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Article

A High-Resolution Map of Emerald Ash Borer Invasion Risk for Southern Central Europe

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Abstract: Ash species (*Fraxinus* spp.) in Europe are threatened by the Emerald Ash Borer (*Agrilus planipennis*, EAB), an invasive wood boring beetle native to East Asia and currently spreading from European Russia westwards. Based on a high-resolution habitat distribution map (grid cell size: 25 × 25 m) and data on distribution and abundance of Common Ash (*Fraxinus excelsior*), the most widespread and highly susceptive host species of EAB in Europe, we assess the spatial distribution of EAB invasion risks for southern Central Europe (Austria, Switzerland, Liechtenstein, southern Germany, South Tyrol). We found highest *F. excelsior* abundance and thus invasion risks in extensive lowland floodplain forests, medium risks in zonal lowland forests and low risks in upper montane and subalpine forests. Based on average velocities of spread in Russia (13–31 km/year) and North America (2.5–80 km/year) from flight and human-assisted transport, EAB is likely to cover the distance (1500 km) between its current range edge in western Russia and the eastern border of the study region within few decades. However, secondary spread by infested wood products make earlier introductions likely. The high susceptibility and mortality of *F. excelsior* leave no doubt that this beetle will become a major forest pest once it reaches Central Europe. Therefore, developing and testing management approaches with the aim to halt or at least slow down the invasion of EAB in Europe have to be pursued with great urgency.

Keywords: *Agrilus planipennis*; alien species; EAB; forests; *Fraxinus*; impact; management

1. Introduction

Ash species (*Fraxinus* spp.) are widespread in temperate and subtropical zones of the northern hemisphere. Three of the 43 species of this genus are native in Europe and also occur in Central Europe: the Common Ash (*F. excelsior*), the Narrow-leaved Ash (*F. angustifolia*) and the Manna Ash (*F. ornus*) [1]. Those ash species are widespread components of mixed deciduous forests—*F. excelsior* throughout Europe, *F. angustifolia* in the South and Southeast, and *F. ornus* in South and South-East Europe [2]. Another ash species occurring in Europe is the American species *F. pennsylvanica*, which has been planted across Europe for timber or as ornamental tree [2,3]. This species has become a fast-spreading alien species in parts of Central Europe, in particular in floodplain forests [4].

European ash species are at risk of getting- or already are -attacked by the Emerald Ash Borer (EAB) (*Agrilus planipennis* Fairmaire, Coleoptera: Buprestidae) (Figure 1). This wood-boring beetle native to Asia has been introduced to North America probably in the 1990s and has had substantial impact on ecosystems and economy since then [3,5]. EAB has also been found in European Russia in 2003 (Figure 2) and is making its way westwards towards Central Europe [6] putting European forestry and environment in danger [7].

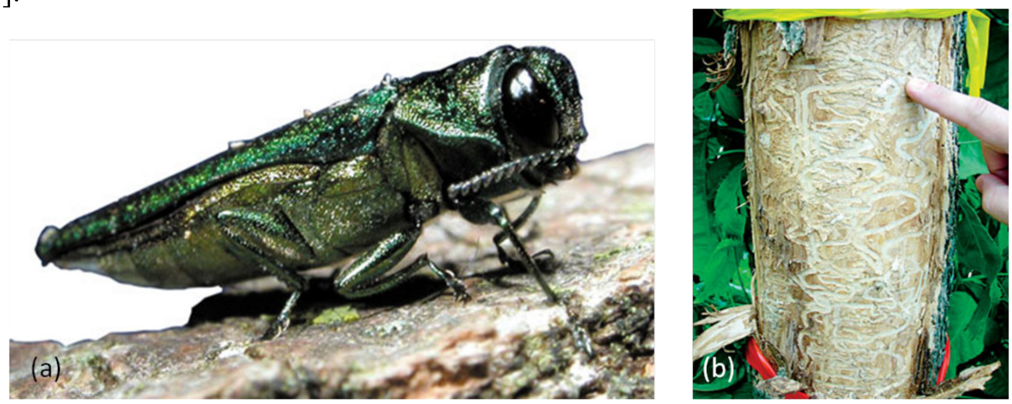

Figure 1. Pictures of adults (**a**) and galleries (**b**) of *Agrilus planipennis*. (Sources: Wikimedia Commons)

Therefore, here we assess the risk of EAB invasion for the by far most widespread ash species (*F. excelsior*) in southern Central Europe, *i.e.*, Austria, Switzerland, Liechtenstein, southern Germany, and South Tyrol. We use a recently compiled high-resolution habitat distribution map [8], data on ash distribution and abundance, and on the impact caused by EAB on *F. excelsior* in Russia, to assess the spatial distribution and scale of impacts by future EAB invasion.

2. Material and Methods

2.1. Forest Distribution Map

We used a recently compiled high-resolution habitat distribution map with a spatial resolution of 25 × 25 m [8]. This map is based on fine-scaled data from a range of data sources (e.g., habitat mapping campaigns, biotope inventories), which were harmonized and supplemented by remote mapping and modeling techniques (see [8] for details). This habitat distribution map contains two forest land cover classes (Broad Leaved Forests; Conifer Forests), which were refined by additional data from various sources in the public domain (e.g., forest inventory databases; [9,10]) to assess the distribution and abundance of *F. excelsior*. These data were harmonized and supplemented by remote mapping and modeling techniques (see [8] for details).

