to industrial or inhabited areas in Scotland could provide such food. There is a risk of this unmanaged birch being overlooked or unmonitored with respect to tree pests and diseases.

Online craft retailers that sell plant products to the UK from North America pose a potentially high risk of introduction as they could be more likely to avoid phytosanitary checks by bypassing seaports and arriving in much smaller quantities through mail couriers. However, the size and risk of this potential pathway is a clear data gap. As only a relatively small founder population of BBB is required, introduction could begin with a Scottish consumer making an online purchase of a birch log with bark directly from North America, opening the parcel and placing that log in their home or garden for decorative purposes. Large scale imports of birch appear to be predominately highly processed and regulated, whereas small scale imports could slip through the cracks and offer a potential opportunity for the introduction of BBB.

Birch in the UK is used for firewood locally, however, discussions in the workshop noted that it could potentially play a larger role in the biofuel economy as a local fuel source for biomass or in ethanol production as it has a higher sugar content than other deciduous trees. Stricter regulations on the importation of unprocessed birch would help protect against the introduction of BBB through this pathway, with participants noting the example of new regulations that came into place at the end of 2021 for Emerald Ash Borer which (along with regulations associated with ash dieback) regulated the movement of ash throughout and into the UK.

There was broad agreement in the workshop that the focus should be on preventing BBB from leaving its native range, and from entering Scotland or the wider UK. This is perhaps unsurprising as early action is generally desired to perturb all potential new pest species, but it was highlighted that practical difficulties in detection and monitoring for BBB and in treating infested trees were particularly high for the species. The workshop discussion focussed on the early stages of the risk pathway (pre-introduction and introduction); further work is required to understand the internal risk pathway associated with the later stages of a BBB introduction, including internal movement of birch as discussed above.

4.5 Risk reduction planning for BBB incursion

- There is low potential for BBB to survive the processes used to turn birch into pellets or chips for large scale biomass energy production use, and it is therefore unlikely that BBB will enter Scotland via this pathway. However, economic or political impacts (e.g. EU exit or the war in Ukraine) may impact the biomass sector and cause currently unused or marginal products, processes, or pathways, to become economically or politically attractive. *Developing realistic policy and economic scenarios for use in trade modelling could reveal potential tipping points for large scale changes in processed or unprocessed birch imports to the UK.*

- There remains high uncertainty around the characteristics of small pathways of unprocessed birch into the UK from North America, for example as part of the craft trade. Knowledge, awareness, and behaviours of both producers and end consumers are likely to be key. *Investigations are required into the plausibility of this and other small shipment volume pathways for entry of BBB.*

5 Sub-Project 3: Agrilus surveillance methodologies

5.1 Background & Aims

The aims of this sub-project were to:

- Review available surveillance methodologies for *Agrilus* species, and their potential suitability for use with bronze birch borer (BBB, *Agrilus anxius*) in Scotland.
- Assess the potential feasibility and efficacy of using three trap types to monitor *Agrilus* species in Scotland, including their potential for use in BBB surveillance activities.

5.2 Review of surveillance methodologies

The distributions of many insect pest species are expanding, primarily in response to growing global trade and changing climate patterns (Freer-Smith and Webber 2017). The distribution of *Agrilus* beetles, given their abundance and extent, are highly likely to echo this expansion trend. Accordingly, interceptions of *Agrilus* pests are likely to become more frequent. Understanding which trapping approaches offer the best methods for detecting these wood-boring insects and monitoring their spread is therefore crucial.

Of the ten *Agrilus* species recorded in the UK (one of which has yet to be confirmed as established), the majority are restricted to the south of England (Hackston, 2019; Duff, 2020) with only one historic record from Scotland (Curtis, 1840). Although the larvae of these *Agrilus* species feed on plants and trees, their restricted abundance and distribution mean the majority are not considered pests in the UK. The exception is *Agrilus biguttatus*, which is believed to be associated with Acute Oak Decline (AOD) disease, although the role of the beetle is not yet fully understood (Forest Research, 2021).

