Department
for Environment
Food & Rural Affairs

Conserving our ash trees and mitigating the impacts of pests and diseases of ash:

A vision and high-level strategy for ash research

June 2019

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Ministerial foreword

Ash trees are a precious, widespread, and much-loved feature of our landscapes, providing beauty and value to our rural and urban settings alike. They are home to almost 1000 other species including birds, insects, mosses, fungi and lichen and their wood is highly valued to make tools and furniture. The beauty of our ash woodlands cannot be monetised but we have calculated their social and environmental value at over £230m per year.

In common with other trees, the ash is under threat from pests and diseases. Ash Dieback was first discovered in 2012, but it is likely it arrived at least 10 years before that. Most parts of the country are now experiencing the impact of ash tree decline. Emerald Ash Borer is not present in the UK but has caused significant damage in North America and is moving west from Russia towards Europe. It is imperative that we do all we can to arrest these threats.

In May 2018 Defra launched the Tree Health Resilience Strategy - a landmark publication that sets out plans to protect England's trees from pests and diseases to meet our 25 Year Environment Plan pledge to be the first generation to leave our environment in a better state than we found it. The strategy sets out a new proactive approach to tree health with landowners, charities, the public, scientists and government working together to take actions to build resilience against pests and diseases to protect the nation's trees. That approach provides the foundation for this Vision and High-level Research Strategy for Ash.

Since 2012 government has invested over £6 million in research to protect the ash from pest and disease threats. As well as basic research into the biology and pathology of the disease, we have sequenced the ash genome and the Ash Dieback fungus. Good progress has been made in screening for tolerant trees and conserving the genetic diversity of our native ash trees. We have worked closely with those managing ash on the ground to develop management approaches and toolkits, and have identified alternative species to provide the ecological benefits of lost ash trees. It is now appropriate to take stock of what has been achieved and to identify what further research is required.

In this research strategy we lay out priority themes for research. Addressing these research needs will ensure the best possible management of the immediate impacts of ADB and an optimal response to any incursion of EAB. In the longer term, the research themes will deliver the restoration of our landscapes. Defra is already committed to several key research activities. For example, we are supporting the development of both a new nationwide map of ash using remote sensing technologies, and an early warning system for Emerald Ash Borer that takes into account where and how the pest might arrive. In early 2020 we will be establishing the UK's first archive of trees tolerant to Ash

Dieback and will continue efforts to screen for more such individuals. Genomics will continue to play a key role to understand and identify tolerance.

I thank all those funders, stakeholders and researchers that have contributed to the development of this strategy and look forward to working collectively to achieve the vision of this strategy - to retain native ash in our landscape for future generations to enjoy.

Gardiner of Kimble

Lord Gardiner

Parliamentary Under Secretary of State for Rural Affairs and Biosecurity

Chapter 1 - Introduction

Purpose

The primary purpose of this research strategy is to consolidate existing knowledge in relation to pest and disease threats to ash and their management, and to identify key research needs for the future. By identifying priority research themes and research activities within these themes, the strategy should provide a road map for research to support delivery of Defra's ash policy priorities in the immediate (1-5 years) and long term. It is hoped that this roadmap will inform the investment decisions of research funders and the priorities of researchers across the UK and beyond.

The strategy has been developed in collaboration with stakeholders including academics and practitioners who will deliver evidence and practical actions to protect our ash populations and to minimise the wider impacts of pests and disease on ash. Our aspiration is to deliver a research roadmap which is feasible and user-focused, generating practical solutions for the threats we currently face as well as helping us to be prepared for and resilient to future threats.

This strategy should be implemented within the wider framework of the Tree Health Resilience Strategy, and for this reason does not include wider actions to improve the resilience of our trees and woodlands.

Context

Ash trees form a vital part of our treescape but are under considerable threat from Ash Dieback (ADB), which has swept through Europe and was first identified in the UK in 2012 (although evidence confirms the disease has been present here for at least 10 years prior to this). Since then, considerable investment and effort has been spent in building our understanding of the pathogen, how ash trees are affected by the disease, and the wider impacts and potential mitigation actions. Six years on it is timely that we take stock of what we have learned and identify future direction for the research, taking into account recent policy updates.

This strategy presents an opportunity to learn from our experience of ADB and to ensure that our ash trees are resilient to additional future threats. In particular, Emerald Ash Borer (EAB), which has devastated ash trees across North America, presents a looming threat and will be a key focus for future studies.

Policy context

The government's 25 Year Plan to Improve the Environment set out actions to meet the government's ambition to be the first generation to leave our environment in a better state than we found it. Through the plan, government recognises the need to enhance biosecurity and build the resilience of trees to withstand pressures.

In May 2018, Defra published the Tree Health Resilience Strategy (THRS). The THRS aims to support action to strengthen our treescape to withstand pests and diseases, whilst reducing the impacts of other pressures such as climate change, and limiting the entrance of new biosecurity threats where possible. It presents three desired outcomes, set within a resilience circle comprising three segments:

- Resistance: Reducing the threat or absorbing the impact of a risk with no substantial change or loss to the treescape[1]

- Response and Recovery: Facilitating a speedy response when threats do occur, and allowing our existing trees to recover wherever possible after a pest or disease has been eradicated or contained

- Adaptation: Driving long term changes which will strengthen our natural resource and favour the survival of our trees and woods, supporting landscapes in adapting to established pest and diseases

The THRS outlined priority areas for focus, including a commitment to develop and apply a robust interdisciplinary evidence-based approach to risk management. It also recognises the need to build the knowledge and capability to apply the concepts of resilience at all levels. This document will draw on these concepts of resilience to set out our road map for delivering a holistic evidence base for ash.

The THRS presents a case study on ash and identifies some key priority actions to secure the long-term future of our nation's ash trees. These include continuous review of the risk to ash, through the Plant Health Risk Group, a task group of Local Authorities and landowners to manage the impact of ADB on the ground, and an EAB Preparedness Board to ensure a swift and effective response should the pest enter the UK.

More recently Defra policy objectives for ash have been further developed within the resilience circle framework

[1] Note this doesn't include breeding trees resistant to a threat, which is covered under adaptation.

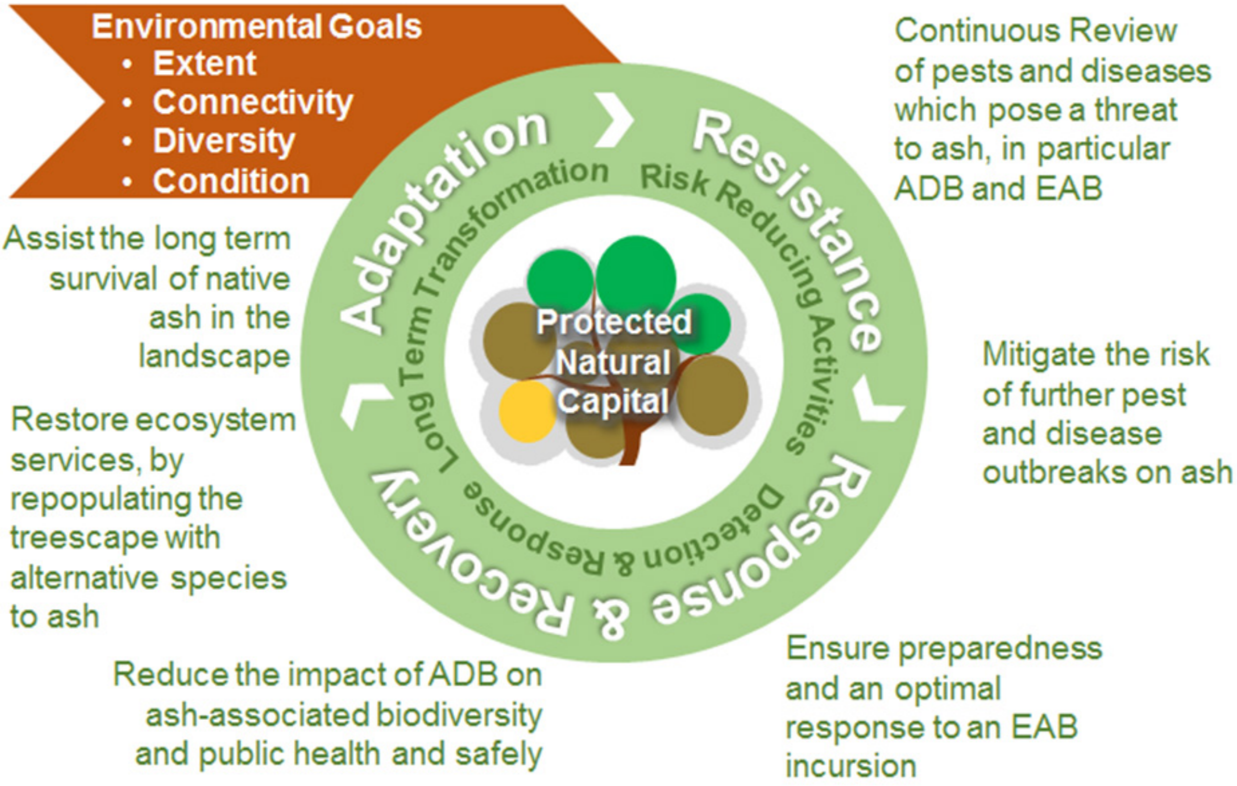


Figure 1: Policy objectives for ash developed within the resilience circle framework

