

# How does the Emerald Ash Borer (*Agrilus planipennis*) affect ecosystem services and biodiversity components in invaded areas?

G. Schrader<sup>1</sup>, R. Baker<sup>2</sup>, Y. Baranchikov<sup>3</sup>, L. Dumouchel<sup>4</sup>, K. S. Knight<sup>5</sup>, D. G. McCullough<sup>6</sup>, M. J. Orlova-Bienkowskaja<sup>7</sup>, S. Pasquali<sup>8</sup> and G. Gillioli<sup>9</sup>

<sup>1</sup>Julius Kuehn Institute (JKI)-Federal Research Centre for Cultivated Plants, Institute for National and International Plant Health, Messeweg 11/12, 38104, Braunschweig (Germany); e-mail: Gritta.schrader@julius-kuehn.de

<sup>2</sup>Formerly: Plant Health Risk and Horizon Scanning Team, Defra, National Agri-food Innovation Campus, York, YO41 1LZ (UK)

<sup>3</sup>V.N. Sukachev Institute of Forest FRC KSC Siberian Branch, Russian Academy of Sciences, 50/28 Akademgorodok, Krasnoyarsk, 660036 (Russia)

<sup>4</sup>Formerly Plant Health Risk Assessment Unit, Science Division, Canadian Food Inspection Agency (CFIA), 59 Camelot Drive Ottawa, Ontario, ON K1A 0Y9 (Canada)

<sup>5</sup>USDA Forest Service Northern Research Station, 359 Main Rd., Delaware, OH 43015 (USA)

<sup>6</sup>Department of Entomology and Department of Forestry, Michigan State University, East Lansing, MI 48820 (USA)

<sup>7</sup>A.N. Severtsov Institute of Ecology and Evolution, Russian Academy of Sciences, 33 Leninskij prosp., 119071, Moscow (Russia)

<sup>8</sup>CNR-IMATI, Via A. Corti 12, 20133, Milano (Italy)

<sup>9</sup>Dipartimento di Medicina Molecolare e Traslazionale, Università degli Studi di Brescia, Viale Europa 11, 25123, Brescia (Italy)

Environmental risk assessment (ERA) is an important component of risk analysis for plant pests and invasive alien species (IAS), and a standardized and consistent methodology has recently been developed for evaluating their impact on ecosystem services and biodiversity. This paper presents the application of this innovative methodology for ERA to *Agrilus planipennis*, the emerald ash borer, which causes significant mortality to *Fraxinus* (ash) species in forests and urban areas of North America (here: USA and Canada, excluding Mexico) and Russia. The methodology follows a retrospective analysis and summarizes information and observations in invaded areas in North America and Russia. Uncertainty distributions were elicited to define quantitatively a general pattern of the environmental impact in terms of reduction in ecosystem provisioning, supporting and regulating services, and biodiversity components. The environmental impacts of *A. planipennis* are time- and context-dependent, therefore two time horizons of 5 and 20 years after introduction and two ecosystems (urban and forest) were considered. This case study shows that the quantitative assessment of environmental impacts for IAS is both possible and helpful for decision-makers and risk managers who have to balance control costs against potential impacts of IAS.

## 1. Introduction

The emerald ash borer, *Agrilus planipennis* Fairmaire, 1888 (Coleoptera: Buprestidae), is native and widespread in North-Eastern China, Japan, North and South Korea, and the Russian Far East (Haack *et al.*, 2015). Though Mongolia and Taiwan are indicated as a part of the native range of emerald ash borer in many articles, no documented records for these countries are available (Orlova-Bienkowskaja & Volkovitch, 2018).

The beetle was introduced into Canada, the USA and the European part of Russia most probably in the early 1990s. Recently, it was found in the Ukraine (Droghvalenko *et al.*, 2019; EPPO, 2019). Detailed information on introduction history in North America (in this article, North America refers to USA and Canada) and Russia can be found in, for example, Baranchikov *et al.*, 2008; Siegert *et al.*, 2014;

Haack *et al.*, 2015). Recently, the beetle has also been found in St. Petersburg, Russia, close to the EU border (Volkovish & Suslov, 2020).

In invaded areas, the beetle may kill trees in the genus *Fraxinus* and thus harm ecosystems, since *Fraxinus* often plays an important role in riparian habitats and in remnant forests (e.g. McKenney *et al.*, 2012, citing others). For this reason, a detailed environmental risk assessment (ERA) was deemed important to assess properly the full scale of the impact *A. planipennis* can have. A pest risk analysis (PRA) for *A. planipennis* in the EPPO (European and Mediterranean Plant Protection Organization) region was conducted by EPPO (2013) in which the probability and/or magnitude of entry, establishment, spread, impact and different management options for this invasive alien species (IAS) were assessed. However, environmental impacts were not assessed in detail. The intent of this paper is to conduct

an in-depth analysis of the beetle's impact on the environment and to assess quantitatively the impact of this species on ecosystem services and biodiversity in newly invaded areas. Ecosystem services are benefits recognized by humans as obtained from ecosystems that support, directly or indirectly, humans' survival and/or quality of life. They include provisioning, regulating and cultural services that directly benefit people, and the supporting services needed to maintain the direct services (MEA, 2003; Harrington *et al.*, 2010). In this study, impacts to urban areas and forested areas were rated separately for selected ecosystem services grouped into provisioning, regulating and supporting services (see also Gilioli *et al.*, 2014). To fulfil this aim, this study focused on the introduction and spread of *A. planipennis* in North America and the European part of Russia.

Assessing evidence of adverse impacts of IAS on native species and ecosystems requires the development of consistent, standardized tools to identify, prioritize and manage the environmental impact of IAS, which can be used by risk assessors with varied knowledge.

Recently, a novel standardized approach has been developed to obtain comparable and reproducible outputs for ERA based on the impact on ecosystem services as a part of PRA. The quantitative methodology, described in detail by Gilioli *et al.* (2014) and applied to the apple snail *Pomacea* spp. (EFSA, 2014a; Gilioli *et al.*, 2017), assesses the environmental risks by integrating the impacts of a pest on different components of the environment, with ecosystem services and biodiversity as the key elements of the analysis, and the probabilities of occurrence of these impacts, taking into account the uncertainties related to the estimations (EFSA, 2018). An expert knowledge elicitation (EKE) procedure can be applied (EFSA, 2014b) that allows a transparent method of rating, even if data are scarce (EFSA, 2018).

The impacts for the two categories of habitat and the two time horizons are assessed based on an in-depth review of the published information available for North America and Russia. To conduct the assessment, a panel of experts on the pest from these recently invaded regions was created.

## 2. Methodology

Five emerald ash borer experts (Y. Baranchikov, L. Dumouchel, K.S. Knight, D.G. McCullough, M.J. Orlova-Bienkowskaja – co-authors of this paper) from North America and Russia assessed the impact of *A. planipennis* on ecosystem services and biodiversity. Questionnaires were sent to these experts with a detailed description of how they should be completed. The experts selected the relevant publications by systematic literature review. Their own publications and direct observations were considered as well. They applied their expert judgment with regard to the impacts on ecosystem services and biodiversity components, and identified the relevant biological and ecological circumstances

and conditions as well as any management measures that had been applied.

The methodology described in EFSA (2011, 2014a) and Gilioli *et al.* (2014, 2017) for environmental risk assessment was originally proposed to prospectively assess impacts in a specific area. In this paper the methodology is applied to describe the sequence of events and impacts from the introduction of the emerald ash borer into new areas in order to derive a general pattern for environmental risk associated with *A. planipennis* based on observations and studies conducted in those areas. In this retrospective analysis, to account for the temporal evolution of the environmental consequences of *A. planipennis*, the analysis considered two time horizons and two broad habitat categories.

