Saving the world's ash forests calls for international cooperation now

Ash forests in North America and Eurasia are rapidly being lost to two invasive alien species: the emerald ash borer and *Chalara* ash dieback fungus. We argue that better regulatory policy and science-based intervention can help slow losses, and recommend an international consortium to coordinate science-based intervention.

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Global losses of ash (*Fraxinus*) species can be traced to the emerald ash borer (*Agrilus planipennis* Fairmaire; EAB), a wood-boring beetle, and *Chalara* ash dieback fungus (*Hymenoscyphus fraxineus* (T. Kowalski) Baral, Queloz and Hosoya; ADF), an ascomycete fungus, both of which are indigenous to Asia (Fig. 1). Ash losses to both harmful organisms can be abated by swift international cooperation using readily available resources. To illustrate this, we analyse the problem, then examine policy solutions including harmonized phytosanitary regulations, best practices for detecting pathogen infection and available research resources. These solutions, both policy and scientific, will be best coordinated by forming an international consortium.

Problem analysis

The world's 48 *Fraxinus* species in the Northern Hemisphere consist of large and small trees or shrubs (Supplementary Table 1)[1]. Among them, five species, namely North American white ash (*F. americana*), green ash (*F. pennsylvanica*) and black ash (*F. nigra*), European common ash (*F. excelsior*) and northeast Asian Manchurian ash (*F. mandshurica*), are the most widely distributed and commercially important species. Ash species are also prized for ecological value, comprising over 20% of the urban tree species across the United States alone[2], and are deemed essential for urban-coupled human–forest ecosystems. They serve as keystone species in a variety of forest ecosystems while providing food sources and habitats for wildlife.

In North America, ash forests are rapidly being lost to the EAB, dating back to the late 1990s[3] when it arrived via China's wood trade from Hebei province and nearby Tianjin city[4], although freight packing materials, live plants and various manufactured wood articles[5] are also implicated as vectors. EAB spends most of its life cycle hidden under bark causing no visible symptoms[5,6]. It takes only a few beetles to rapidly infest an entire forest and kill trees within a few years[3]. Since the 1990s, EAB has been detected in 35 US states and in five Canadian provinces (www.emeraldashborer.info; accessed 11 October 2018). Total losses to date are roughly 689 million m^3 for standing ash timber in the United States[7], while estimated costs of ash losses in urban areas from EAB alone, including tree removal and replacements, are US$7.6 billion in Ohio and US$26 billion for Illinois, Indiana, Michigan and Wisconsin combined[8]. Annual damages from EAB have reached US$38 million for the federal government, US$850 million for local governments, US$380 million for residential property value loss and US$60 million for forest landowner timber sales[9]. Thus, EAB is the most costly forest insect to have invaded the United States so far.

In Europe, ADF is the most acute forest pathogen problem and is also thought to have been introduced from East Asia, particularly Japan and northeastern China[10]. While ADF spores are airborne across landscapes, its dispersal is aided by the movement of nursery plants and possibly by movement of firewood and logs[11,12]. ADF has decimated *F. excelsior* since the early 1990s; millions of trees are now dying[11].

Until recently, ADF and EAB occupied discrete territories without overlap, but now Russia has reported losses due to both ADF and EAB. ADF is found nearly everywhere in European Russia, from its western borders to the Volga River[13]. EAB has spread over a total area of 150,000 km^2 from Moscow outward to 11 other regions of the Russian Federation and is presently moving westward at a rate of 12 km per year[14]. It is predicted to reach Central Europe within 15–20 years[6], though it may be moving faster towards areas with higher-density ash forests.

ADF infection of North American ash species may be only a matter of time as seven North American ash species already exhibit susceptibility to the fungus[14]. Like EAB in North America, the impact of ADF will become more pronounced when forest owners accelerate logging of uninfected forests in order to acquire maximum prices for healthy logs[15].

Observations in Europe have shown that while some trees can withstand the infection of ADF[15], far greater losses are to be expected if EAB meets ADF[6]. Similarly, ash trees surviving EAB attacks in North America may be damaged by ADF if the fungal pathogen is introduced there[14]. Now nearly extinct, chestnut and elm forests were lost to two ascomycete fungal species, namely chestnut blight (*Cryphonectria parasitica*) and Dutch elm disease (*Ophiostoma novo-ulmi*), both of which altered North American forest ecosystems in the early twentieth century[5].

Once invasion of EAB is combined with ADF, ash forests could follow the demise of American chestnut and elm forests. Each pest has its own way of killing ash trees and their combined attack is therefore expected to be more lethal than either of them alone. Even so, loss of ash forests in North America and Eurasia need not be a foregone conclusion. Policy solutions exist and the best available scientific knowledge for ash forests is now abundant yet underutilized (Table 1). For example, ash species from eastern Asia are more resistant to EAB and ADF than other ash species, possibly due to shared co-evolutionary history between the forest species and its attackers[6,14]. Breeding pest resistance is thus feasible as a policy solution, but an international consortium will be required to put these plans into action.