Bronze birch borer (BBB, *Agrilus anxius*), which damages and kills birch trees in its native and extended range in N. America, is one of a small number of *Agrilus* species that are significant pests. Introduced ornamental birch trees, including European species silver (*Betula pendula*) and downy birch (*B. pubescens*), are particularly susceptible to this beetle. Whereas emerald ash borer (EAB, *A. planipennis*) causes extensive damage and mortality to Ash (*Fraxinus*) species. To date, neither BBB nor EAB have been detected in the UK, although the latter has been recorded in eastern Europe.

Monitoring methods have been developed to detect and assess the population levels of these pest species. The primary methods used to monitor BBB and EAB in North America are purple or green sticky prism traps and green multi-funnel traps (EFSA et al. 2020). As BBB showed no preference between these trap types (Rutledge, 2020), all are potentially suitable for monitoring BBB in Scotland. Traps are normally positioned in the canopy but can also be attached to posts adjacent to trees. Trap captures can be maximised by positioning traps in direct sunlight and BBB captures tend to be significantly higher when traps are placed in artificially girdled (stressed) birch trees (Silk et al. 2020). Discussions with North American researchers during this project indicated that girdling is a key aspect of BBB monitoring and hugely increases likelihood of detecting BBB, especially at low population density (A. Roe, personal communication, 15 March 2022). Other methods, including larval surveys and DNA methods are sometimes used to detect BBB populations, in contrast aerial surveys are rarely conducted for BBB (EFSA, 2020). Surveillance for BBB in the UK and Scotland is therefore likely to rely on the use of monitoring traps.

5.3 Field trials

5.3.1 Introduction

A small feasibility trial testing three trap types was conducted in south Scotland. A larger field study was also conducted to compare the efficacy of two of the trap types, in collaboration with a wider Euphresco project. Due to the lack of *Agrilus* species in Scotland, few, if any, *Agrilus* beetle captures were anticipated. Instead, these trials aimed to gain experience of the logistical practicalities of using these trap types to survey invasive *Agrilus* species were they to be introduced.

5.3.2 Methods

Two field trials were conducted between May and August 2021 within a mixed broadleaf woodland in the Scottish Borders (Grid reference: NT390372). In total three trap types were tested (purple and green sticky prism traps and green Lindgren multifunnel traps), see Table 5. For the feasibility trial, three traps (one replicate of each type) were deployed in birch trees and assessed four times over six weeks. For the trap comparison trial, 10 replicates of two trap types were deployed in oak trees and assessed between four and seven times over 14 weeks.

Table 5 - Details of the three trap types assessed in two field trials in Scotland for their feasibility and efficacy for monitoring Agrilus beetle species

Treatment		**Trial**	
Trap type	**Colour**	**Feasibility**	**Trap comparison**
Sticky prism trap[1]	Purple	1 replicate	Not included
	Green	1 replicate	10 replicates
Lindgren 12 funnel, Fluon coated multifunnel trap[2]	Green	1 replicate	10 replicates

[1]Supplied by Sylvar Technologies Inc., www.sylvar.ca
[2] Supplied by ChemTica Internacional, www.chemtica.com

Equipment list: slingshot system, rope, pulleys, extendable ladder, telescopic pole, GPS, vertex, diameter at breast height (DBH) tape, Toughbook®, traps (including all components), weights, 50% propylene glycol solution (diluted with tap water), collection tubes, labels, camera, assessment sheet, sieve, tweezers, waterproof pens.

Setting up process. Three birch trees and twenty oak trees of a suitable height and position were chosen: 16-24m high, a minimum of 20m between trees and with branches in open canopy, avoiding extreme shade. Birch DBH varied from 25cm to 32cm, oak DBH varied from 40cm to 72cm. A slingshot system was used to set up canopy ropes and pulleys in each tree. Each trap was assigned to a tree, attached to the ropes, and raised to the mid-canopy (6-10m high).

Trap assessment process. The sticky prism traps were assessed by inspecting the three sides of the trap for beetle specimens. If present, tweezers were used to remove individual beetles and place them into a small collection tube containing 50% propylene glycol solution. The multi-funnel traps were assessed by transferring the collection cup contents to a medium collection pot on site. Specimens / samples from both trap types were transported to the Entomology lab at FR's Northern Research Station (NRS) for inspection and identification.