### 2.1. Components of the retrospective analysis

Emerald ash borer affects plant growth, reproduction and survival. This triggers a cascade of effects on one or more components of biodiversity and ecosystem functions that provide the ecosystem services. The ERA is undertaken at the level of the service providing units (Vandewalle *et al.*, 2008) – functional units in which the components (individuals, species or communities) are characterized by functional traits defining their ecological role and contributing to the generation and regulation of ecosystem services. The influence of the pest on the ecosystem services provision level and biodiversity is assessed by expert judgment (Fig. 1). Components of uncertainty that have to be taken into account when such a retrospective analysis is done are the variability in the population abundance, and the influence of resistance, resilience and management (EFSA, 2011; Gilioli *et al.*, 2014).

#### 2.1.1. Population abundance

Population abundance is seen as the main driver of the environmental impact of an IAS (Gilioli *et al.*, 2014). The typical spatial pattern of *A. planipennis* abundance is characterized by areas with high density, with large areas with very low densities surrounding those (Taylor *et al.*, 2010; Siegert *et al.*, 2015; Mercader *et al.*, 2016). Long-distance spread of *A. planipennis* can be attributed to human transport of infested ash trees from nurseries, unprocessed logs and firewood causing numerous infestations, which has substantially accelerated spread in Michigan, for example (Prasad *et al.*, 2010; Siegert *et al.*, 2014, 2015). From Moscow, the beetle has spread mainly along roads and railways, via train and car (Prasad *et al.*, 2010; Selikhovkin *et al.*, 2017). As of August 2020, *A. planipennis* infestations have been identified in 35 US states and five Canadian provinces ([www.aphis.usda.gov/aphis/ourfocus/planthealth/plant-pest-and-disease-programs/pests-and-diseases/emerald-ash-borer](http://www.aphis.usda.gov/aphis/ourfocus/planthealth/plant-pest-and-disease-programs/pests-and-diseases/emerald-ash-borer); [www.emeraldashborer.info](http://www.emeraldashborer.info)). In Russia, the invasive range of *A. planipennis* has now expanded over 17 administrative districts in the Russian Federation (Musolin *et al.*, 2017; Orlova-Bienkowskaja & Bienkowski, 2018; Baranchikov &

Seraya, 2019; Baranchykov & Musolin, pers. comm.). Recently, the beetle was found in Ukraine (Drogvalenko *et al.*, 2019, EPPO, 2019).

High densities of host plants may decrease spread rates of the beetle and will eventually increase local density. Attempts to reduce pest populations by cutting large numbers of host trees may reduce available food resources, thereby increasing dispersal and local spread rates (Mercader *et al.*, 2011). In European Russia, the rate of spread encompassing natural and possibly human-assisted dispersal was estimated to be 10 km per year since the beetle's introduction (early 1990s) which is found now more than 250 km west of Moscow. Though most of the ash trees in Moscow have been damaged by *A. planipennis*, a large proportion of these have survived (Orlova-Bienkowskaja & Bieńkowski, 2018). It is possible that the *A. planipennis* population is suppressed by the parasitoid *Spathius polonicus* (Orlova-Bienkowskaja & Belokobylskij, 2014; Orlova-Bienkowskaja, 2015) and furthermore the climate in Moscow is colder than in most regions of North America affected by *A. planipennis*, which might have an effect on *A. planipennis* abundance. However, it has to be noted that at the south-western front of the emerald ash borer's expansion (the city of Voronezh, Orel) the damage is still ongoing.

Following Gilioli *et al.* (2017) the methodology for ERA presented here disregards the spatial dynamics and focuses the assessment on a scenario considering ideal service-providing units representing the conditions favourable for *A. planipennis*. In these habitats the emerald ash borer population abundance per area unit is assumed to vary according to the environmental conditions, the availability of resources (e.g. the host plant density and susceptibility), the ecosystem resistance and resilience (see Section 2.1.3), and management measures applied (see Section 2.1.4). The variability in the population abundance and its role in explaining the variability of the impact are taken into account in the elicited uncertainty distributions (Gilioli *et al.*, 2014; EFSA, 2014a, 2018).

### 2.1.2. Identification of the service-providing units in relation to the impacts of emerald ash borer

Emerald ash borer feeds primarily on ash tree species (*Fraxinus* spp.), with some interspecific differences in preference or resistance (Herms & McCullough, 2014). In addition to *Fraxinus*, *A. planipennis* may colonize and develop on white fringetree, *Chionanthus virginicus* L. (Cipollini, 2015).

Damage is caused by larvae feeding on the phloem and cambium in serpentine galleries, disrupting transport of nutrients and water (Cappaert *et al.*, 2005; Flower *et al.*, 2013a). Trees generally die within a few years once external symptoms become apparent (Knight *et al.*, 2013; Herms & McCullough, 2014). Details on damage in North America can be found in Aukema *et al.* (2011) and Herms & McCullough (2014). With its impacts on forest and urban ecosystems, *A. planipennis* initiates a cascade of effects on other species and ecosystem processes,

ultimately affecting ecosystem services and biodiversity components.

Based on the observed impacts in North America and Russia, and to cover the most important habitats, two service-providing units were defined: urban areas (streets, urban and suburban parks, and gardens where ash trees are dominant) and forests (pure or mixed forest stands where ash trees are dominant).

### 2.1.3. Ecosystem resistance and resilience

The impact of *A. planipennis* can be modified or mitigated by its interaction with the invaded ecosystems. Resistance of most North American ash trees to *A. planipennis* is low, given the lack of a co-evolutionary history with this or related insects (Herms & McCullough, 2014). A small percentage of ash trees appear to survive *A. planipennis* infestation (Knight *et al.*, 2012) and may exhibit resistance to the beetle (Koch *et al.*, 2015). Interspecific (Tanis & McCullough, 2012, 2015) and intraspecific (Koch *et al.*, 2015) differences in *A. planipennis* host preference and ash resistance or tolerance have been identified; multiple mechanisms may be responsible for tree survival (Koch *et al.*, 2015). Effects of parasitoids and predators may also contribute to resilience (Lindell *et al.*, 2008; Orlova-Bienkowskaja & Belokobylskij, 2014; Flower *et al.*, 2014; Orlova-Bienkowskaja, 2015; Duan *et al.*, 2017). The time needed to develop significant ecosystem resistance to emerald ash borer is estimated to be at least 20 years. In Moscow it took approximately 25 years for local biota to counter *A. planipennis* invasion.

### 2.1.4. Influence of management measures

In general, the first steps in managing *A. planipennis* are early detection techniques and mechanical control. Although a lot of effort has been made to manage *A. planipennis* (see, e.g., McCullough *et al.*, 2009; Herms & McCullough, 2014; Knight, 2014; Iverson *et al.*, 2016; Siegert *et al.*, 2017; Flower *et al.*, 2018), it is too early to determine the degree to which these efforts may mitigate the ecological effects of *A. planipennis*. It has been found that, if the stem of the ash tree dies or is cut off, the epicormic or basal sprouts may survive and grow (Kashian, 2016). Many ash trees in Moscow have been replaced by their epicormic shoots, which are already 10 cm in breadth and produce seeds. Biocontrol by native or introduced natural enemies allows ash seedlings, saplings and young trees to recover in forest ecosystems in Michigan (Duan *et al.*, 2017). The combination of these tactics can significantly reduce emerald ash borer population growth rates and decrease the rate of ash decline and mortality (Mercader *et al.*, 2015).

### 2.1.5. Temporal horizon

The environmental impact of emerald ash borer relates to the local pest population abundance influenced by environmental conditions and the interactions with the communities in newly invaded areas. In North-Eastern China,

*A. planipennis* completes one generation usually in 1 year, some individuals take 2 years, and in some parts of China 2 years are more common (Wei *et al.*, 2007). Reasons for this are suggested by Cappaert *et al.* (2005), EPPO (2013), and Flø *et al.* (2014). The semivoltine cycle slows population growth in newly established, low-density populations (Mercader *et al.*, 2011; Herms & McCullough, 2014). In European Russia, the complete life cycle for most of the specimens took 2 years (Orlova-Bienkowskaja & Bienkowski, 2016).