The policy objectives include:

- assisting long term survival of native ash in the landscape
- restoring ecosystem services by repopulating the treescape with alternative species to ash
- reducing the impact of ADB on ash-associated biodiversity and public health and safety
- ensuring preparedness and an optimal response to an EAB incursion
- mitigating the risk of further pest and disease outbreaks on ash
- continuous review of pests and diseases which pose a threat to ash, in particular ADB and EAB

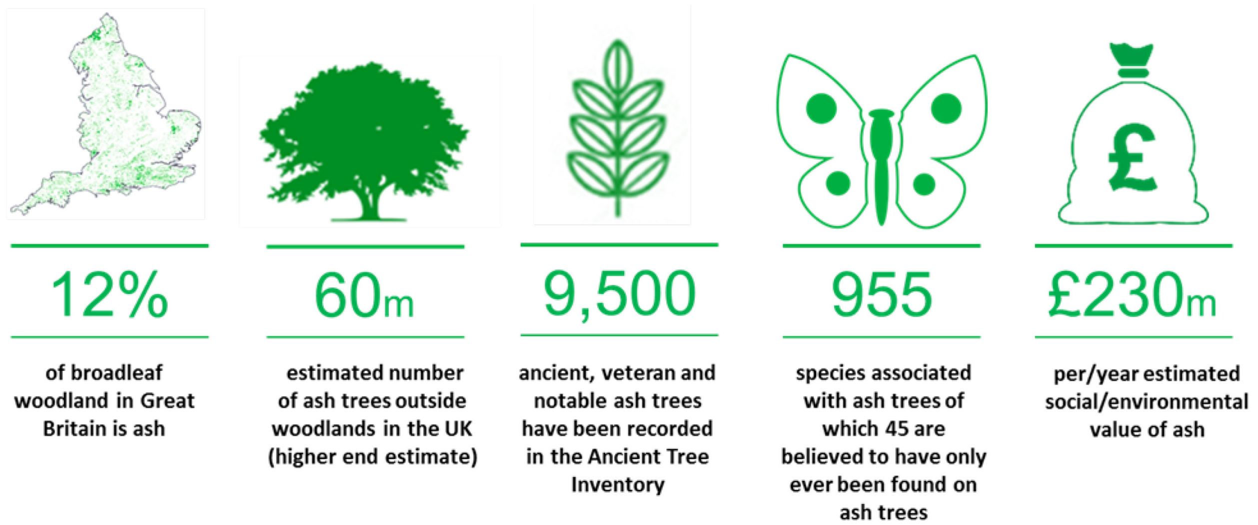
Definitions

This strategy is focused on the management of *Fraxinus excelsior*, known as European ash or common ash. Throughout we use the word ‘ash’ to refer specifically to this species, which is the only *Fraxinus* species native to the UK.

Throughout this document we use the word tolerance to refer to all mechanisms by which ash trees have low susceptibility to ADB and/or EAB.

Chapter 2 - What we know

By adopting a holistic approach through the THRS, our aspiration is to generate research and supporting action which ensures that our ash population is resilient to and able to withstand a range of potential future pest and disease threats, including those which are not yet on our horizon. However, the Plant Health Risk Register which assesses the threats posed by over 1000 pests and pathogens identifies that ash dieback and emerald ash borer currently present the greatest threats to ash. Evidence summaries have been produced covering what is known about ash, and these threats to it and are provided in the annex to this document. There follows a high level summary of what is known, drawn from these documents.



Fraxinus excelsior is a large tree, native to the UK and found across much of mainland Europe. In Britain, ash is the second most abundant tree species in small woodland patches after the native oak species, the third most abundant in larger areas of forest and the most common hedgerow tree species. Outside of woodlands, ash grows, or is planted, in hedgerows, next to roads and railways and in urban environments. It is estimated that there are 125 million ash trees in woodlands and between 27-60 million ash trees outside of woodlands in the UK, plus potentially 2 billion saplings and seedlings in woodlands and non-woodland situations.

Ash wood is highly valued for specialist uses such as tool handles and furniture, as well as for firewood, making ash timber one of the most valuable native hardwoods.

Ash also fulfils important roles in supporting biodiversity and ecological functioning which no single alternative UK native tree species will be able to provide. 955 species are associated with ash trees, of which 45 are believed to have only ever been found on ash. Ash woodlands typically also support a rich and diverse ground flora. Compared to other trees, ash encourages faster litter decomposition which results in relatively low carbon, and high nitrogen concentrations in the soil.

Ash dieback (ADB)

Ash dieback is caused by the fungus *Hymenoscyphus fraxineus*, which originated in Asia and is now widespread in Europe, causing the large-scale loss of European ash trees. Genetic analysis has demonstrated that the European population of *H. fraxineus* has low diversity, indicating a small number of introductions into the region to date.

Ash dieback was first officially recorded in England in 2012 but the fungus had already been present in some locations since at least 2004, and is likely to have arrived in the UK on both infected planting material and as airborne spores.

Trees are infected with *H. fraxineus* via air-borne spores produced from fruit bodies. The fruit bodies occur in the summer, mostly on infected fallen leaves in the leaf litter. Moist conditions favour the production of fruit bodies. Once the spores infect the tree leaves, the fungus grows into the woody material and causes the characteristic diamond shaped lesions. Repeated infection of the woody material from the leaves causes crown dieback and drives mortality.

In larger trees, especially on wet sites, *H. fraxineus* is also able to cause basal lesions at the root collar, often associated with secondary pathogens such as Armillaria, making the trees structurally unstable. In some cases basal lesions have been observed on trees with minimal crown damage.

Whilst the disease is naturally spread via airborne spores, it can also be spread via the movement of infected trees through trade or through movement of fallen leaves.

H. fraxineus has infected many species of *Fraxinus*, but with differing intensities. *F. excelsior* appears to be one of the most severely affected species. The pathogen has been identified on alternative hosts in the UK, but these are not native or commonly planted species and it is not yet known if it can complete its life cycle on these hosts.

Predicting mortality rates in mature ash trees is difficult as the disease progresses slowly. One recent analysis of data across Europe found that the maximum mortality recorded so far was~85% in plantations, ~70% in woodlands and ~82%in naturally regenerated saplings.

Observations in the UK and Europe have suggested that 1-5% of the ash population may be usefully tolerant to *H. fraxineus*. While there is no evidence of full resistance to the pathogen, this natural tolerance in some individuals across populations provides an opportunity to maintain ash in Europe. The tolerance seems to be partially heritable which offers hope for a future breeding programme. The ash genome has been sequenced and studies have started to identify genetic markers which may play a role in tolerance. Both spectroscopy and inoculum methods have been explored as means to quantify tolerance in ash trees.

Whilst tolerance exists, the climate and site appear to play a large role in how trees succumb to the disease, including soil type, and moisture, air humidity, temperature, stand age and stocking density. The disease has been observed to progress quickly in young trees, trees growing in stressed conditions and in ash dominated woodlands with higher levels of leaf litter and consequently spore loads. Fewer symptoms have been observed so far in ash trees growing on well managed open sites, such as parklands. Basal lesions represent a different infection pathway to crown dieback but their incidence also has a genetic component. For these reasons, the impact and required management of ADB is expected to vary considerably by site and context.

There is limited evidence around viable management options for ADB. It is unlikely that hypovirulence could be effective as a biological control tool. Removal of leaf litter may be an effective way to reduce the level of inoculum in urban environments and fungicides may have a small role to play in treatment and prevention, for example in nurseries. Natural regeneration will encourage the process of natural selection for tolerance, so healthy trees should be maintained for as long as possible to ensure regeneration from tolerant mother trees.

Emerald ash borer (EAB)

Ash trees are also under threat from the EAB, (*Agrilus planipennis*), a pest from eastern Asia. The beetle was first detected outside Asia in 2002 when it was found in USA and Canada. Despite intensive efforts to eradicate or contain the pest it has since spread to 34 states in USA and 5 provinces in Canada where it has caused mortality to tens of millions of ash trees and loss of ecosystem services, resulting in hundreds of millions of dollars of economic losses. The pest was first confirmed in Europe in Moscow in 2005 and continues to move west. It has been reported close to the borders of Ukraine and Belarus.

Adult beetles emerge from host trees, by chewing characteristic D-shaped exit holes, usually in spring. The adults live for three to six weeks in which time they feed on the foliage of ash trees, and after mating, females lay eggs in bark crevices and cracks. Once the eggs hatch, larvae begin burrowing into the trees’ cambium layer to feed, damaging the ash trees in the process. As the densities of larvae within the tree increase, symptoms become more visible with thinning and discolouration of the canopy, branch death and tree mortality. Usually the beetle has a one year lifecycle but this can extend to two years under some conditions which still require investigation.