Policy solutions

Harmonizing phytosanitary regulations across North America and Eurasia could slow entry of EAB, ADF and other pests of *Fraxinus* species. Although regulations are in place to prevent the introduction and spread of forest pests via transport and trade[16], they should be continuously updated with science-based knowledge.

Ash (*Fraxinus*)

- 48 species[1]
- >20% of the urban tree species across the United States alone[2]
- Keystone species in forest ecosystems

Emerald ash borer (*Agrilus planipennis*)

- Arrived in North America in 1990s via China's wood trade[4]
- Since then detected in 35 states and five Canadian provinces
- Life cycle is hidden under bark causing no visible symptoms[5,6]
- Total losses to date are roughly 689 million m^3 volume in the United States[7]
- Most costly forest insect to have invaded the United States so far
- Annual damages[9]:
  - federal government: US$38 million
  - local governments: US$850 million
  - residential property value loss: US$380 million
  - forest landowner timber sales: US$60 million

Chalara ash dieback fungus (*Hymenoscyphus fraxineus*)

- Introduced from East Asia, particularly Japan and northeastern China[10]
- Aided by the movement of nursery plants and possibly by movement of firewood and logs[11,12]
- Millions of *F. excelsior* trees are now dying[11]

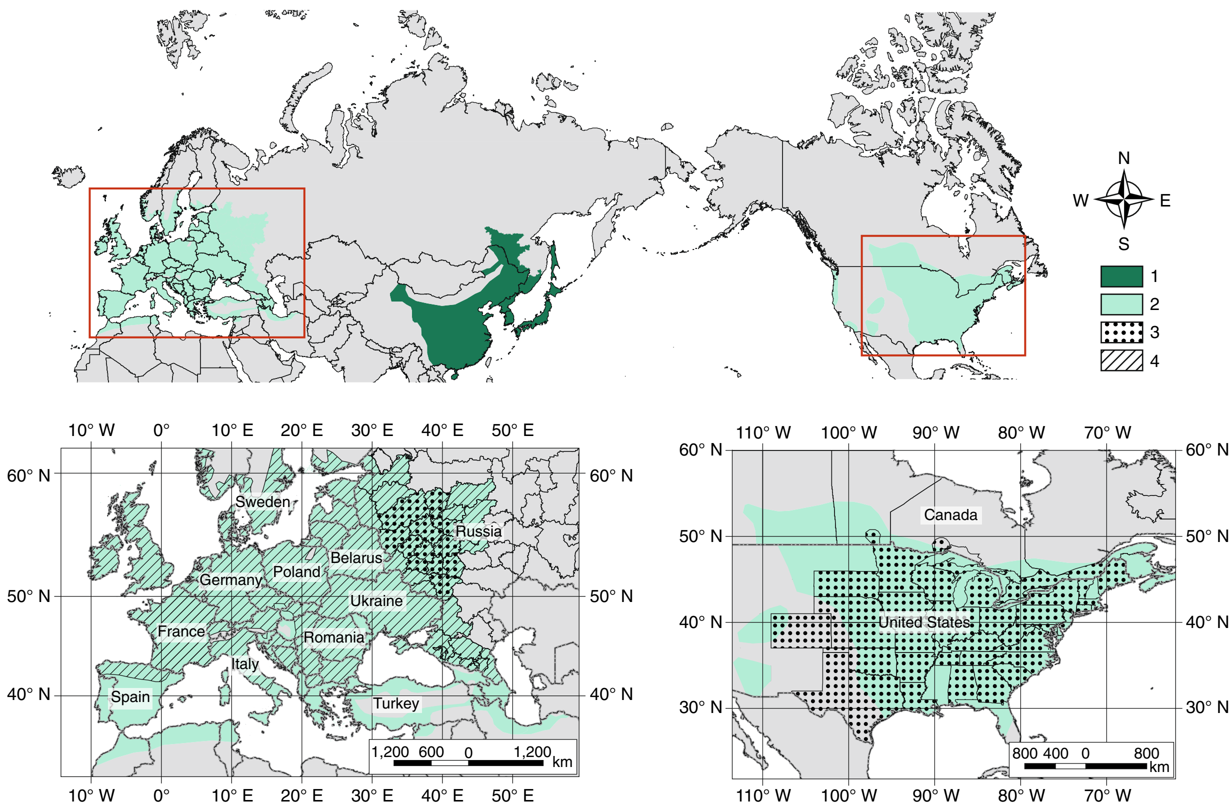

Fig. 1 | Ash (*Fraxinus*) species distribution and secondary ranges of two invaders, EAB (*A. planipennis*; www.emeraldashborer.info)[6] and *Chalara* ADF (*H. fraxineus*)[13,15]. (1) Distribution of Asian ash species with primary ranges of EAB and ADF; (2) distribution of European and North American ash species; (3) secondary range of EAB; (4) secondary range of ADF. Distributions in Canada, Scandinavia and Spain are generated based on real observations, and in Russia and the United States based on administrative regions (districts and states) where EAB and ADF were found. Top photo shows *F. excelsior* in Tuse Næs, Denmark; middle photo shows EAB observed in Voronezh District, Russia; bottom photo shows fruiting bodies of ADF observed in Denmark. Publ. note: Springer Nature is neutral about jurisdictional claims in maps. Credit: top and bottom photos, Lene R. Nielsen; middle photo, Yuri N. Baranchikov.

Table 1 | Key recommendations and interventions from policy and science

Policy	Science
• Harmonize phytosanitary regulations for transport, travel and trade across North America and Eurasia • Continuously update phytosanitary regulations with science-based knowledge • Educate phytosanitary inspectors on use of rapid diagnostic kits or similar resources and media tools • Raise awareness of EAB and ADF among professionals and policy leaders in all affected countries • Classify ADF as a regulated pest in North America • List ADF as an A2 pest in the Eurasian Economic Union • Apply stricter regulations in the European Union • Take proactive action against invasive alien species	• Find effective biological control agents against EAB • Identify reliable SNP markers and test them for rapid resistance screening for ADF • Establish experimental plots to characterize susceptibility of different ash species to EAB, ADF or both • Identify genotypes possessing both ADF and EAB resistance by using ash populations in European Russia having both EAB and ADF • Quantify the presence of resistant phenotypes and assess their fitness in situ • Combine knowledge from genetics, ecology and silviculture • Utilize available scientific resources, for example, reference genome of *F. excelsior*, metabolomics, comparative genomics and transcriptomics, to better understand resistance mechanisms in ash