Taking into account the information available, two relevant time horizons have been chosen so that a comparison can be made on the short- and long-term prevalence of the pest in the two service-providing units. For short-term effects, mainly dependent on ecosystem resistance, a temporal horizon of 5 years was set, a period considered necessary for the first significant impacts, close to the time of introduction. Then 20 years were set to account for the more long-term effects of the pest when it is already widespread in the receiving ecosystem, also taking into account ecosystem resilience. The variability in the population abundance in the area in which the beetle could establish at the end of the two selected temporal horizons is considered in the estimation of the uncertainty distribution of the impact.

#### 2.1.6. Assessed ecosystem services and biodiversity components

In this study, the five experts separately rated the impacts to urban areas and to forested areas for each of the following ecosystem services:

- provisioning services: food, fibre, biochemical and natural medicines, ornamental resources, genetic resources, fresh-water
- regulating services: air quality regulation, climate regulation, water regulation and cycling, erosion regulation
- supporting services: nutrient cycling, photosynthesis and primary production, pest and disease regulation.

Furthermore, impacts on the following biodiversity components were assessed: genetic diversity, native species diversity, composition and structure of habitats, communities and/or ecosystems, rare or vulnerable species, and habitats of high conservation value (see also Gilioli *et al.*, 2014).

## 2.2. Uncertainty distributions of the reduction in ecosystem service provision levels and biodiversity components

Experts were asked in a semiformal EKE (EFSA, 2014b) to evaluate the percentage of reduction in the level of ecosystem services and biodiversity components. The impacts have been estimated using the above-mentioned questionnaires by applying a quantitative scoring system to ensure consistency and transparency (Fig. 1). Five classes of ratings were considered: minimal, minor, moderate, major and massive, which are defined in detail in EFSA (2011) and Gilioli *et al.* (2014, 2017). The rating system was

developed based on the estimation of uncertainty distributions representing the percentage reduction in the different ecosystem services and of the pest's impacts on components of structural biodiversity. Experts worked independently to assign a probability for each interval of magnitude of impact for each ecosystem service and biodiversity component, thus creating a discrete probability distribution which quantified uncertainty in the magnitude of the impact. Uncertainty distributions also account for the variation in impacts reported for North America and Russia as a consequence of the interaction of the beetle with the community and the ecosystem functioning of the receiving ecosystems. The contribution of management measures to uncertainty has also been considered. Figure 1 gives an example of the rating process. Large differences between these distributions were discussed by experts afterwards to come to closer agreement based on published evidence and strict adherence to the specified scenarios.

## 3. Results and discussion

### 3.1. Overview of ecosystem services assessed

Table 1 gives an overview of the ecosystem services that were considered in this study.

Table 2 shows the ratings obtained by the experts.

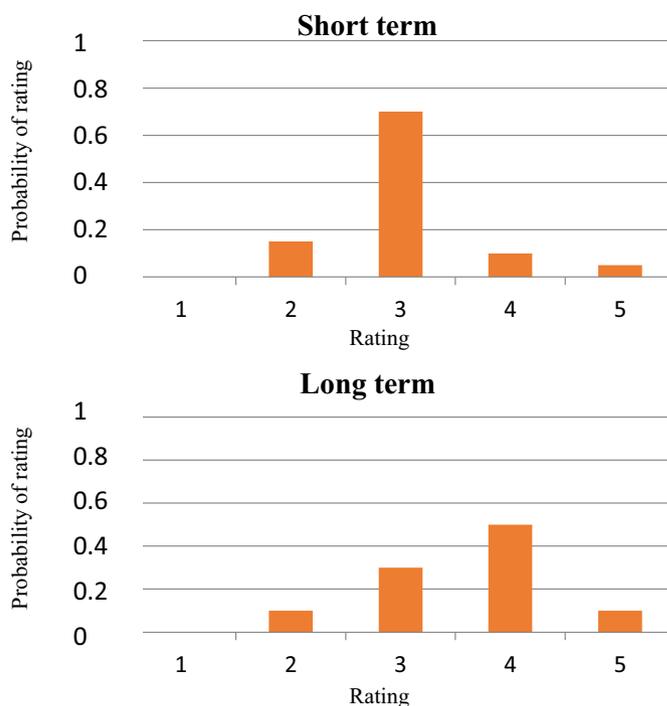
In the following sections, some explanations are given for the ratings chosen by the experts. The rating is based on areas where ash is dominant; the actual impact depends on the proportion of host plants within the service-providing units, on the role played by natural enemies of *A. planipennis* and on biological control of the pest over time. Uncertainty is often due to the inter- and intraspecific resistance among ash species and the occurrence of environmental stresses (e.g. drought events) affecting tree vulnerability to *A. planipennis*, to the amount of ash trees affected, time since infestation, the use and effectiveness of systemic pesticides, and the replacement of ash trees with other species. Considerable uncertainty in the magnitude of effects stems also from variation in landscape features, precipitation and mechanisms related to the removal of pollutants from air and water, how quickly ash trees are replaced and with which species, and the time it takes for replacement trees to reach similar properties (height, root system etc.).

### 3.2. Provisioning services affected by *A. planipennis*

#### Fibre

Initially, due to the infestation with emerald ash borer, the availability of wood fibres is expected to increase. In North America, urban trees, even if not valuable as sawn timber, have been harvested in some areas invaded by *A. planipennis*, and in forests large white ash trees have been pre-emptively harvested and salvaged, so even in highly impacted forest areas, there was and still is a significant amount of timber that can be processed. In the long term,

Photosynthesis and primary production of macrophytes in forests							
RATING		Minimal	Minor	Moderate	Major	Massive	Sum
Short term	USA 1	0	0.15	0.7	0.1	0.05	1
Long term	USA 1	0	0.1	0.3	0.5	0.1	1



**Fig. 1** Example of the assessment by one of the experts of the ecosystem service 'photosynthesis and primary production' for the service providing unit 'forests' and the two time horizons 5 years and 20 years. 1, minimal/negligible; 2, minor; 3, moderate; 4, major; 5, massive. The expert had to estimate the probability (in percent) of each score. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

the availability of fibre is reduced. At the urban level, only ash trees not protected with insecticides die and investment in treatment may reduce harvesting, but since in urban areas timber of *Fraxinus* is rarely harvested, the impact remains low. In forests, in the long term, the entire industry has to use other hardwood species or switch to different products.

#### *Ornamental resources*

The reduction in impacts depends on the availability of management measures and the presence of (effective) natural enemies. In urban areas, impacts mainly depend on the effectiveness of systemic insecticides (Herms *et al.*, 2009) and the extent to which *Fraxinus* have been killed/replaced with other trees. In forests, impact also depends on whether these forests are used for ornamental purposes. Since the emerald ash borer is able to kill its hosts and the detection of an infestation leads to host destruction, this is a seriously affected service.

#### *Genetic resources*

Planted urban trees are typically a few clonally propagated genotypes, and therefore unlikely to be genetically important. However, naturally regenerated ash in urban parks and the species that depend on them would likely represent some genetic diversity.

#### *Freshwater*

Effects may vary depending on the size of trees and the topography and hydrology of the landscape.

### 3.3. Regulating services affected by *A. planipennis*

#### *Air quality regulation*

In particular in urban areas, ornamental trees contribute to the removal of pollutants with possible direct consequences for human health (e.g. Escobedo *et al.*, 2001; Freer-Smith *et al.*, 2004). Larger trees would likely have a greater effect on air quality, so even if all urban ash trees are replaced, the replacement of large ash trees with small trees of other species will not make up for the air quality losses in the 20-year time scale assessed. Donovan *et al.* (2013) suggest that increased tree mortality by *A. planipennis*, which may have led to a decrease in air quality, was linked to an increase in cardiovascular and lower respiratory tract illness in 15 US states.