EAB feeds on a wide range of *Fraxinus* species, with species in the USA such as *F. pennsylvanica, F. americana, F. nigra* being particularly susceptible. *F. excelsior* is considered to be moderately susceptible, but the susceptibility of trees infected with ADB is unknown. Genomic studies have identified some possible candidate genes for tolerance to EAB.

Spread of EAB occurs via long-range human assisted transport and short range natural dispersal. Estimates from the USA indicate that natural dispersal can be dependent on the availability of ash trees. Human assisted transport through the movement of infested material, usually firewood, has played a significant role in further spread.

The cryptic lifecycle of the beetle and the delay in observable symptoms mean visual surveillance is likely to be ineffective for early detection of EAB. Girdled trees and branch sampling are sensitive but invasive methods of detection used in USA and Canada, where baited traps are also used.

Eradication is only likely to be possible for localised outbreaks where the beetle has not had time to spread. The principle method of controlling EAB is through felling of ash trees and restricting the movement of susceptible material. Tree injections have been used to protect high value trees in Canada and USA but are not currently approved for use in the UK. Four non-native parasitoids have been released in the USA and are having a positive impact on ash recovery*. Spathius polonicus*, a parasitoid of EAB identified in Russia may also be of value.

Movement restrictions of ash trees, branches, logs and firewood, accompanied by a public awareness campaign in the USA have shown value in reducing spread.

Chapter 3 - Collaborative working and achieving impact

Approach and impact of work to date

The THRS outlines the importance of access to robust evidence to provide the foundation for decisions. Our interdisciplinary evidence base combines a long term programme of strategic research with more applied, responsive studies.

Since 2012 Defra, UK research councils and others have invested in research around pest and disease threats to ash. UK researchers have contributed substantially to the global knowledge of these risks and their management, whilst also developing better understanding of the unique needs of the UK context. Strong links have been developed with stakeholders who are managing impacts of ADB on the ground to ensure research is appropriate and applied.

Much of the Defra funding has been provided as contributions to collaborative research programmes. For example, several projects on ADB have been supported through the Tree Health and Plant Biosecurity Initiative (THAPBI), co-funded with support from BBSRC, ESRC, Forestry Commission, NERC and Scottish government. In addition, with BBSRC, Defra funded the Nornex consortium of British and Scandinavian scientists which worked on better molecular understanding of ADB disease (2012-2015). Defra has also supported various PhDs in collaboration with a range of other funders, including Network Rail and the Woodland Trust.

British researchers have collaborated closely with European colleagues via their participation in European programmes such as FRAXBACK. International collaboration has been developed through the EUPHRESCO network, which has funded inter alia the PREPSYS project bringing together researchers from North America and Europe to develop preparedness for EAB.

Research with impact - key principles

Consistent with the THRS, open and collaborative working between government, industry, landowners, forestry and arboriculture professions, the research community, tree and environmental charities, and the public will continue to be vital to achieving the maximum impact from research. This will ensure that developments in our understanding of problems and their potential solutions are shared and implemented by a wide range of stakeholders. This means that ash research must be closely linked into action on the ground. To achieve this we have identified a set of principles for high impact research which will underpin work across the Strategy.

1. **Involve stakeholders in research design and delivery**
   Much of the research outlined in this strategy offers opportunities to work with stakeholders throughout the research process, including research and experimental design, data collection, analysis and interpretation. This is especially the case with research that involves field-based experimental work where close working with stakeholders should allow management responses informed by science to be trialled and tested, facilitating direct feedback to tree and woodland owners and managers, and the co-development of management best practice.

2. **Think and act in the short and long term**
   Truly understanding how ADB (and potentially EAB) acts in different contexts, and the impacts of different response, recovery and adaptation actions will require in-depth, long-term study and monitoring sites. However, action in the short term is needed to minimise threats. Researchers and practitioners must work together to design and implement management responses in the short term that can be monitored, evaluated, tested and refined over the medium to long term.

3. **Maximise collaboration across borders**
   It is vital that work on EAB and ADB is developed in collaboration with international stakeholders and researchers. The UK has much to learn from the research and management experiences of countries with longer histories of living with ADB and EAB. There are also opportunities for the UK to contribute to the international effort to gather evidence and improve shared understandings of host-pathogen/pest interactions in different contexts. Particular effort should be made to facilitate and incentivise collaboration between scientists and stakeholders in countries across the likely pathways of EAB. It is also imperative that research is coordinated and results shared between all countries within the UK.

4. **Facilitate more and better fundamental science**
   Success will require activities to encourage a wide range of interdisciplinary researchers with different skills and experience to engage with this strategy in order to increase the pool of expertise and develop more innovative and ambitious solutions. This should be encouraged by improving the research infrastructure, for example through increasing availability of trial sites, and recognition of the particular need for long term studies. Technology transfer from other sectors will also be important. Interdisciplinary working between the natural and social sciences will be needed to ensure evidence-based policy and management solutions are co-produced, tested and refined.

5. **Better co-ordinate the resources that we have**
   Significant progress has already been made but research outcomes could be more impactful if they were more joined up. For example, a key research theme relates to making survey networks more joined up. It is also important that all

research outputs are widely shared, including with policy makers, in order to maximise impact.

6. **Capture the learning**
   Many of the issues faced today with respect to ash have been faced before, for example with Dutch Elm Disease. It will not only be important to make the best use of existing data, but also to learn from tried and tested research methodologies and past experiences of delivering research-based solutions. It is also vital to start to capture data better and generic lessons from this experience for the future.

7. **Tell the Story**
   We need to get much better at telling the story of ash and threats to it, in order to develop a nation that understands the issues and wants to get involved in the solutions. This includes better communication of the values of ash, and of the threats from ADB and EAB. It is important that interested individuals can find accurate information so key webpages and data resources should be designed to be kept up to date and research outcomes shared publicly.

Chapter 4 – Future research areas

Having identified what evidence is already available with regard to the risks to ash, this chapter seeks to outline what future research will be required to support our ash policy objectives, using the resilience circle approach. For each section of the resilience circle we note the overarching aim from the THRS, and also the corresponding policy aims. We then propose research themes which are intended to suggest areas of work to meet key evidence needs. Each research theme includes a description of the current key evidence gaps and why they are important, and also suggests additional areas of research that might be useful. We have not prescribed specific activities to be completed under each theme as specific evidence needs in each theme will change over time, but overarching outcomes are described.

Resistance: Reducing the threat or absorbing the impact of a risk with no substantial change or loss to the treescape

Policy aims

- Continuous review of pests and diseases which pose a threat to ash, in particular ADB and EAB
- Mitigate the risk of further pest and disease outbreaks on ash

Proposed research themes

1. **Further understanding of the biology of pest and disease threats to ash, with a focus on ADB and EAB**

   Ongoing work is required to continue to understand the threats posed to ash by pests and diseases, focusing on all potential forms and adaptations of EAB and ADB. It is particularly important to understand the interaction between the two threats, through studies in places such as Russia where they are co-existing on novel hosts, and to predict how this interaction is likely to play out in the UK environment. Understanding may also be informed through studies in the native range. Understanding potential tolerance of our ash trees to EAB will enable better planning for an incursion.

2. **Develop better evidence on risk pathways for EAB**

   Studies to model international risk pathways should provide evidence to identify key risks and how best to direct prevention measures. These would cover all kinds of trade pathways (formal and informal) including firewood and other products. It is also important to model domestic risk pathways including entry points and distribution networks to identify high risk sites where we can deploy sensitive methods of detection. Such modelling studies require scoping work to assess the availability of data, and analysis to map the range of stakeholders along risk pathways and understand their motivations, constraints and level of engagement with biosecurity.

If these pathways were coupled with data on ash in the landscape it would be possible to create risk maps. It would also be useful to assess the costs and benefits of different prevention measures. Further work might develop better understanding of the major social, economic and environmental drivers in the risk pathways and how these could change the risk pathways in future

It is vital that the outcomes of this research provide the basis for actions to build awareness of these threats and how risks can be minimised.

3. **Develop an optimal early warning system for EAB**

   Building on the evidence developed in theme 2, further studies should assess how best to monitor the spread of EAB in Europe, taking into account existing sentinel networks. It is also important to optimise detection methods such as girdling, traps and other technologies, for use at high risk sites in the UK. Analysis of relevant professional and amateur stakeholders, their capacity to contribute to detection (and surveillance), and the means to maximise their contribution, in order to improve chances of noticing a first incursion.

Response and recovery: Facilitating a suitable response when threats do occur, to allow our existing trees to recover wherever possible.

Policy aims

- Ensure preparedness and an optimal response to an EAB incursion
- Reduce the impact of ADB on ash-associated biodiversity and public health and safety

Research themes

4. **Develop detailed mapping of the distribution and health of ash, and understand how environmental factors influence ash tree health.**

   A priority evidence need for effective responses to ADB and EAB is better mapping of ash across all environments, and monitoring of disease progression and impact. This will require the development of more standardised, structured and joined up long-term monitoring approaches, optimising use of stakeholders, citizen science networks and technology. Further approaches should develop better understanding of the extent to which we can anticipate likely ADB/EAB impact or progression based on site factors (site type, species composition and diversity, ash density, aspect, soil, mycorrizal fungi, associated micro-organisms, grazing etc), and assess whether such knowledge would make it possible to classify sites to aid risk assessment and management decisions. This should take into account how ADB disease impacts and progression vary between basal lesion and canopy infection routes. It is also vital to understand the relative importance of genotype and environment on disease progression. These activities should be linked with studies under theme 9 to identify tolerant trees for use in adaptation measures.