In North America, both EAB and ADF appear in the Phytosanitary Alert System of the North American Plant Protection Organization (www.pestalert.org), but ADF exists only as an emerging pathogen because it is not yet present in North America. Classifying ADF as a 'regulated pest' could help prevent its introduction into North America.

In Eurasia, the European and Mediterranean Plant Protection Organization (EPPO; www.eppo.int) recommends its 52 member countries to regulate pests as quarantine pests according to two lists: A1 (pests absent in the EPPO region) and A2 (pests locally present in the EPPO region). The current listing of EAB and ADF in the EPPO Global Database (https://gd.eppo.int) is presented in Supplementary Table 2. Treating the European Union as a single biosecurity unit with a stricter regulation may slow the spread of future invasive alien species. Our concern is that current legislation is insufficient to prevent the invasion, establishment and spread of non-indigenous pests unless general pathways of introductions are controlled earlier, along with earlier professional and public engagement[17].

Professional awareness, which is currently at a low level, as indicated by a survey conducted in nine European countries with 392 tree professionals[18], is also a necessary complement to better phytosanitary regulations. Many lacked awareness or knowledge about either EAB (64.9%) or ADF (40%)[18]. Raising awareness can be an effective intervention strategy: wood packaging material infestation rates in the United States dropped by 36–52% after International Standards for Phytosanitary Measures No. 15 came into force, leading to better inspection and treatment of such materials[19].

A related problem is that specific phytosanitary action against a particular organism often takes place too late. A pest is sometimes banned only after proven economic damage[17]. The better course of action is to be proactive. One option is for phytosanitary inspectors to implement the rapid molecular diagnostic kits already available for ADF[20]. This kit can be integrated with other best practices in phytosanitary regulations harmonized across North America and Eurasia.

Scientific solutions

Using biological control agents against EAB. Biological controls can be effective, yet have unpredictable outcomes. For example, hymenopteran insects parasitic to EAB were previously introduced in North America from East Asia as control agents. Although these EAB parasites failed to protect mature ash trees, they did enhance saplings' survival and promoted some recovery of the ash in southern Michigan[21]. However, this was not the outcome for the Moscow region, the epicentre of the EAB secondary range in Europe. Here, EAB invader populations collapsed due to the polyphagous parasite *Spathius polonicus* Niezabitowski[6]. *S. polonicus* is indigenous to Western Europe and may reduce outbreak incidence once it spreads to the central distribution of European ash[22]. This observation emphasizes the need for interacting population dynamics of host and parasite across national borders to achieve the most effective biological controls. Thus, research coordination is essential.