#### *Climate regulation*

In all regions, and in particular in areas with abundant ash, tree mortality caused by *A. planipennis* reduces cooling

**Table 1.** Overview of ecosystem services discussed in this study including a short description, and why these were or were not considered

Ecosystem service		
Provisioning services	Food	<i>Fraxinus</i> species are in general not a food source (except from some very indirect effects). The effects of <i>A. planipennis</i> on <i>Fraxinus</i> spp. food production are therefore considered negligible in all scenarios considered and are not discussed here.
	Fibre	White ash ( <i>F. americana</i> ) is a valued timber and veneer species used for tool handles, furniture, cabinets, flooring, etc. <i>F. angustifolia</i> has the potential to produce high-quality wood fibres and to be used in the pulp and paper industry; <i>F. pennsylvanica</i> is planted not only for landscaping purposes but also as merchantable saw timber and pulpwood.
	Biochemicals and natural medicine	The effects of <i>A. planipennis</i> on the extraction of biochemicals from ash trees is considered to be negligible and is not further considered here.
	Ornamentals	<i>Fraxinus</i> spp. has a high ornamental value in urban areas, including parks, and a moderate to high ornamental value in forests that depends on the use and management of the forest itself (e.g. numbers of visitors, recreational activities, etc.).
	Genetic resources	All ash tree species seem to be vulnerable to emerald ash borer (with some difference between the severity of impacts) and a number of species depend on ash (Gandhi & Herms, 2010), thus <i>A. planipennis</i> has the capacity to reduce genetic resources especially over longer time periods as impacts spread regionally.
	Freshwater	Large ash trees in urban areas provide major services in terms of stormwater capture. Ash trees take up stormwater, with the associated pollutants and debris that would otherwise eventually end up in rivers and lakes.
Regulating services	Air quality regulation	In urban areas ornamental trees contribute to the removal of pollutants with possible direct consequences for human health (e.g. Escobedo <i>et al.</i> , 2001; Freer-Smith <i>et al.</i> , 2004).
	Climate regulation	In urban areas, trees play a key role in modifying the urban microclimate: they humidify the surrounding atmosphere, ameliorate the urban heat island effect, and provide shade and wind shelter.
	Water regulation and cycling	The loss of ash can reduce stormwater retention and alter the hydrology of forests, generally increasing water yields and increasing moisture in the soil (Slesak <i>et al.</i> , 2014).
	Erosion regulation	Urban ash trees play a key role in erosion prevention along riverbanks and streams, but also streets and railroads. Ash tree mortality and felling may increase erosion in urban sites and the probability of urban landslides (Pfeil-McCullough <i>et al.</i> , 2015). Tree removal leaves soils vulnerable to increases in soil erosion by wind and water.
Supporting services	Nutrient cycling	Species composition changes resulting from ash mortality or replacement affects litter quality and abundance, subsequently altering nutrient profiles.
	Photosynthesis and primary production	<i>Fraxinus</i> spp. primary production is reduced due to the alteration of plant physiology and mortality caused by <i>A. planipennis</i> .
	Pest and disease regulation	The establishment of <i>A. planipennis</i> can cause cascading ecological effects, in particular the introduction and spread of wood-damaging species.

effects and carbon capture in the short term. It is difficult to estimate the impact of depleted ash tree resources on the climate of the region, hence the ratings given for both short-term and long-term effects attempt to reflect the high uncertainty related to this factor. It is possible that ash mortality will tip the balance from carbon sink to carbon source for forests across the region (Flower *et al.*, 2013b).

#### *Water regulation and cycling*

The magnitude of impacts on this ecosystem service depends in particular on the time and conditions of replacement by other tree species, the dominance of *Fraxinus* in the area under consideration, landscape features and precipitation.

#### *Erosion regulation*

In the long term, ash is replaced by other species in most areas, reducing potential erosion. In general, the topography of the landscape influences impacts. In flatter terrains, for example (e.g. in much of Russia or the US Midwest), impacts are generally lower.

### **3.4. Supporting services affected by *A. planipennis***

#### *Nutrient cycling*

In forests, nutrient cycling is affected by the nutrient composition of leaf litter inputs. The loss of ash, with its high-nitrogen litter, may affect nutrient cycling if the leaf litter of the species that replace ash differ in the chemistry of their leaves (Nisbet *et al.*, 2015). This change will increase from the short term to the long term as more ash trees die and the species composition of ecosystems changes. While some ecosystems may experience little change, others, for example ash swamp forest replaced with herbaceous swamp communities dominated by invasive plants, could experience a large impact on nutrient cycling, affecting the long-term biogeochemical cycle.

#### *Photosynthesis and primary production*

The impact in forests will depend on the dominance of ash and the presence of species that can rapidly grow to

**Table 2.** Results of the assessment of estimated impacts on ecosystem services caused by *Agrilus planipennis* for the two service-providing units (urban areas and forests) and the two time horizons (5 years and 20 years) [Colour table can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

Ecosystem services – Urban areas –		
Ecosystem service	Short-term risk/uncertainty	Long-term risk/uncertainty
Fibre	0.01/0.46	0.02/0.53
Ornamentals	0.19/0.87	0.49/0.64
Genetic resources	0.02/0.52	0.08/0.71
Freshwater	0.01/0.46	0.03/0.61
Air quality	0.07/0.79	0.1/0.76
Climate	0.03/0.65	0.08/0.81
Water regulation	0.02/0.45	0.06/0.69
Erosion	0.06/0.73	0.07/0.73
Nutrient cycling	0.023/0.57	0.063/0.72
Primary production	0.1/0.85	0.2/0.74
Pests/diseases	0.05/0.71	0.2/0.96

Ecosystem services – Forests –		
Ecosystem service	Short-term risk/uncertainty	Long-term risk/uncertainty
Fibre	0.007/0.37	0.18/0.9
Ornamentals	0.08/0.76	0.14/0.86
Genetic resources	0.02/0.53	0.09/0.82
Freshwater	0.02/0.55	0.06/0.76
Air quality	0.03/0.6	0.06/0.7
Climate regulation	0.04/0.7	0.08/0.82
Water regulation	0.03/0.65	0.12/0.85
Erosion	0.03/0.62	0.08/0.79
Nutrient cycling	0.06/0.71	0.11/0.79
Primary production	0.1/0.84	0.2/0.89
Pests/diseases	0.02/0.49	0.1/0.78

Risk ratings are demonstrated by colour coding. Colour codes do not consider uncertainty. Values for impacts: 0, minimal/negligible; >0–0.05, minor (light green); >0.05–0.2, moderate (yellow); >0.2–0.5, major (orange); >0.5, massive. Values for uncertainty: 0–0.33, low; >0.33–0.67, moderate; >0.67–1, high.

replace ash (Flower *et al.*, 2013b). In both service-providing units, if dead ash trees are not replaced, net primary production (NPP) is reduced over the long term. However, loss of black ash or other ash species that are highly vulnerable, abundant and unlikely to be replaced are likely to have serious effects on NPP.

#### *Pest and disease regulation*

The establishment of *A. planipennis* has resulted in some ecological effects, e.g. the frequent appearance of other xylophagous beetles in *A. planipennis*-infested trees which may have impacts on ash and other host plants (Orlova-Bienkowskaja & Volkovitsh, 2014; Orlova-Bienkowskaja, 2015).

### 3.5. Overview of biodiversity components assessed

Table 3 gives an overview of the biodiversity components that were considered in this study.

Table 4 shows the ratings obtained by the experts.