5. **Develop approaches to reduce the impacts of ADB and EAB**

Using the knowledge developed under theme 4, further studies should seek to understand what management techniques might be used to promote environmental conditions favourable to ash and detrimental to ADB and EAB. These will enable short to medium term planning to respond to ADB and EAB, whilst longer term adaption measures are explored under research themes 7-12. These studies should be established working closely with landowners and managers.

Studies to understand better the distribution and density of ash obligate species would help identify priority sites for management of ash-dependent biodiversity. Better understanding the importance of ash genotype in shaping the community of ash-associated species and also understanding the functional roles of ash associated species, will help protect these.

Land owners and managers would benefit from a review of tools and technology for quickly and cheaply assessing the level of likely tolerance or risks associated with individual trees, and for planning measures to mitigate these. However, it will also be important to further understanding of socio-economic drivers for management responses, and innovation of potential new mechanisms to support widespread adoption of approaches which will meet policy objectives.

A fully costed assessment of the full range of benefits and values of ash in the landscape and the impact of their loss, against the costs of managing ADB and EAB could help build support for action to protect ash.

6. **Develop preparedness for an optimal response to an EAB incursion**

Although much has already been learnt from experiences in north America, further studies are required to optimise our response to a potential EAB incursion. This will require assessment of the possible benefits, impacts and applications of a range of response tools including native and non-native biocontrol agents, stem injections and tree felling. These assessments would enable recommendations on how to apply an integrated management strategy in different contexts. It is also important to assess which surveillance approaches would be most appropriate to apply in the event of an outbreak. Such work would benefit from better understanding of how many outbreaks are likely and consideration of which scenarios would require switching from an eradication approach to containment or management of the pest.

Following these studies it would be possible to assess the resources and capacity required to respond to an incursion of EAB.

The experience in North America clearly illustrates the importance of a strong outreach campaign to prevent/minimise impact of an EAB outbreak. Achieving an effective approach would benefit from early stakeholder mapping and analysis to identify key communication messages and approaches.

Adaptation: Driving long term changes which will strengthen our natural resource and favour the survival of our trees, woods and forests and supporting landscapes in adapting to established pest and diseases.

Policy aims

- Restore ecosystem services, by repopulating the treescape with alternative species to ash
- Assist the long-term survival of native ash in the landscape

Research themes

7. **Understand impacts of planting or natural succession of other species**

An adaptation measure which can be implemented early is replacing ash with a diverse mix of other species (including other *Fraxinus* species where applicable). This might be achieved by active planting but in any case other species will naturally replace the gaps left by ash. It is important to understand better the impacts of replacing ash with other species on maintenance of biodiversity, ecological functioning, and susceptibility to other pests and diseases, as well as socio-cultural impacts, in order to develop guidance for land managers. It would also be useful to assess whether this has negative impact on natural selection for tolerance in remaining ash populations. Additional studies might explore further whether management techniques, including silviculture techniques could be used to enhance the 'ash-replacement' value of other species.

8. **Better understand genetic tolerance to EAB and ADB, identify tolerant trees and ensure ash genetic diversity is conserved**

   Further studies are required to build deeper and more robust understanding of the genetic basis, and the mechanisms, for tolerance to ADB and EAB in ash. This includes investigating the possible correlation between tolerance to ADB and susceptibility to EAB. While some genetic markers have already been identified further work is required to refine and test the results to date in a UK context.

   One use of genetic markers would be the identification of tolerant trees in the field, to inform better management of existing ash populations. Genetic tests for tolerant trees would need to be interpreted in context given the strong environmental influences on tolerance. Another use of genetic markers would be the acceleration of a breeding programme, as markers would help the rapid choice of which individuals to breed from. In either case, further work is required to establish what degree of tolerance is considered useful and how best to identify or measure this.

   In parallel, an assessment for the genetic basis for tolerance in natural populations and the speed at which susceptible trees of different ages die from ADB, would help to estimate reliably the speed and degree at which natural selection might lead to greater resistance in the population. This would inform choices about alternative adaptation pathways.

   Building on work in theme 4, efforts are also required to optimise and co-ordinate work to identify putatively tolerant trees in the landscape, and to build data on the frequency of tolerant ash. This might include development of standardised methods to describe tree health based on phenotypic (visual) assessment

   It is vital that we capture a wide diversity of ash genetic resources in *ex situ* collections and ensure they are documented and accessible for future research and use. Methods should be enhanced to capture adequately putatively tolerant trees in archives including seed banks, field trials and seed orchards, and to quantify tolerance (for example through controlled inoculation or spectroscopy).

9. **Better understand the possibilities for encouraging and enhancing natural selection for tolerant ash in the landscape**

   Like replacement of ash with alternative species, natural selection for tolerance is expected to occur naturally, but could be enhanced through human intervention. The objective would be to maintain the widest possible genetic pool of tolerant ash in the landscape. Management interventions might range from excluding herbivores such as deer through to deploying seed from putatively tolerant mothers, or cloned tolerant trees in the landscape to enhance populations (taking into account provenance issues). Experimental studies should be developed with landowners and managers to explore which management interventions best promote natural selection and how these might be employed. They should also assess the costs, benefits, barriers, opportunities and risks to each approach.

Management responses under theme 5 should emphasise the biodiversity and ecosystem services value of maintaining susceptible trees in the landscape. However, it would be helpful to understand the potential negative impact on natural selection of this approach.

10. **Assess and, as appropriate, implement a breeding programme for tolerant ash**

A conventional breeding programme for trees providing tolerance to ADB could be implemented relatively easily following identification of tolerant trees in theme 4. It might be based on the same material used to enhance natural selection under theme10.

However, to accelerate such a breeding programme, and ensure tolerance to both ADB and EAB, requires completion of studies to understand the genetic basis of tolerance (theme 9) and development of advanced breeding techniques. Further studies are required to establish whether this would require hybridisation of ash with other *Fraxinus* species and/or genetic engineering. It is also necessary to assess the timeframe for this approach (in comparison with natural selection), what resources would be required, whether an acceptable level of tolerance would be achieved, and the potential risks including loss of resistance, loss of genetic variation, impacts on biodiversity and biosecurity, and socio-economic and cultural factors. On-going stakeholder engagement is required to understand clearly what traits are considered important in a breeding programme and the acceptability of different possibilities.

11. **Assess the optimal mechanisms to produce and deploy large numbers of tolerant trees in the landscape.**

As outlined in Fig 2, it is likely that a range of adaptation pathways will be used to maintain trees tolerant to ADB and EAB and recover lost ecosystem services. It follows that a range of formal and informal seed supply systems will arise, from informal use of seed from putatively resistant mothers and alternative species, to seed orchards developed from breeding programmes. These will offer trees with different kinds and levels of tolerance, and which might require different growing conditions. It is important to map and assess the effectiveness of the different seed supply systems, and consider how issues such as intellectual property and commercial aspects would be managed. Provenance of seed is an additional important consideration for users.

Ongoing consultation with stakeholders should develop understanding of what kinds of incentives and support will be required to encourage large scale replanting by all kinds of landowners and manager, and what price they would be willing to pay for tolerant trees of different kinds. As a basis for this debate, and building on evidence from theme 4, an assessment of where and how many tolerant trees should be planted for maximum impact.

A better understanding of the historic distribution and abundance of ash in the UK would also inform this debate.