Rapid resistance breeding coupled with phenotype-based methods. The good news is that European ash species show high genetic variation in ADF resistance[15], and ADF resistance is currently being identified in a range of genetic backgrounds using both field testing and genome- and transcriptome-wide screening of European ash. A population survey of ash trees in Denmark showed ADF tolerance can be screened using single nucleotide polymorphisms (SNPs) and gene expression markers[23,24]. Even so, further research is necessary to identify a larger set of reliable SNP markers. These markers must be tested on phenotyped trees across Europe before rapid screening can become operational. This too requires international cooperation. Identification of resistance mechanisms in European ash will provide new insights and better policy solutions.

A related point is that seeds and pollen of European ash spread rapidly across landscapes[25], allowing ADF-resistant trees to increase in frequency. Both newly established and old-growth forests may be protected by combined natural and artificial selection if ash phenotypes selected for high resistance spread their alleles into naturally occurring ash forests. Resistance breeding for ash trees is ongoing in both North America and Europe[15,26], but molecular shortcuts are essential[24].

Research continues towards characterizing susceptibility of different ash species to either EAB or ADF, or to both pests. Although studies in Europe show that *F. americana* and *F. pennsylvanica* are susceptible to ADF[14], and observations from Russia show that *F. excelsior* is infested by EAB[22], there seems to be variation among species. Establishing experimental plots is a necessary action step. Ideal phenotypic candidates are those selected from ash populations in the territory of European Russia, which already have both EAB and ADF. Doing so would provide timely insights into EAB and ADF resistance in European ash forests.

Ash co-evolution and adaptation

Emerging infectious diseases often leave a fraction of surviving trees and these survivors are critical to the future of the species[27]. It is important to quantify the presence of resistant phenotypes and to assess their fitness under in situ conditions. For ADF, the presence of naturally occurring genetic resistance is based on field testing of survival and crown damage, but this is just one part of measuring fitness[28]. The potential recovery of ash species in forest ecosystems will also depend on: (1) reproductive success of surviving trees; (2) extent of gene flow among populations; and (3) how the disease influences relative competitiveness with other species in ecosystems. Such studies are complex to conduct under heterogeneous in situ field environments and require cooperation across genetics, ecology and silviculture. Application of DNA markers is another tool that allows precise paternity assignment even in naturally occurring forests[25]. In addition, these markers can reveal signatures of past and ongoing natural selection, also critical for guiding the management of infected ash forests.

Genomics for resistance

Another powerful scientific resource is the reference genome sequence of *F. excelsior* recently published to facilitate studies on ADF resistance[24]. Metabolomic analyses found low levels of iridoid glycoside to be closely associated with ADF resistance in *F. excelsior*[24], suggesting a likely trade-off between resistance to ADF and to EAB, but more testing is still needed. Similarly, defence-related proteins may be involved in EAB resistance in Manchurian ash[29], and therefore candidates for screening and comparison among Asian, European and North American ash species. Pest resistance may also be identified using the reference transcriptome generated for North America's green ash[30], but the reference ash genome does not yet lead us to markers for EAB resistance.

Taken together, the best available scientific knowledge includes a wide portfolio of intervention options ranging from comparative genomics, transcriptomics and metabolomics platforms to field testing. More research is required to identify ash genotypes possessing resistance to both ADF and EAB. The tools to mine resistance genes are available, meaning ash forest losses in both North America and Eurasia can be stemmed.

Need for an international consortium

Though there are widespread policy and science-based intervention options, they are currently fragmented, and the solutions clearly require international cooperation. We recommend an international consortium, charged with taking swift, integrative action to slow the loss of ash forests. The consortium would initiate and coordinate activities as follows: (1) harmonize phytosanitary regulations for transport, travel and trade; (2) raise awareness of ADF and EAB among professionals and policy leaders in all affected countries; (3) educate officials on use of rapid diagnostic kits and media tools; and (4) the application of the best available scientific resources including mining ash phenotypes for joint EAB and ADF resistance.

As a start, we propose that this consortium is organized with stakeholders including governments, non-governmental organizations and private companies to share knowledge and coordinate international action. The organization could be similar to the European Cooperation in Science and Technology action known as FRAXBACK where knowledge on ADF is shared among scientists and stakeholders in Europe (http://www.cost.eu/COST_Actions/fps/FP1103). However, this new consortium should be global in its scope and focus on both EAB and ADF. The international consortium would have a time-limited charter based on measurable outcomes, and will require multilateral support, perhaps best organized under the International Plant Protection Convention treaty.

In summary, we show that reliable policy and science-based solutions are at hand, but what is lacking is international coordination of these efforts. Now is the time to act swiftly and save the world's ash forests. ❐

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Competing interests

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Additional information

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