### 3.6. Biodiversity components affected by *A. planipennis*

#### *Genetic diversity*

Genetic diversity is generally not high in urban areas where *A. planipennis* is established, and genetic diversity is also limited in landscape trees produced in nurseries, which

**Table 3.** Overview of biodiversity components discussed in this study, including a short description and why these were considered

Biodiversity component	
Genetic diversity	Changes in species richness are expected due to the loss of ash species, insects and other species that depend on ash trees with these taxa potentially experiencing significant changes in genetic diversity.
Native species diversity	In urban areas, the effects will depend on the abundance of ash relative to other tree species. Organisms that require ash in their life cycle can be negatively affected. In forested areas, loss of canopy ash reduces canopy diversity, and a decline in native species diversity can promote the establishment of invasive species.
Composition structure	Where ash trees are replaced by multiple species, diversity increases but the vertical structure is negatively affected until the trees mature.
Rare and vulnerable species	Massive or complete loss of ash trees could impact rare or vulnerable species that depend on ash for some aspect of their life cycle.
Habitat conservation	Ash forests play a more important role than urban ash in terms of habitat conservation value. There may be a few examples of urban areas where relatively rare ash species are growing, but these are uncommon.

may be used as replacements. In the short term there will still be numerous live ash trees or parts of trees (e.g. root systems) available to arthropods that feed exclusively on ash trees. However, in the long term, if the whole tree dies, insect diversity and the species, which depend on them, decline as well. Early succession species not previously present in some older forests are able to take advantage of gaps created by dead ash trees, thus in some sites the local diversity of native trees and plants may increase slightly or remain unchanged. However, if non-native invasive plants or very aggressive native plants take advantage of the disturbance and become very abundant, local decreases in plant species diversity are possible. Therefore, in forests, species and genetic diversity of native insects is likely to be seriously impacted (Wagner & Todd, 2015; Musolin *et al.*, 2017).

#### *Native species diversity*

Efforts to replant other tree species following *A. planipennis* infestation may increase diversity, given the major emphasis on using a variety of trees in landscapes, however, native species diversity related to ash will be reduced or lost. Local changes in native species diversity vary tremendously among different types of ash ecosystems, while regional-scale diversity will likely experience negligible or small changes.

#### *Composition and structure of habitats, communities and/or ecosystems*

In forests, the gaps in the canopy that occur when *A. planipennis*-infested ash trees are killed in a relatively synchronous timing cause direct and indirect effects on forest composition by altering the understory vegetation, affecting nutrient cycling, changing successional patterns, facilitating the spread of shade-intolerant plants, facilitating woody (invasive) plant species and increasing the amount of dead wood (Herms & McCullough, 2014; Hoven *et al.*, 2017; Higham *et al.*, 2017; Costilow *et al.*, 2017). Uncertainty depends on ash species, their relative importance in the habitat, community and ecosystem under consideration, and potential non-native plant invasions (see review Wagner & Todd, 2015).

#### *Rare or vulnerable species*

In urban areas, blue ash (*F. quadrangulata*) and the flooded jellyskin lichen (*Leptogium rivulare*) are examples of threatened species of special concern that are directly or indirectly affected by *A. planipennis* (Environment Canada, 2013, 2016). In the short term, as in the case of blue ash, noninfested individuals of the rare or vulnerable species are still present both inside and outside of the *A. planipennis*-infested areas plus, in the case of *L. rivulare*, any infested ash trees present in the habitat of the threatened species might not yet have lost the bark with which the lichen is associated. In the long term, populations of *L. rivulare* may be severely impacted where lichen is abundant and growing principally on the bark of ash trees. In forests, local populations of invertebrates or other organisms that require ash can be affected, especially in the long term.

#### *Habitats of high conservation value*

Concerning forest environments little is known about the most vulnerable habitats, making it difficult to project *A. planipennis* impacts. For example, black ash dominated swamps are likely to support unique populations or communities.

### 3.7. Summarizing risks and uncertainties

The overall impact (Table 5) has been calculated according to the methodology in EFSA (2011, appendix C) and is rated as minor (short term) and moderate (long term). For the provisioning services the overall risk is rated as minor (short term) and moderate (long term), with highest impacts (long term) on ornamental resources (urban area) and fibre (forests). For the regulating and supporting services the same overall risk applies as for the provisioning services. Here the strongest impacts can be seen on photosynthesis and primary production for both urban areas and forests (Table 2). The biodiversity services are expected to be most affected by *A. planipennis*, in particular because of the impact on the composition and structure of habitats, communities and/or ecosystems (Table 4). The long term impact on biodiversity components in forests is major (Table 5).

**Table 4.** Results of the assessment of biodiversity components for the two service-providing units (urban areas and forests) and the two time horizons (5 years and 20 years) [Colour table can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

Biodiversity components – Urban areas –		
Biodiversity component	Short-term risk/uncertainty	Long-term risk/uncertainty
Genetic diversity	0.04/0.68	0.08/0.73
Native species diversity	0.02/0.55	0.06/0.54
Composition structure	0.08/0.82	0.4/0.8
Rare and vulnerable species	0.02/0.52	0.12/0.84
Habitat conservation	0.02/0.52	0.08/0.81

Biodiversity components – Forests –		
Biodiversity component	Short-term risk/uncertainty	Long-term risk/uncertainty
Genetic diversity	0.02/0.5	0.21/0.79
Native species diversity	0.02/0.6	0.23/0.76
Composition structure	0.06/0.75	0.3/0.83
Rare and vulnerable species	0.02/0.58	0.3/0.92
Habitat conservation	0.03/0.62	0.2/0.71

Risk ratings are demonstrated by colour coding. Colour codes do not consider uncertainty. Values for impacts: 0, minimal/negligible; >0–0.05, minor (light green); >0.05–0.2, moderate (yellow); >0.2–0.5, major (orange); >0.5, massive. Values for uncertainty: 0–0.33, low; >0.33–0.67, moderate; >0.67–1, high.

The overall uncertainty (in terms of the Shannon Entropy from 0 to 100%) is rated medium for the short term and high for the long term. The highest uncertainties derive from the evaluation of the biodiversity components. Especially in the long term, impacts on composition and structure of habitats, communities and/or ecosystems and rare or vulnerable species are difficult to estimate. The sources for these uncertainties are the same for all services: the impact of management measures on *A. planipennis* abundance, the reaction of the ecosystem in terms of resistance and resilience, the variation in impacts in different ecosystems across

the landscape, and the different impacts on urban areas and forests.

#### 4. Conclusions

The assessment of impacts caused by *A. planipennis* on the environment, based on consequences on ecosystem services and biodiversity, shows the implementation and practicability of the method described in Gilioli *et al.* (2014, 2017) and in EFSA (2014a). It demonstrates how the impacts on ecosystem services can be assessed quantitatively, including

**Table 5.** Overall risk and uncertainty for provisioning, regulating and supporting ecosystem services, and for biodiversity components, defined as the average of the risks and uncertainties for each category for the short (5 years) and the long (20 years) term (see appendix C in EFSA, 2011) [Colour table can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

Overall risk and uncertainty		
	Short-term risk/uncertainty	Long-term risk/uncertainty
Provisioning services - urban	0.039/0.45	0.104/0.449
Provisioning services - forest	0.023/0.47	0.08/0.67
Regulating and supporting - urban	0.05/0.68	0.11/0.77
Regulating and supporting - forest	0.044/0.66	0.107/0.8
Biodiversity components - urban	0.036/0.618	0.148/0.744
Biodiversity components - forest	0.03/0.61	0.248/0.802

Risk ratings are demonstrated by colour coding. Colour codes do not consider uncertainty. Values for impacts: 0, minimal/negligible; >0–0.05, minor (light green); >0.05–0.2, moderate (yellow); >0.2–0.5, major (orange); >0.5, massive. Values for uncertainty: 0–0.33, low; >0.33–0.67, moderate; >0.67–1, high.

the consideration of uncertainties. The method makes these uncertainties transparent by explicitly considering and presenting the probability of different levels of impact, confirming that the approach is particularly useful when uncertainties are present.

The analysis presented here is based on the general patterns of the temporal evolution of the impact. The authors did not deal with the spatial variation of the impacts, nor did they interpret the factors that locally influence impact (the host plant and the other components of the ecosystem). Applying this approach, the assessed invaded areas (in Russia, Canada and the USA) could be considered together to acquire a general view of potential or realized impacts, although the level of impact between the two macro-areas (Russia and North America) differs for several reasons, e.g. the effect of natural enemies and the fact that in Russia affected *F. excelsior* usually does not die but develops epicormic shoots. Differences between the two macro-areas of North America and Russia were considered a component of variability.