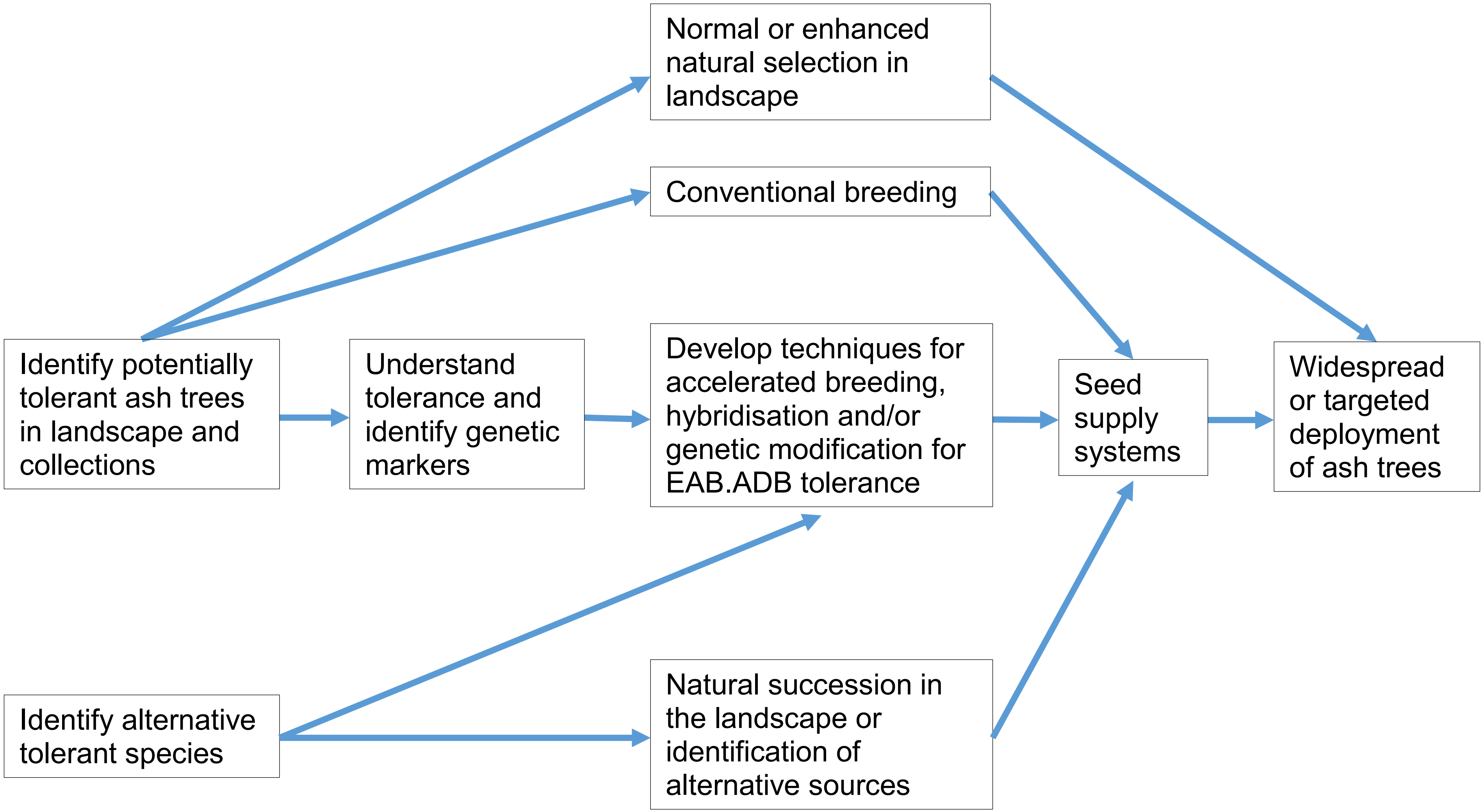


Figure 2: Flowchart showing the steps between identifying potentially tolerant or alternative tolerant ash tree species and widespread or targeted deployment of ash trees to aid recovery

Chapter 5 – A roadmap for future research

Our goals

This research strategy has consolidated existing knowledge in relation to key pest and disease threats to ash and their management, and identified key research needs for the future. It has also proposed principles to enable this research to have most impact.

Defra has already used this framework to plan research to fund in the current year and to identify priority next steps. It is expected that in the financial year 2019-20 Defra will commit approximately £650,000 to ash-related research. These activities are outlined in Table 1 below.

Table 1: Priority research actions

Research Themes			
	Resistance	**Defra supported projects underway or planned in 2019-20**	**Priority next steps**
1	Further understanding of the biology of pest and disease threats to ash, with a focus on EAB and ADB	PhD investigating the relationship between temperature and development rate of EAB, which will help model potential spread in the UK (Forest Research).	Studies in Russia to understand better interactions between EAB and ADB on *F. excelsior.*
2	Develop better evidence around the risk pathways for EAB	Project analysing the data associated with importation and movement of firewood (organisation tbc)	Couple risk pathways and ash distribution data to model and create UK risk maps for EAB
3	Develop an optimal early warning system for EAB	Collaborating with international partners to develop an early warning system for EAB that takes account of known high risk pathways and the biology of the pest (Forest Research)	Enhance the International Plant Sentinel Network to monitor ash across Eastern Europe
	Response and recovery		

4	Develop detailed mapping of the distribution and health of ash, and understanding how environment factors influence ash tree health	Mapping and stress identification in UK ash trees, based on remote sensing tools (Rezatec Ltd). Identification of infection behaviour of *H. fraxineus* and the interaction between ADB and Armillaria on ash (Forest Research and Cardiff University) PhD studentship to identify environmental, host genetic and microbial factors to fully understand the factors that promote tolerance to ADB. (University of Salford and partners)	Further work towards a more standardised, structured and joined-up long-term monitoring approach, optimising use of stakeholders, citizen science and technology. Assess the possibility of classifying sites based on environmental criteria to aid risk assessment and management decisions
5	Develop approaches to reduce the impact of ADB	Continue work with Local Authorities and other land owners to evaluate, enhance and expand resources such as the ADB Toolkit which are aimed to help planning and decision making to reduce impact of ADB. Also assess how roadside ash canopy surveys can inform decisions on tree removal/replacement. (Fera, Forest Research and Tree Council)	Assess which management techniques might be used to promote environmental conditions favourable to ash and detrimental to ADB and EAB. Identify priority sites for management of ash-dependent biodiversity. Gather further evidence on the full range of benefits and values of ash
6	Develop preparedness for an optimal response to an incursion of EAB	Explore stem injection technology for use in the UK against EAB and assess and fill knowledge gaps in its use (Fera). Investigate native and non-native parasitoids for potential use for biocontrol of EAB in the UK. (Fera and Forest Research)	Assess which detection and surveillance approaches would be most appropriate to apply in the event of an outbreak. Stakeholder mapping and analysis to identify key communications approaches

	Adaptation		
7	Understand impacts of planting or natural succession of other species		Gather further evidence on the biodiversity and ecological function/service provision of alternative species
8	Better understand genetic tolerance to ADB and EAB, identify tolerant trees and ensure ash genetic diversity is conserved	Continue to monitor mass screening trials and develop an archive of tolerant trees. Develop UK capacity to quantify tolerance in putatively tolerant trees. (Forest Research and Future Trees Trust) Further understand the potential tolerance markers identified in genomic studies. (RBG Kew) Characterise the diversity of tolerance in UK ash and investigate the potential relationship between tolerance to ash die back and susceptibility to herbivory from insects. (John Innes Centre, BBSRC funding, supported by Defra)	Establish what degree of tolerance is considered useful and how this can be quantified. Develop estimates for the likely speed and effectiveness of natural selection at developing tolerance in ash populations. Building on Theme 4, develop widespread monitoring of putatively tolerant trees in the landscape, and capture this genetic diversity in *ex situ* collections.
9	Better understand the possibilities for encouraging and enhancing natural selection for tolerant ash trees in the landscape	Work on this theme is dependent upon completion of studies in theme 8.	
10	Assess and, as appropriate, develop a breeding programme for tolerant ash	Work on this theme is dependent upon completion of studies in theme 8.	
11	Assess the optimal	Work on this theme is dependent	

	mechanisms to produce and deploy large numbers of tolerant trees in the landscape	upon progress under research themes 7-11.	

Expected outcomes

It will take more time and further work to complete all the tasks outlined in this document. New tasks and questions may be revealed along the way. Nevertheless, this strategy provides a clear vision to meet policy aims, and its achievement will deliver a number of important outcomes, the most important of which are shown in Fig 3 below.

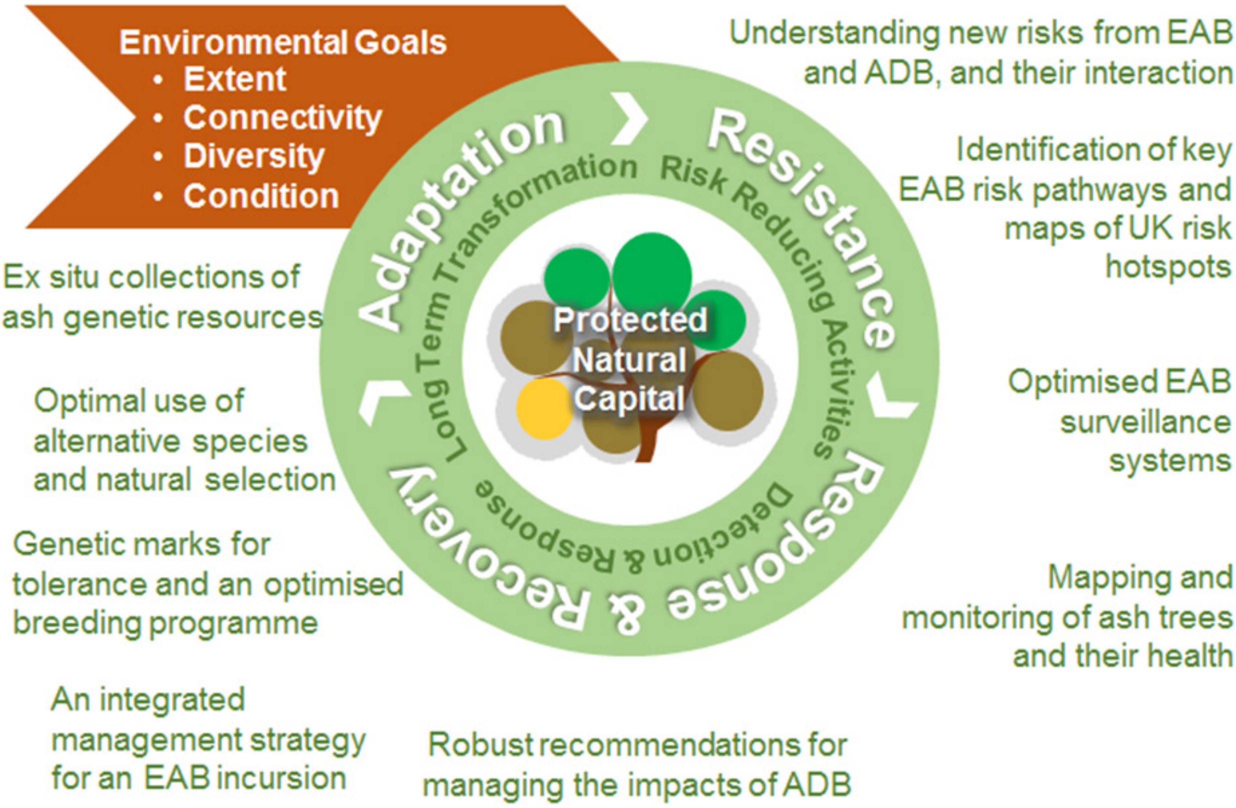


Figure 3: Resilience circle showing the important expected outcomes from this strategy