5.3.3 Results

Unsurprisingly, given the lack of known records from Scotland, we caught no native or non-native *Agrilus* species in any of the traps. We did, however, catch a large number of non-target invertebrate species in all trap types, see Table 6.

Table 6 - Average numbers of non-target invertebrates caught in total and per week in each of the three trap types tested

Trap type	Average number of non-target invertebrates caught	
	Total	**Per week**
Purple sticky prism trap	c. 4,000 per trap (over 6 weeks)	c. 650
Green sticky prism traps	c.10,000 per trap (over 14 weeks)	c. 700
Green multi-funnel trap	c. 550 per trap (over 8 weeks)	c. 100

We recorded several observations regarding the feasibility of setting up and assessing the traps, which are outlined in Table 7, Table 8, and Table 9.

Table 7 - Observations: general

Observation	Comments
Heavy / bulky equipment	The traps plus the equipment required for setting up and assessing them were unwieldy and / or heavy (particularly the extendable ladder). Two to four people were required to set up the experiments, including carrying equipment onto and around the site. This may cause issues on other, more remote, sites depending on vehicle access.
Labour / time requirement for set up and assessment	Traps were deployed in the mid-high tree canopy using a slingshot system. Each trap took 30-45minutes to set up (10 x traps = 5-7.5hrs). Each trap took 15-30minutes to assess. It took two people 5-7 hours to assess 20 traps in one woodland. This does not include time taken to travel to site.
Training needs identified	Several training needs were identified during the field trials: using the slingshot system, safe use of extendable ladders in forests, and insect identification.

Table 8 - Observations: sticky prism traps (green / purple)

Observation	Comments
Handling sticky traps	Traps were supplied in pairs that were stuck together face-to-face and needed separating and assembling on site. The traps were difficult to handle as the glue was incredibly sticky. It was particularly difficult to transport the traps once separated. This could be avoided by deploying a minimum of two traps per site, although this would have obvious cost implications. The sticky surface readily picked up debris (leaves etc.) and attached to other surfaces (vegetation, clothing etc.).
Lightweight traps	The traps were lightweight, which made hoisting them into the canopy easier, but meant they tended to blow around in the wind and got stuck in tree branches. It also hindered assessments as the traps were too light to drop down, this was counteracted by adding weights to the metal trap hanger. In future, we recommend traps are positioned a reasonable distance (3m+) away from the trunk and on a branch that is unobstructed by other branches.
By-catch	These sticky traps caught a large amount of by-catch. It would have been prohibitively time-consuming to individually remove all the specimens during an assessment. Instead, the traps were checked for beetle (Coleoptera) species and only these were collected. This method requires the assessor to have reasonable insect identification knowledge and skills. A minimum requirement is the ability to identify the target species. Bronze birch borer (*Agrilus anxius*) is similar in appearance to some native British *Agrilus* species and would therefore be harder to differentiate than other more distinctive species (e.g. Emerald ash borer, *Agrilus planipennis*). The by-catch impacted the efficacy of the trap, which dropped over time as the sticky surface became covered in invertebrates leaving less available surface area for subsequent captures. (For reference it took c.2-4weeks for the trap surfaces to become well covered in this trial). As these specimens weren't removed, they also started to disintegrate and / or go mouldy after several weeks. This may impact subsequent captures, by either repelling or attracting different species (e.g. carrion specialists). These impacts may be somewhat reduced by timing trap deployment with the activity period of the target species. For example, *Agrilus anxius* adult emergence is temperature-dependant and varies between May - July in N. America (Muilenburg & Herms, 2012). Further work is required to predict BBB adult emergence in a Scottish / UK climate. The on-site identification of specimens enables suspect target species to be flagged early, although verification via a lab would require more time.
Insect identification	Identification was hindered by captured specimens being coated in the thick sticky glue. This masked key identification features or caused their removal during collection. These issues are more problematic for identifying soft bodied inverts (e.g. flies) than beetles, but the loss of antenna or legs may cause issues in separating *Agrilus* species. For example, BBB ID features include size, colour, and small details on sections of the abdomen. During this project the following product has been recommended for removing glue: Histo-Clear II Histology Clear | NAT1334 | INAT006 | SLS (scientificlabs.co.uk).
Non-recyclable waste	These traps are single-use plastic that cannot be reused and therefore get thrown into general land fill after one season of monitoring.