A more detailed analysis that considers the mechanisms at the origin of the variability in the impacts must first consider that the population abundance of the pest is the fundamental driver of impacts. Simply, the higher the abundance of the pest, the higher the impact. For this reason, a more local, in-depth knowledge of the relation between abundance and impact, and the spatial distribution of abundance is necessary for a more detailed and point-based analysis of environmental consequences. The availability of this local information would allow for the definition of more specific interpretative and forecasting tools that permits more detailed predictions or assessments to be made. However, for the purpose of the assessment presented here, the focus was on the general analysis of the impacts of *A. planipennis* on ecosystem services. That means that in this assessment a nomothetic approach was followed, generalizing the service-providing units, looking at certain general properties in comparison to an idiographic approach, where the individual situation is considered, looking at each service-providing unit separately and divided into the different areas.

Continued improvement in the techniques outlined above, as well as the development of new techniques to control or mitigate the effects of *A. planipennis* (including early detection and survey, Schrader *et al.*, 2020), may lead to future reductions in the risks estimated in this assessment. For example, a program to breed ash trees with increased resistance to emerald ash borer is underway in the USA and could provide planting stock in urban and forested areas for future restoration efforts (Koch *et al.*, 2015). By combining more sophisticated tools and techniques to respond to *A. planipennis*, managers may be able to reduce the future impacts of this pest.

In this case study, it was shown that the quantitative assessment of environmental impacts for IAS is both possible and helpful for decision-makers and risk managers who

have to balance control costs against potential impacts of IAS.

## Acknowledgments

The study by M.J. Orlova-Bienkowskaja was supported by the Russian Science Foundation, Project No 16-14-10031. Open access funding enabled and organized by Projekt DEAL.

## Comment l'agrile du frêne (*Agrilus planipennis*) affecte-t-il les services écosystémiques et les composantes de la biodiversité dans les zones envahies ?

L'évaluation des risques environnementaux est une composante importante de l'analyse de risque des organismes nuisibles aux plantes et des espèces exotiques envahissantes. Une méthodologie standardisée et cohérente a récemment été mise au point afin d'évaluer leur impact sur les différents services écosystémiques et sur la biodiversité. Ce document présente l'application de cette méthodologie innovante pour l'évaluation des risques environnementaux d'*Agrilus planipennis*, l'agrile du frêne, causant la mortalité d'espèces de *Fraxinus* (frêne) dans les forêts et zones urbaines d'Amérique du Nord (ici : États-Unis et Canada, à l'exclusion du Mexique) et de Russie. La méthodologie suit une analyse rétrospective et synthétise les informations et observations des zones envahies en Amérique du Nord et en Russie. Des distributions d'incertitude ont été établies afin de présenter une image globale et quantifiée de l'impact environnemental en termes de réduction de l'apport des services écosystémiques, des services de support et de régulation, et des composantes de la biodiversité. Les impacts environnementaux d'*A. planipennis* dépendent de facteurs temporels et contextuels, c'est pourquoi deux horizons temporels (à 5 et 20 ans après introduction de l'organisme) et deux écosystèmes (urbain et forestier) ont été pris en compte. Cette étude de cas montre que l'évaluation quantitative des impacts environnementaux des espèces exotiques envahissantes est à la fois réalisable et utile pour les décideurs et gestionnaires de risques qui doivent comparer les coûts de la lutte avec les impacts potentiels de ces espèces.

## Как ясеневая изумрудная узкотелая златка (*Agrilus planipennis*) воздействует на функции экосистемные услуги и элементы биоразнообразия в зонах инвазии ?

Оценка экологического риска (ОЭР) является важным элементом анализа риска для вредных организмов для растений организмов и инвазивных чужеродных видов (ИЧВ). Недавно была разработана стандартизированная и согласованная методология для оценки их воздействия

на функции экосистемные услуги и биоразнообразии. В данной статье представлено применение инновационной методики ОЭР к *Agrilus planipennis*, ясеневой изумрудной узкотелой златке, которая вызывает значительную смертность/потерю видов рода *Fraxinus* (ясени) в лесах и городских зонах/районах Северной Америки (здесь: США и Канада, исключая Мексику) и России. Методология основана на ретроспективном анализе и обобщает информацию и наблюдения в зонах инвазии в Северной Америке и России. Распределение неопределённости было использовано для количественного определения общей тенденции воздействия на окружающую среду с точки зрения сокращения обеспечения экосистемных услуг, по снабжению, по поддержке/вспомогательных и по регулированию функций, а также элементов биоразнообразия. Воздействие *A. planipennis* на окружающую среду зависит от времени и контекста, поэтому были рассмотрены два временных интервала в 5 и 20 лет после интродукции и две экосистемы (городская и лесная). Данное исследование показывает, что количественная оценка воздействия на окружающую среду для ИЧВ является возможной и полезной как для лиц, принимающих решения, так и для специалистов по управлению рисками, которым необходимо обеспечить баланс между затратами на борьбу и потенциальным негативным воздействием ИЧВ.

## References

- Aukema JE, Leung B, Kovacs K, Chivers C, Britton KO, Englin J *et al.* (2011) Economic impacts of non-native forest insects in the continental United States. *PLoS One* **6**, e24587.
- Baranchikov Y, Mozolevskaya E, Yurchenko G & Kenis M (2008) Occurrence of the emerald ash borer, *Agrilus planipennis* in Russia and its potential impact on European forestry. *EPPO Bulletin* **38**, 233–238.
- Baranchikov YN & Seraya LG (2019) The emerald ash borer on the way to Belgorod. *Botanic Gardens Conservation 390 International Russian Division Newsletter* **12**: 91–94 (in Russian).
- Cappaert D, McCullough DG, Poland TM & Siegert NW (2005) Emerald ash borer in North America: a research and regulatory challenge. *American Entomologist* **51**: 152–165.
- Cipollini D (2015) White fringetree as a novel larval host for emerald ash borer. *Journal of Economic Entomology* **108**, 370–375.
- Costilow KC, Knight KS & Flower CE (2017) Disturbance severity and canopy position control the radial growth response of maple trees (*Acer* spp.) in forests of northwest Ohio impacted by emerald ash borer (*Agrilus planipennis*). *Annals of Forest Science* **74**, 10.
- Donovan GH, Butry DT, Michael YL, Prestemon JP, Liebhold AM, Gatzliolis D *et al.* (2013) The relationship between trees and human health. *American Journal of Preventive Medicine* **44**, 139–145.
- Drogvalenko AN, Orlova-Bienkowskaja MJ & Bienkowski AO (2019) Record of the Emerald Ash Borer (*Agrilus planipennis*) in Ukraine is confirmed. *Insects* **10**, 338.
- Duan JJ, Bauer LS & Van Driesche RG (2017) 5.3 Impacts of North American Native and Introduced Natural Enemies on Population Dynamics of the Invasive Emerald Ash Borer. In *Proceedings of the 5th International Symposium on Biological Control of Arthropods* (eds. Mason, PG, Gillespie DR & Vincent C). CAB International.
- EFSA (European Food Safety Authority) (2014b) Guidance on expert knowledge elicitation in food and feed safety risk assessment. *EFSA Journal* **12**:3734 (278 pp.).
- EFSA (European Food Safety Authority) Panel on Plant Health (PLH) (2011) Guidance on the environmental risk assessment of plant pests. *The EFSA Journal* **9**: 2460 (121 pp.).
- EFSA (European Food Safety Authority) Panel on Plant Health (PLH) (2014a) Scientific opinion on the environmental risk assessment of the apple snail for the EU. *The EFSA Journal* **12**, 3641 (97 pp.).
- EFSA (European Food Safety Authority) Scientific Committee, Benford D, Halldorsson T, Jeger MJ, Knutsen HK & More S *et al.* (2018) Guidance on uncertainty analysis in scientific assessments. *EFSA Journal* **16**: 5123 (39 pp.).
- Environment Canada (2013) *Recovery Strategy for the Flooded Jellyskin Lichen (Leptogium rivulare) in Canada*. Species at Risk Act Recovery Strategy Series. Environment Canada, Ottawa, ON. iv + 23 pp.
- Environment Canada (2016) *Management Plan for the Blue Ash (Fraxinus quadrangulata) in Canada*. Species at Risk Act Management Plan Series. Environment Canada, Ottawa. iv + 25 pp.
- EPPO (European and Mediterranean Plant Protection Organization) (2013) Pest risk analysis for *Agrilus planipennis*. [http://www.eppo.int/QUARANTINE/Pest\\_Risk\\_Analysis/PRA\\_intro.htm](http://www.eppo.int/QUARANTINE/Pest_Risk_Analysis/PRA_intro.htm) [accessed on 15 December 2020].
- EPPO (European and Mediterranean Plant Protection Organization) (2019) Presence of *Agrilus planipennis* confirmed in Ukraine. EPPO Reporting Service No. 10, Article No. 2019/202. <https://gd.eppo.int/reporting/article-6632> [accessed on 15 December 2020].
- Escobedo FJ, Kroeger T & Wagner JE (2001) Urban forests and pollution mitigation: Analyzing ecosystem services and disservices. *Environmental Pollution* **159**, 2078–2087.
- Flø D, Krokene P & Økland B (2014) Importing deciduous wood chips from North America to northern Europe—the risk of introducing bark- and wood-boring insects. *Scandinavian Journal of Forest Research* **29**, 77–89.
- Flower CE, Fant JB, Hoban S, Knight KS, Steger L, Aubihl E *et al.* (2018) Optimizing conservation strategies for a threatened tree species: In situ conservation of white ash (*Fraxinus americana* L.) genetic diversity through insecticide treatment. *Forests* **9**, 202.
- Flower CE, Knight KS & Gonzalez-Meler MA (2013b) Impacts of the emerald ash borer (*Agrilus planipennis* Fairmaire) induced ash (*Fraxinus* spp.) mortality on forest carbon cycling and successional dynamics in the eastern United States. *Biological Invasions* **15**, 931–944.
- Flower CE, Knight KS, Rebeck J & Gonzalez-Meler MA (2013a) The relationship between emerald ash borer (*Agrilus planipennis*) and ash (*Fraxinus* spp.) tree decline: Using visual canopy condition assessments and leaf isotope measurements to assess pest damage. *Forest Ecology and Management* **303**, 143–147.
- Flower CE, Long LC, Knight KS, Rebeck J, Brown JS, Gonzalez-Meler MA *et al.* (2014) Native bark-foraging birds preferentially forage in infected ash (*Fraxinus* spp.) and prove effective predators of the invasive emerald ash borer (*Agrilus planipennis* Fairmaire). *Forest Ecology and Management* **313**, 300–306.
- Freer-Smith PH, El-Khatib AA & Taylor G (2004) Capture of particulate pollution by trees: a comparison of species typical of semi-arid areas (*Ficus nitida*) and *Eucalyptus globulus* with European and North American species. *Water, Air, and Soil Pollution* **155**, 173–187.