The most important outcomes this strategy is expected to achieve are:

- understanding new risks from EAB and ADB, and their interaction
- identification of key EAB risk pathways and maps of UK risk hotspots
- optimised EAB surveillance systems
- mapping and monitoring of ash trees and their health
- ex situ collections of ash genetic resources
- optimal use of alternative species and natural selection
- genetic marks for tolerance and an optimised breeding programme

- an integrated management strategy for an EAB incursion
- robust recommendations for managing the impacts of ADB

Next steps

This strategy will inform Defra's decisions on what research to encourage and support. In order to deliver ash policy priorities. Its achievement depends on continued collaboration between government, academia, research councils, charities, researchers and stakeholders managing ash on the ground. Wherever possible Defra will use its support in order to facilitate additional research activities, using tools such as letters of support or provision of matched funding, to encourage funders to support work which is covered in this document.

It is hoped that this roadmap will also inform the investment decisions of other research funders, and the priorities of researchers, across the UK and beyond.

References

The references for this document can be found in the Annex: Evidence summaries.

Annexes: Evidence summaries

Confidence ratings

Data in this paper has been sourced from different organisations/publications. In order to help the reader understand the data presented a confidence rating has been applied where appropriate.

1. CR High: Based on significant evidence (e.g. recent survey, statistically sound using up to date methods, HMRC data, current industry practices; published in peer reviewed papers; recent qualitative research (interviews, focus groups etc.) with sound methodology that includes results from a number of studies in different locations with different types of people that report similar findings).

2. CR Medium: Based on incomplete or dated evidence (e.g. an estimate based on old survey data, trade association estimates, a survey result which may not be entirely representative of the whole; qualitative research from one or two case studies; published in only one or two peer reviewed papers; published in grey literature).

3. CR Low: Based on speculative or incomplete evidence (e.g. rough estimate from a single expert, or industry body lacking supporting analysis, or early result based on fast developing situation on ground, not published in peer reviewed papers, qualitative research that involves a single case or does not provide details of the sample studied or method used.

Evidence summary: ash

- *Fraxinus excelsior* is a large tree, native to the UK and found across much of mainland Europe. In Britain ash is the second most abundant tree species in small woodland patches after the native oak species, and the third most abundant in larger areas of forest. Outside of woodlands ash grows, or is planted, in hedgerows, next to roads and railways and in urban environments [1].(CR Medium)
- 12% of broadleaf woodland in Great Britain is ash [2]. (CR High)
- It is estimated that there are 125 million ash trees in woodlands and between 27-60 million ash trees outside of woodlands in the UK, plus potentially 2 billion saplings and seedlings in woodlands and non-woodland situations. [3, 4] (CR Medium)
- 9,500 ancient, veteran and notable ash trees have been recorded in the Ancient Tree Inventory [5]. (CR High)
- The social and environmental value of ash woodlands in Great Britain have been estimated at over £230 million per year reflecting recreation, landscape, carbon sequestration, air pollution absorption and elements of biodiversity value. [6] (CR Medium)

- The population structure of British common ash shows that the majority of the population belongs to the same population as mainland western and central Europe. With a few exceptions found in eastern Scotland and north Wales. [7] [8] (CR Medium)

- The UK National Tree Seed Project has conserved over 59 seed collections from 659 mother trees and as a result captured >90% of all British ash alleles. [9] (CR Medium)

- 955 species have been identified as having all or part of their lifecycle associated with ash woodlands in the UK, for example as a habitat, food source or hunting ground. Of these 44 are only recorded on ash and are considered obligate, a further 62 are highly associated but have also been recorded on other species. [10-12] (CR High)

- No single tree species will be able to fill the niche provided by ash trees in terms of both its ecosystem function (e.g. nutrient cycling and light penetration properties that influence other ground cover) and biodiversity contribution. The most appropriate strategy for managing the biodiversity impacts of loss of ash will vary from site to site. [13, 14] (CR Medium)

- Ash wood is highly valued for specialist uses such as tool handles and furniture, as well as for firewood, making ash timber one of the most valuable native hardwoods.[15] (CR High)

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Evidence summary: ash dieback

Pathogen

- Ash dieback is a disease caused by the fungus *Hymenoscyphus fraxineus (*formerly *Chalara fraxinea* and *Hymenoscyphus pseudoalbidus).* [16, 17] (CR High)
- *H. fraxineus* is native to Asia where it is a weak pathogen of the Asian species of ash (*Fraxinus mandshurica* and *F. rhynchophylla*) [18]. It was first identified in Poland in 2006 but is thought to have established in Europe as early as 1992. [16] The disease has now been recorded in most European countries [19]. (CR High)
- The first recorded incidence of *H. fraxineus* in the wider environment in England was 2012, new research has demonstrated that the fungus had already been present in some locations since at least 2004. [20] (CR High)
- Genetic analysis has demonstrated that the European population of *H. fraxineus* is very similar, indicating a single or small number of introductions into Europe. [21, 22] (CR High)
- *H. fraxineus* arrived in the UK both through airborne spores and through infected planting material, the mode of arrival has not influenced the genetic diversity of the pathogen. [23] (CR Medium)
- Research into the dynamics and genetic structure of *H. fraxineus* suggests that there is a high fitness cost to pathogenicity. In addition, the large population size and frequent mating of *H. fraxineus* has generated a high genotypic diversity which natural selection can act on. Coevolutionary theory predicts that in this scenario natural selection will act to make the pathogen less pathogenic. It is likely that this will take several hundred years. [23] (CR Medium/Low)

Lifecycle

- *H. fraxineus* undergoes both sexual and asexual reproduction. Sexual reproduction happens on the fallen ash petioles in the leaf litter, this results in fruit body production. Asexual reproduction takes place in autumn and winter, the role these conidia have in the lifecycle of *H. fraxineus* is not yet clear. [24-26] (CR High)
- Infection is via air-borne spores produced from fruit bodies on leaf litter. The fruit bodies occur on infected fallen leaves and shoot material in the growing season (June – August) after infection for up to 5 years [27]; trees are likely to need a high dose of spores to become infected. Spore density is highest close to the ground. [28, 29] *(CR High)*
- Spores germinate soon after they are released in the presence of water, a small proportion can survive dry conditions for 7 days. [30] (CR Low)
- Moist conditions favour the production of fruit bodies. In addition, occasionally fruit bodies can be produced on dead shoots, stems and root collars of recently dead young trees. [20, 31] (CR High)
- Natural spread occurs with wind-blown spores (ascospores) from the fruiting bodies. [16, 32]. Spread can also occur via the movement of infected trees in leaf through trade

or through movement of fallen leaves. Data from Europe has shown that the disease is capable of dispersing 50-75km per year. [24, 33, 34] (CR High)

- *H. fraxineus* infection starts primarily on leaves and is progressive over time with dieback and stem lesions becoming pronounced over the next growing season. Stem lesions are considered to be a reproductive dead end for the fungus. [24] (CR High).
- On susceptible hosts the disease causes loss of leaves, dieback of the crown of the tree, basal lesions and often leads to tree death. [24, 35] (CR High)
- Basal lesions can be caused primarily by *H. fraxineus* and also in conjunction with secondary pathogens, such as honey fungus (*Armillaria* spp.). Basal lesions drive mortality in larger trees and trees can become structurally unstable. Basal lesions are more likely to be found on sites which are wet and already suffering from crown dieback. [36-39] (CR High)
- Basal lesions correlate with crown dieback [38], however in some cases basal lesions have been observed on trees with minimal crown damage. [40] (CR Medium)

Host

- *H. fraxineus* has infected many species of *Fraxinus*, but with differing intensities [18, 41][i]. Common ash (*Fraxinus excelsior*) is one of the most severely affected species and is the only native species of ash in the UK. *F. angustifolia, F. quadrangulata* and *F. nigra* are also considered to be highly susceptible. [18, 42] (CR High)
- Recently *H. fraxineus* has been found to infect other species in the Oleaceae; *Philyrea latifolia, P. angustifolia* and *Chionanthus virginicus*, it is not yet known if *H. fraxineus* can complete its lifecycle on these hosts. (CR Low)
- Other species in the Oleaceae family have been tested including *Forsythia* x *intermedia* and *Ligustrum vulgare* and these were found not to be susceptible to *H. fraxineus*.[43] (CR Medium)
- The disease progresses quickly in young trees (as their stem diameter is quickly girdled), trees growing in stressed conditions (for example on sites with and extreme excess of or lack of moisture) and in ash dominated woodlands with higher levels of leaf litter and consequently spore loads. [36, 44] (CR High)
- Fewer symptoms have been observed in ash trees growing on well managed sites in open spaces, such as parklands. It is thought that trees are escaping the disease and at these sites, trees can survive for years without many observed symptoms [36, 44]. (CR High)

Tolerance

Definition: In this summary we use the word tolerance to refer to all terms used in the scientific literature where ash trees have low susceptibility to ash dieback; this includes tolerance, resistance, partial resistance, low susceptibility and disease avoidance.