Table 9 - Observations: multi-funnel trap (green)

Observation	Comments
Easier handling than SP traps	Operationally the multi-funnel traps were easier to set up and assess than the sticky prism traps. Rather than needing to identify and collect individual specimens in the field, the entire contents of the multi-funnel collection pot was emptied into another pot and returned to the lab for identification.
Training requirement	Although this collection method was easier in the field, it increased the laboratory time required to sort and identify the specimens caught. This process was time consuming and required a skilled entomologist with access to a microscope. Again, a minimum requirement is the ability to identify the target species. This method had the disadvantage of delaying the identification of specimens until the lab work had been completed. Use of this method may delay the verification of a target pest (i.e. BBB).
By-catch	Trap modifications (using chicken wire) are required to prevent bat captures. The multi-funnel traps caught fewer non-target species than the sticky prism traps, the majority of which were invertebrates.

5.3.4 Discussion

5.3.4.1 Trap feasibility

Despite being heavier, the multifunnel trap was generally more straightforward to deploy in the field than the sticky prism trap. The large sticky surface of the latter hindered handling and therefore deployment. Due to lethal bat capture incidents, the multifunnel traps require modifications prior to deployment, whereas this has not been reported for the sticky prism traps. More preparation time is therefore required to set up the multifunnel traps. From a practical perspective any trap system aimed at monitoring *Agrilus* adults will require deployment in tree canopies, which will incur certain equipment and time requirements. The advantage of the stiky prism traps is that they can be assessed in the field (invertebrate captures are visible) and therefore give an early warning of positive *Agrilus* pest captures. Invertebrate captures collected in the multifunnel traps tend to be higher, increasing the likelihood of Agrilus captures. However, these can not be easily assessed in the field, instead requiring laboratory verification. This delay in results may delay action were a pest species to be found. As neither trap type offers an optimum solution, either could be used to monitor *Agrilus* pest species, with the sticky prism traps being better suited to early detection and the multifunnel trap offering a more reliable population assessment.

5.3.4.2 Trap efficacy for Agrilus monitoring

In Scotland, both the sticky prism traps and the multifunnel traps caught invertebrates, including beetles, but not any *Agrilus* species. In parallel trials conducted elsewhere (England, Europe, and North America), however, *Agrilus* species were caught in both trap types. This included BBB and EAB captures in all trap types in the known North American ranges of these *Agrilus* species. Preliminary results are however inconclusive, and it is not yet clear if one trap performs better than the other, or if certain *Agrilus* species prefer a particular trap type. A clearer picture may emerge once all results have been collated. Results so far indicate that other factors (such as trap position and climatic conditions including temperature and sunlight) influence the abundance of *Agrilus* captured so these should be considered in future trials. For example, higher *Agrilus* captures were reported from traps in open canopy and direct sunlight than from traps positioned in closed canopy and shaded positions (D. Williams, personal communication, 13 January 2022).

These preliminary results reflect findings from other *Agrilus* surveillance studies which tend to focus on EAB and BBB. Of these species, more research has been conducted on EAB, reflecting the invasive and more destructive nature of this pest in North America. Key findings from previous studies are summarised below.

EAB captures are impacted by trap height, with higher catches reported from traps 6m above ground compared to 1.5-2m above ground (Ryall et al. 2012). Higher EAB captures were also recorded in traps positioned in higher Ash densities (Tobin et al. 2021).

The most efficient type and colour of trap for EAB monitoring is inconclusive with some studies reporting higher captures in purple sticky prism traps (80% detection rate) compared to girdled trap trees (47% detection rate) and green sticky prism traps (42% detection rate) (Marshall et al. 2010). Whereas other EAB studies found green sticky prism and green or purple multifunnel traps were as good as or better than purple prism trap (Francese et al. 2011; Tobin et al. 2021). Black multifunnel traps were not effective (Francese et al. 2011). Another study found green multifunnel traps were most successful at catching EAB, especially when treated with a fluon coating (Francese, Rietz, and Mastro 2013). Larger multifunnel traps (12-16 units) were also found to capture more EAB beetles than smaller (4-8 unit) traps (Francese, Rietz, and Mastro 2013).