- Gandhi J K J & Herms DA (2010) North American arthropods at risk due to widespread *Fraxinus* mortality caused by the alien emerald ash borer. *Biological Invasions* **12**, 1839–46.
- Gilioli G, Schrader G, Baker Rha, Ceglarska E, Kertész V, Lövei G *et al.* (2014) Environmental risk assessment for plant pests: a procedure to evaluate their impacts on ecosystem services. *Science of the Total Environment* **468**, 475–486.
- Gilioli G, Schrader G, Carlsson N, van Donk E, van Leeuwen CHA, Martin PR *et al.* (2017) Environmental risk assessment for invasive alien species: a case study of apple snails affecting ecosystem services in Europe. *Environmental Impact Assessment Review* **65**, 1–11.
- Haack RA, Baranchikov YN, Bauer LS & Poland TM (2015) Emerald ash borer biology and invasion history. Biology and control of emerald ash borer. In Van Driesche RG & Reardon RC (eds.). USDA Forest Service, Forest Health Technology Enterprise Team (FHTET), Morgantown, WV. FHTET-2014-09. P. 1–14. [https://www.fs.fed.us/foresthealth/technology/pdfs/FHTET-2014-09\\_Biology\\_Control\\_EAB.pdf](https://www.fs.fed.us/foresthealth/technology/pdfs/FHTET-2014-09_Biology_Control_EAB.pdf) [accessed on 15 December 2020].
- Harrington R, Anton C, Dawson TP, de Bello F, Feld CK, Haslett JR, *et al.* (2010) Ecosystem services and biodiversity conservation: concepts and a glossary. *Biodiversity and Conservation* **19**, 2773–2790.
- Herms DA & McCullough DG (2014) Emerald ash borer invasion of North America: history, biology, ecology, impacts, and management. *Annual Review of Entomology* **59**, 13–30.
- Herms DA, McCullough DG, Smitley DR, Sadof C, Williamson RC & Nixon PL (2009) Insecticide options for protecting ash trees from emerald ash borer. *North Central IPM Center Bulletin* **12**. <https://mountainscholar.org/handle/10217/198685>
- Higham M, Hoven BM, Gorchov DL & Knight KS (2017) Patterns of coarse woody debris in hardwood forests across a chronosequence of ash mortality due to the emerald ash borer (*Agrilus planipennis*). *Natural Areas Journal* **37**, 406–411.
- Hoven BM, Gorchov DL, Knight KS & Peters VE (2017) The effect of emerald ash borer-caused tree mortality on the invasive shrub *Amur honeysuckle* and their combined effects on tree and shrub seedlings. *Biological Invasions* **19**, 2813–2836.
- Iverson L, Knight KS, Prasad A, Herms DA, Matthews S, Peters M *et al.* (2016) Potential species replacements for black ash (*Fraxinus nigra*) at the confluence of two threats: emerald ash borer and a changing climate. *Ecosystems* **19**, 248–270.
- Kashian DM (2016) Sprouting and seed production may promote persistence of green ash in the presence of emerald ash borer. *Ecosphere* **7**, e01332.
- Knight KS (2014) Outlook for ash in your forest: results of emerald ash borer research and implications for management. *Indiana Woodland Steward* **23**, 7.
- Knight KS, Brown JP & Long RP (2013) Factors affecting the survival of ash trees (*Fraxinus* spp.) infested by emerald ash borer (*Agrilus planipennis*). *Biological Invasions* **15**, 371–383.
- Knight KS, Herms D, Plumb R, Sawyer E, Spalink D, Pisarczyk E *et al.* (2012) Dynamics of surviving ash (*Fraxinus* spp.) populations in areas long infested by emerald ash borer (*Agrilus planipennis*). In: Sniezko RA *et al.*, *Proceedings of the 4th International Workshop on the Genetics of Host-Parasite Interactions in Forestry: Disease and Insect Resistance in Forest Trees*. July 31 – August 5 2011, Eugene, OR. General Technical Reports PSW-GTR-240. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA, 143–152.
- Koch JL, Carey DW, Mason ME, Poland TM & Knight KS (2015) Intraspecific variation in *Fraxinus pennsylvanica* responses to emerald ash borer (*Agrilus planipennis*). *New Forests* **46**(5-6), 995–1011. <https://doi.org/10.1007/s11056-015-9494-4>.
- Lindell CA, McCullough DG, Cappaert D, Apostolou NM & Roth MB (2008) Factors influencing woodpecker predation on emerald ash borer. *The American Midland Naturalist* **159**, 434–444.
- McCullough DG, Poland TM, Anulewicz AC & Cappaert D (2009) Emerald ash borer (*Agrilus planipennis* Fairmaire) (Coleoptera: Buprestidae) attraction to stressed or baited ash (*Fraxinus* spp.) trees. *Environmental Entomology* **38**, 1668–1679.
- McKenney DW, Pedlar JH, Yemshanov D, Lyons DB, Campbell KL & Lawrence K (2012) Estimates of the potential cost of emerald ash borer (*Agrilus planipennis* Fairmaire) in Canadian municipalities. *Arboriculture & Urban Forestry Online* **38**, 81–91. <http://joa.isa-arbor.com/articles.asp?JournalID=1&vol=38&issue=3>
- MEA (Millennium Ecosystem Assessment) (2003) *Ecosystems and human well-being: a framework for assessment*. Report of the Conceptual Framework Working Group of the Millennium Ecosystem Assessment. Island Press, Washington, DC.
- Mercader RJ, McCullough DG, Storer AJ, Bedford JM, Heyd R, Poland TM *et al.* (2015) Evaluation of the potential use of a systemic insecticide and girdled trees in area wide management of the emerald ash borer. *Forest Ecology and Management* **350**, 70–80.
- Mercader RJ, McCullough DG, Storer AJ, Bedford JM, Heyd R, Siegert NW *et al.* (2016) Estimating local spread of recently established emerald ash borer, *Agrilus planipennis*, infestations and the potential to influence it with a systemic insecticide and girdled ash trees. *Forest Ecology and Management* **366**, 87–97.
- Mercader RJ, Siegert NW, Liebhold AM & McCullough DG (2011) Influence of foraging behavior and host spatial distribution on the localized spread of the emerald ash borer, *Agrilus planipennis*. *Population Ecology* **53**, 271–285.
- Musolin DL, Selikhovkin AV, Shabunin DA, Zviagintsev VB & Baranchikov YN (2017) Between ash dieback and emerald ash borer: two Asian invaders in Russia and the future of ash in Europe. *Baltic Forestry* **23**(1), 316–333.
- Nisbet D, Kreutzweiser D, Sibley P & Scarr T (2015) Ecological risks posed by emerald ash borer to riparian forest habitats: a review and problem formulation with management implications. *Forest Ecology and Management* **358**, 165–173.
- Orlova-Bienkowskaja MJ (2015) Cascading ecological effects caused by establishment of the emerald ash borer *Agrilus planipennis* in European Russia. *European Journal of Entomology* **112**, 778–789.
- Orlova-Bienkowskaja MJ & Bienkowski AO (2016) The life cycle of the emerald ash borer *Agrilus planipennis* in European Russia and comparisons with its life cycles in Asia and North America. *Agricultural and Forest Entomology* **18**, 182–188.
- Orlova-Bienkowskaja MJ & Belokobylskij SA (2014) Discovery of the first European parasitoid of the emerald ash borer *Agrilus planipennis* (Coleoptera, Buprestidae). *European Journal of Entomology* **111**, 594–596.
- Orlova-Bienkowskaja MJ & Bieńkowski AO (2018) Modelling long-distance dispersal of emerald ash borer in European Russia and prognosis of spread of this pest to neighboring countries within next 5 years. *Ecology and Evolution* **8**, 9295–9304.
- Orlova-Bienkowskaja MJ & Volkovitch MG (2014) Range expansion of *Agrilus convexicollis* in European Russia expedited by the invasion of emerald ash borer, *Agrilus planipennis* (Coleoptera: Buprestidae). *Biological Invasions* **17**, 537–544.
- Orlova-Bienkowskaja MJ & Volkovitch MG (2018) Are native ranges of the most destructive invasive pests well known? A case study of the native range of the emerald ash borer, *Agrilus planipennis* (Coleoptera: Buprestidae). *Biological Invasions* **20**, 1275–1286.
- Pfeil-McCullough E, Bain DJ, Bergman J & Crumrine D (2015) Emerald ash borer and the urban forest: changes in landslide potential due to canopy loss scenarios in the City of Pittsburgh, PA. *Science of the Total Environment*, **536**, 538–545.