- Observations from young planted trials in the UK and Europe have demonstrated that between 1-5% of the population may be tolerant to *H. fraxineus*. This tolerance varies between genotypes demonstrating that tolerance has a genetic component. [45-49] (CR High)

- Different experimental approaches have been used to quantify tolerance of individual ash trees to the *H.fraxineus* pathogen. Most use direct exposure to the pathogen but recently spectroscopy has been suggested as a means of phenotyping individuals. [35, 50-52] (CR Medium)
- Basal lesions represent a different infection pathway to crown dieback but their incidence also has a host genetic component. [53] (CR Medium)
- The climate and site factors play a large role in how trees succumb to *H. fraxineus*, this includes soil type, soil moisture, air humidity, temperature, stand age and stocking density. [36] (CR Medium)
- In Europe, narrow sense heritability for tolerance has been calculated at between 0.3-0.5 which offers hope for a future breeding programme. [46, 47, 54] (CR High)
- Variation in tolerance exists in all populations of ash rather than in specific regions. This natural tolerance within all populations provides an opportunity to maintain ash as a species. [36, 46] (CR High)
- In a trial in Denmark, tolerant female trees have been found to produce more seed when compared to very susceptible trees, demonstrating that ash forests could recover in time. [55] (CR Medium)
- The *F. excelsior* genome has been sequenced and 38,852 protein-coding genes have been annotated .[56] (CR Medium)
- Transcriptomic markers have been developed which predicted 25% of the observed variation seen in a Danish panel of trees. [56, 57] (CR Medium)
- A small survey of forest managers in the UK identified that this sector have a strong interest in the concept of tolerant ash if this ash has similar characteristics, retains genetic diversity and withstands future pest and disease threats. [58] (CR Low)
- A metabolomics study using a small sample of Danish trees demonstrated that trees tolerant to ash dieback may have less iridoid glycosides, well known anti herbivory chemicals. This suggests that low susceptibility to ash dieback may result in increased susceptibility to insect pests such as emerald ash borer (*Agrilus planipennis)*. [59] (CR Low)
- A genome wide association study of 1250 ash trees has identified genomic markers associated with ash dieback damage scores. The markers can distinguish between trees with high and low ash dieback damage with 69% accuracy. The identified markers could speed up any breeding programme for ash dieback tolerance.[60] (CR Low)
- A survey of the public acceptability to tree breeding solutions in response to ash dieback showed the majority of respondents were concerned about the loss of ash from the British countryside and were looking for an active response. Breeding native ash through conventional means was preferable but accelerated breeding with the assistance of markers was also acceptable. . [61, 62] (CR Medium/Low)

Management

- Managing *H. fraxineus* in forest stands depends on the management objective, stand condition, age, type, site conditions and the extent of *H. fraxineus*. Disease progression is generally faster in young, pure ash stands. Other tree species can influence the amount of ash crown dieback by changing the conditions for sporulation of *H. fraxineus*. [63] (CR High)

- Hypovirulence involves the infection of a fungal pathogen with a virus and can reduce the pathogenicity of the fungus. Success depends on low vegetative compatibility group diversity of the fungus. Populations of *H. fraxineus* in the UK have shown a wide variation in vegetative compatibility groups. This makes the introduction of hypovirulence as a form of control very unlikely. [23] (CR High)

- Some evidence suggests that clear felling areas of pure ash will result in less natural regeneration of ash. Healthy seed trees should be maintained for as long as possible to ensure regeneration from tolerant mother trees. Promoting ash regeneration will encourage the process of natural selection. Regeneration should be promoted as a mix of species to avoid a more susceptible pure ash stand. [36, 64] (CR Medium)

- Some fungicides can be used as preventative treatment and could be used in forest nurseries. [36, 65] (CR Medium)

- Removal of leaf litter is an effective way to reduce the level of inoculum in certain conditions i.e. urban environments. [36] (CR Medium/Low)

- Data from Europe has demonstrated that coppice regrowth becomes severely infected, it is thought this could be to do with the proximity of the regrowth to the high spore load. [64] (CR Low)

Impacts

- The impact of *H. fraxineus* infection depends on tree age, provenance or genotype, location, weather and microclimate conditions, and presence of honey fungus (*Armillaria)* or opportunistic secondary pathogens. Trees in forests are more likely to be more affected because of the greater prevalence of honey fungus and favourable microclimates for spore production and infection. Trees cannot recover from infection, but larger trees can survive infection for a considerable time and some might not die. [36] (CR Medium)

- Reported mortality rates from ash dieback vary. Predicting mortality in mature trees is difficult as the disease progresses slowly. One recent analysis of data across Europe found that the maximum mortality recorded so far was~85% in plantations , ~70% in woodlands and ~82% in naturally regenerated saplings.[66] (CR Medium)

- It is difficult to relate the European experience with ash dieback to what might happen in the UK as it is estimated ash comprises less than 1% of the total wooded area in Europe, although locally it can occupy a higher proportion. [67] (CR Medium)

- The European experience with *H. fraxineus* has demonstrated that foresters have proactively felled the healthiest and therefore removed the most tolerant trees to achieve the greatest returns. In addition, some countries have reported mass felling for health and safety reasons because of basal lesions making trees liable to fall over. [36, 37, 68] (CR High)
- The total cost of ash dieback to the UK has been estimated at £14.6 billion, based on the cost of dealing with the impacts of the disease (e.g. felling), replanting and loss of ecosystem services. [69] (CR Low)

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Evidence summary: emerald ash borer

Pest and distribution

- Emerald ash borer is a xylophagous buprestid beetle, *Agrilus planipennis*, which is native to countries of eastern Asia, including China, eastern Russia, Democratic People's Republic of Korea, Republic of Korea, and Japan [1] (CR High)
- The beetle has also been recorded in Mongolia, but these records are uncertain, as several authors have not reported emerald ash borer from this country, and there is also a near absence of the genus *Fraxinus* in Mongolia [1, 4, 47] (CR Low)
- Emerald ash borer was first recorded outside of Asia in Michigan, USA, in September 2002, and shortly after in Ontario, Canada [1, 2] (CR High)
- Genetic analysis indicates that this was a result of a single introduction, possibly from the Tianjin/Hebei region of China [49] (CR Medium)
- The beetle has since spread to 34 states of the USA and 5 provinces of Canada [1] (CR High)
- Emerald ash borer was first confirmed in Europe in Moscow, Russia, in 2005, and has now been reported within 6 km of Ukraine and 50 km of Belarus, and is likely to be present in Ukraine [3] (Forest Research personal communication, CR Medium)

Hosts

- Emerald ash borer feeds on ash trees (*Fraxinus* spp.) [4] (CR High)
- In China, the beetle is a minor and relatively rare pest of Manchurian ash (*F. manchuria*) and Chinese ash (*F. chinensis*), and mainly attacks stressed trees [4] (CR High)
- Ash species in the USA, including *Fraxinus americana*, *F. nigra*, and *F. pennsylvanica*, on the other hand, are particularly susceptible [4, 5] (CR High)
- The outbreak in and around Moscow has been mainly on *F. pennsylvanica* (planted as an amenity and landscaping tree). The beetle has also been found on *Fraxinus excelsior* (European ash) in Moscow, where it is planted in low numbers, but also in mixed-broadleaf woodland to the south where it is a co-dominant tree species [50] (CR High).
- European ash is considered to be less susceptible than *F. americana*, *F. nigra* and *F. pennsylvanica* [6] (CR Medium)
- The susceptibility of European ash infected with *Hymenoscyphus fraxineus* (ash dieback) is unknown (CR Low)
- *Juglans ailantifolia*, *J. mandshurica*, *Ulmus davidiana* and *Pterocarya rhoifolia* have been reported as further hosts of the beetle in Japan, but these reports may refer to a different species of beetle, and there is no evidence that emerald ash borer can complete its lifecycle on these hosts [4, 47] (CR Low)
- *Chionanthus virginicus* (white fringetree) has been recorded as a host in North America [7, 8] (CR Medium)
- Experimental work suggests that *Olea europaea* (olive) is a host [9] (CR Low)