Results of BBB trap preference are not much more conclusive, Silk et al. (2020) found un-baited purple sticky prism traps placed in girdled trees (*Betula papyrifera*) caught more BBB (*A. anxius*) than traps baited with synthetic lures. Further tests found green sticky prism traps caught more than purple or white sticky prism traps. In a comparison between purple prism traps and green multi-funnel traps hung in girdled and non-girdled birch trees and ash trees, however, Rutledge (2020), found that neither EAB nor BBB showed a preference between trap types. Although higher BBB and EAB captures were recorded in their corresponding host tree. Girdling also increased the number of BBB, but not EAB, caught in traps. Non-target *Agrilus* varied in trap preference. The native North American ash borer (*A. subcinctus*) strongly preferred green multi-funnel traps hung in ash trees whereas *A. bilineatus*, the two-lined chestnut borer, preferred purple prism traps.

A broader review and meta-analysis (Allison and Redak 2017) of the efficacy of different trap types and designs found green and purple traps both caught *Agrilus* beetles (including *Agrilus planipennis* (EAB), *A. graminus*, *A. obscuricollis*, *A. laticornis*, *A. sulcicollis*, *A. fallax*, *A. angustulus*, *A. egeniformis*, and *A. egenus*). BBB (*A. anxius*) was not included in this analysis. Overall purple traps captured more individuals than green traps.

It is worth noting that available monitoring traps sometimes fail to detect *Agrilus* populations at all, particularly at low densities, as demonstrated by Mercader, McCullough, and Bedford (2013) who found EAB larvae in detection trees (girdled Ash trees which they debarked) despite no or low captures in adjacent baited sticky prism traps.

5.3.4.3 Recommendations

The US and Canadian governments run EAB management programmes which include the use of sticky prism and multifunnel traps to monitor the distribution of this invasive beetle (NRCAN 2021; USDA 2022). An equivalent surveillance programme does not, however, exist in North America for BBB and minimal monitoring for this pest is undertaken using traps or any other method, simply because BBB is a native species found across the entirety of North America wherever birch grows. Visual detection methods are instead used to identify trees showing signs of infestation (i.e. dieback, D-shaped holes, woodpecker damage) (Katovish et al. n.d.).

Despite no single BBB monitoring method being deployed in North America, research shows that sticky prism and multifunnel traps are both suitable methods for detecting BBB. The former being lightweight and quick to deploy and assess are best suited early detection objectives, whereas multifunnel traps have higher captures therefore offer a more robust method. Although a BBB lure has not been developed, the volatiles released by artificially girdling birch trees have been found to increase BBB trap captures and is therefore also recommended.

Several priorities for further research have also been identified. European and North American Euphresco project partners plan to undertake further testing of sticky prism and multi-funnel traps in 2022 to better establish the efficacy of each trap and potential *Agrilus* species preferences. Traps will be tested with and without *Agrilus* lures. These results will further inform suitable BBB trapping methods. Opportunities to develop alternative *Agrilus* trap types, particularly methods that reduce by-catch captures, would be beneficial. It is recommended that further trap development considers the morphological (e.g. colour and size) and behavioural traits of the target species. Since completing the trap trial another trap has been identified, which potentially offers a more useable alternative (MULTz trap, http://www.csalomontraps.com). Any alternative trap designs would need to be tested against sticky prism traps and multifunnel traps in fully replicated trials and shown to be effective against these tried and tested methods. The practical issues encountered during this trial, such as handling the sticky prism traps and efficient methods to deploy traps in the canopy, should also be addressed if new traps are developed. The use of aerial surveillance could potentially be useful for detection of BBB in Scotland, however a detailed assessment of logistics (including costs) would need to be undertaken as birch would be particularly difficult to survey due to its ecology - deciduous, relatively small in size, widespread in mixed or scrubby areas rather than as a continuous forest block.

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