- Prasad AM, Iverson LR, Peters MP, Bossenbroek JM, Matthews SN, Davis Sydnor T *et al.* (2010) Modeling the invasive emerald ash borer risk of spread using a spatially explicit cellular model. *Landscape Ecology* **25**(3), 353–369. <https://doi.org/10.1007/s10980-009-9434-9>.
- Schrader G, Ciubotaru RM, Diakaki M & Vos S (2020) EFSA guidelines for emerald ash borer survey in the EU. *Forestry: An International Journal of Forest Research* **93**, 212–219.
- Selikhovkin AV, Popovichev BG, Mandelshtam MY, Vasaitis R & Musolin DL (2017) The Frontline of Invasion: the current Northern Limit of the Invasive Range of Emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae) in European Russia. *Baltic Forestry* **23**, 309–315.
- Siegert NW, McCullough DG, Liebhold AM & Telewski FW (2014) Dendrochronological reconstruction of the epicentre and early spread of emerald ash borer in North America. *Diversity and Distributions* **20**, 847–858.
- Siegert NW, McCullough DG, Poland TM & Heyd RL (2017) Optimizing use of girdled ash trees for management of low-density emerald ash borer (Coleoptera: Buprestidae) populations. *Journal of Economic Entomology* **110**, 1096–1106.
- Siegert NW, Mercader RJ & McCullough DG (2015) Spread and dispersal of emerald ash borer (Coleoptera: Buprestidae): estimating the spatial dynamics of a difficult-to-detect invasive forest pest. *Canadian Entomologist* **147**, 338–348.
- Slesak RA, Lenhart CF, Brooks KN, D'Amato AW & Palik BJ (2014) Water table response to harvesting and simulated emerald ash borer mortality in black ash wetlands in Minnesota, USA. *Canadian Journal of Forest Research* **44**, 961–968.
- Tanis SR & McCullough DG (2012) Differential persistence of blue ash and white ash following emerald ash borer invasion. *Canadian Journal of Forest Research* **42**, 1542–1550.
- Tanis SR & McCullough DG (2015) Host resistance of five *Fraxinus* species to *Agrilus planipennis* (Coleoptera: Buprestidae) and effects of paclobutrazol and fertilization. *Environmental Entomology* **44**, 287–299.
- Taylor RAJ, Bauer LS, Poland TM & Windell KN (2010) Flight performance of *Agrilus planipennis* (Coleoptera: Buprestidae) on a flight mill and in free flight. *Journal of Insect Behaviour* **23**, 128–148.
- Vandewalle M, Sykes MT, Harrison PA, Luck GW, Berry P, Bugter R *et al.* (2008) Concepts of dynamic ecosystems and their services. Deliverable D2, 1. Rubicode Project [Internet]; 21 pp. [www.rubicode.net/rubicode/outputs.html](http://www.rubicode.net/rubicode/outputs.html). 94 pp. [accessed on 15 December 2020].
- Volkovich MG & Suslov DV (2020) The first record of the emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae), in Saint Petersburg signals a real threat to the palace and park ensembles of Peterhof and Oranienbaum. In *Dendrobiotic invertebrates and fungi and their role in Forest Ecosystems*. The Kataev Memorial Readings – XI / Proceedings of the All-Russia conference with international participation. Saint Petersburg (Russia), November, 24–27, 2020. Musolin DL, Kirichenko NI & Selikhovkin AV eds. Saint Petersburg (Russia): Saint Petersburg State Forest Technical University, 2020. 452 p. <https://doi.org/10.21266/SPBFTU.2020.KATAEV>
- Wagner DL & Todd KJ (2015) Ecological impact of emerald ash borer. Biology and control of emerald ash borer. Van Driesche RG & Reardon RC (eds.). USDA Forest Service, Forest Health Technology Enterprise Team (FHTET), Morgantown, WV. FHTET-2014-09. 15–63. [https://www.fs.fed.us/foresthealth/technology/pdfs/FHTET-2014-09\\_Biology\\_Control\\_EAB.pdf](https://www.fs.fed.us/foresthealth/technology/pdfs/FHTET-2014-09_Biology_Control_EAB.pdf) [accessed on 15 December 2020].
- Wei XIA, Wu YUN, Reardon R, Sun TH, Lu MIN & Sun JH (2007) Biology and damage traits of emerald ash borer (*Agrilus planipennis* Fairmaire) in China. *Insect Science* **14**, 367–373.