Lifecycle

- Adults of emerald ash borer emerge in spring and summer, live for about 2-3 weeks, and feed on the foliage of ash trees [4] (CR High)
- Adults mate, and females subsequently lay eggs (~ 68-90 per female) on the bark of ash trees, usually within crevices and cracks [4] (CR High)
- Larvae hatch from the eggs and bore into the inner bark and outer sapwood, where they feed through the summer and autumn and produce long sinuous galleries of 10-50 cm in length, before overwintering in the fourth larval stage or prepupae [4] (CR High)
- Pupation occurs in pupal cells in the outer sapwood or bark in the spring of the following year [4] (CR High)
- Emerald ash borer generally has one generation per year, though some individuals may require two years, in which case the larvae continue to feed until winter of the second year, and pupation occurs in the third year [4] (CR High)
- Studies have found the average lethal temperatures for prepupae and larvae to be -25°C and -30°C, respectively, and have found adults to be active in strong sunlight and temperatures of > 25°C. These studies suggest that climatic conditions in Europe and the UK are suitable for establishment [4, 57, 58, 59] (CR High).
- Symptoms include D-shaped exit holes, larval galleries, discolouration of foliage, thinning, longitudinal bark splits, epicormic growth, dying branches, woodpecker damage, and dead trees [4] (CR High)

Dispersal pathways

- Emerald ash borer is a strong flyer and typically flies in 8-12 m bursts, though longer-distance flights of over 1 km are possible [51] (CR High)
- In flight-mills experiments, the average flight was > 3 km, with 20% of mated females able to fly > 10 km in 24 h, and 1% > 20 km [52] (CR Medium)
- When ash trees are available in the immediate surroundings, dispersal distances tend to be lower and most emerging adults fly < 100 m [53] (CR Medium)
- In North America, human-assisted spread has also played a significant role in spread, especially via the movement of infested firewood for camping trips [4] (CR High)
- Ash commodities and pathways that are likely to introduce and spread the pest include ash wood (including round, sawn and fire wood, with and without bark), ash plants for planting, waste wood and scrap wood containing ash, hardwood woodchips, wood packaging material made from ash, bark products, furniture and finished wood products made from untreated ash wood, cut branches, and hitch-hiking on vehicles [4] (CR Medium).
- It is likely that the pest will spread naturally across Europe from its centre of introduction in Moscow and, potentially rapidly and over long distances, by human-assisted transport of infested ash [4] (CR Medium).
- The probability of detecting the beetle in Belarus, Ukraine, Estonia, Latvia, and Lithuania as a result of spread from Russia by 2022 is 15%–40% [56] (CR Medium)

Impacts

- Trees are generally killed within 4 years of infestation, and within 1-2 years in some cases [4] (CR High)
- Tens of millions of trees have been killed in North America [4] (CR High)
- Timber and other forestry products have been lost, ecosystem services, such as water regulation, have been impoverished, and social benefits like shading, recreation and cultural traditions have been affected [4] (CR High)
- In 2010, the cost of treating, removing, and replacing 17 million ash trees across 25 states of the USA was estimated to be €7.9 billion, while a study in 2012 estimated the cost of removing and replacing ash in Canada would be €332-1476 million over a 30 year period [54, 55] (CR Medium)
- Impacts are also likely to be high in the UK [10] (CR Medium)

Prevention

- Emerald ash borer is a IAI EU listed pest, which means that it is banned from being introduced, and spread within, all EU member states [11] (CR High)
- Wood (of certain types), wood chips, particles, sawdust, shavings, wood waste and scrap, isolated bark and objects made of bark, plants including cut branches, and furniture and other objects made of untreated wood, of *Fraxinus* spp., *Juglans ailantifolia*, *Juglans mandshurica*, *Ulmus davidiana* and *Pterocarya rhoifolia*, originating in Canada, China, Democratic People's Republic of Korea, Japan, Mongolia, Republic of Korea, Russia, Taiwan and USA, must come from a Pest Free Area [11] (CR High)
- Wood (of certain types) may also be treated by removing the bark and outer sapwood or using ionizing radiation, as an alternative to a Pest Free Area [11] (CR High)
- Wood packaging material from third countries must be debarked, treated and marked in line with the International Standard of Phytosanitary Measures No. 15 [11] (CR High)
- Inspections are required in the exporting country for all plants for planting from third countries, as well as wood (of certain types), bark, and cut branches, of *Fraxinus* spp., *Juglans ailantifolia*, *Juglans mandshurica*, *Ulmus davidiana* and *Pterocarya rhoifolia*, originating in Canada, China, Democratic People's Republic of Korea, Japan, Mongolia, Republic of Korea, Russia, Taiwan and USA [11] (CR High)
- Importation of *Fraxinus* plants intended for planting into Britain from any third country or member state must come from an area free from *Hymenoscyphus fraxineus* (ash dieback) [12] (CR High)

Detection and surveillance

- Because of the cryptic lifecycle of the beetle and the delay in observable symptoms, visual surveillance from the ground or by air is not likely to be effective for early detection [4, 13] (CR High)
- The use of girdled trees is a very sensitive method of detection, but is also invasive. Girdled trees are used regularly in the USA [14, 15, 16] (CR High).

- Subsampling, either by branch sampling or trunk windows, is also a sensitive method of detection, but less sensitive than girdling. Branch sampling is regularly used in Canada [13, 17] (CR High).
- In the USA, purple prism traps baited with (3Z)-hexanol, and to a lesser extent Manuka oil and Phoebe oil, are used, while in Canada, green prism traps baited with (3Z)-hexenol are preferred [16, 18, 19, 20, 21] (CR High)
- Double decker traps may be more effective at detecting emerald ash borer at lower levels of infestation than prism traps [19, 22] (CR Medium)
- Biosurveillance using hymenopteran wasps could be used [16, 17, 23] (CR Medium)
- Sniffer dogs have potential for use in a surveillance programme [4, 24] (CR Medium)

Management

- Eradication of emerald ash borer is only likely to be possible for localised outbreaks where the beetle has not had time to spread [4] (CR High)
- Despite intensive management and attempts to restrict long-distance spread, it has not been possible to eradicate the pest after its introduction to North America (both the USA and Canada) [4] (CR High)
- The principle method of controlling emerald ash borer in an eradication programme is through the felling of ash trees and restricting the movement of susceptible material, as instructed in EPPO standard 9/14 [25] (CR High)
- Injecting the tree with the insecticide emamectin benzoate (Tree-Äge and Arborjet) provides 2-3 years of protection for an ash tree from one application, and is used regularly in the USA [26, 27] (CR High)
- Treating a small proportion of ash trees with emamectin benzoate in a woodland has been shown to reduce the progression of ash decline across the woodland [48] (CR Medium)
- Injecting the tree with the insecticide azadirachtin (Treeazin) provides 1-2 years of protection for an ash tree from one application, and is used regularly in Canada [21, 28] (CR High)
- Neither emamectin benzoate or azadirachtin are approved for use as a tree injection in the UK [29] (CR High)
- Because of the cost, chemical treatments are generally limited for use on high value trees, such as those in urban areas or those of historical interest [4] (CR High)
- Biopesticides have been investigated, but do not provide good coverage as sprays and need to be regularly reapplied, and are therefore not used in the USA or Canada [17] (CR High)
- Two native parasitoids in the USA, *Atanycolus cappaerti* and *Phasgonophora sulcata*, have exhibited high parasitism of emerald ash borer and show potential for use in a control programme [30, 31] (CR Medium)
- Four non-native parasitoids from Asia have been released in the USA, including the larval parasitoids *Tetrastichus planipennisi*, *Spathius agrili* and *S. galinae,* and the egg parastioid *Oobius agrili*, and are potentially having a positive impact on ash recovery [17, 32, 33, 34, 35, 36, 37] (CR High)

- *Spathius polonicus*, a European parasitoid of emerald ash borer identified in Russia, may also be of value [38] (CR Medium)
- Movement restrictions of ash trees, branches, logs and firewood, have been accompanied by a public awareness campaign in the USA and have shown value in reducing spread [39, 40] (CR Medium)
- A multiagency project in North America called SLow Ash Mortality (SLAM) incorporates a number of different control techniques to slow the progression of ash loss in recent infestation and outlier sites [41, 42] (CR High)
- Resistance/tolerance to emerald ash borer varies between ash species, and *F. mandshurica, F. platypoda*, *F. chinensis*, *F. baroniana*, and *F. floribunda* are able to kill emerald ash borer larvae that enter their trunks [6] (CR Medium)
- Candidate alleles for resistance/tolerance have been identified in *F. mandshurica, F. platypoda*, *F. baroniana*, and *F. floribunda*, including those in the phenylpropanoid and flavonoid synthesis pathways. These could be searched for in the UK's ash population, assisting a breeding programme [6] (CR Medium)
- In the USA, ecosystem structure of some ash dominated forests is likely to be lost [43] (CR Medium)
- Ecosystem structure can be preserved to a degree by encouraging natural regeneration of non-ash species using appropriate silvicultural techniques and/or by additional planting of non-ash species [44, 45, 46] (CR High)

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