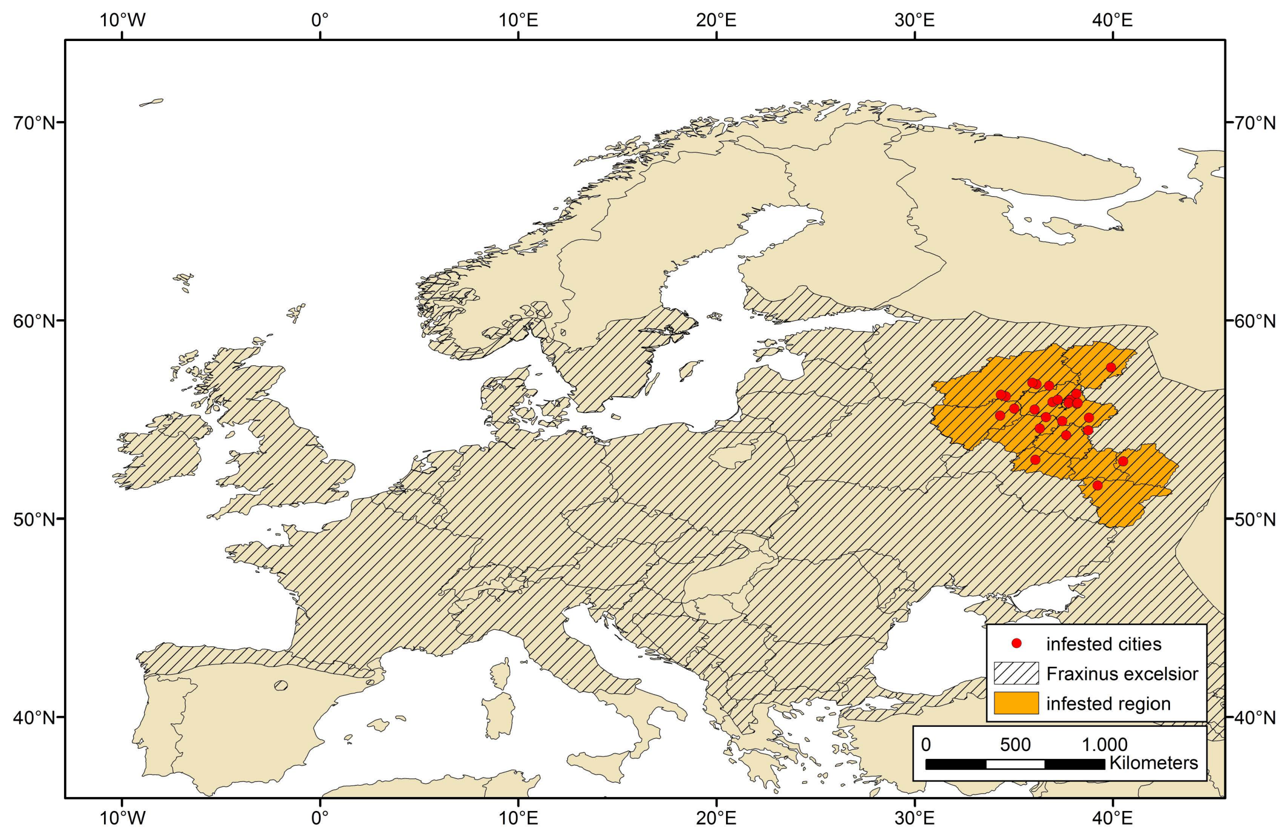

Figure 2. European range of *Agrilus planipennis*, showing infested regions of Russia (orange) and cities (red) where the beetle has been detected together with the distribution of *Fraxinus excelsior* [11]. Based on [6,12].

We note that *F. excelsior* also occurs as an important species in small landscape elements (e.g., hedgerows) in cultural landscapes and public urban spaces, which—due to their small spatial extent—are not shown in the habitat distribution map and hence excluded here.

2.2. Regionalizing Common Ash Distribution and Abundance

Fraxinus excelsior is a widespread species in Central Europe which is a constant and sometimes (sub) dominant component in a range of different forest types (Supplementary Table S1). Highest constancies of occurrence are documented for floodplain forests (Alnenion glutinoso-incanae, Ulmenion, Tillio-Acerion), but also in some zonal (Fagion sylvaticae) and sub-mediterranean extrazonal forests (Quercion pubescenti-petraeae) [13]. In the Austrian Alps, forest inventory data and relevé data from the Austrian Phytosociological Database ([14], Starlinger pers. comm.) show that the species only exceptionally occurs above 1200 m above sea level (a.s.l.) This altitudinal distribution limit holds true across all of Austria, without any conspicuous regional differences.

Below this altitude, Austrian Forest Inventory data [15] show that *F. excelsior* abundance increases towards lower altitudes as the share of ash in deciduous forests is ~2% (900–1200 m a.s.l.) and is ~6% (<900 m a.s.l.). Hence, we applied these altitudinal thresholds by intersecting the distribution of broad leaved forests with a Digital Elevation Model (DEM) to identify forests with different abundance of *F. excelsior* (Table 1). In addition, as *F. excelsior* is a particularly abundant in floodplain forests (>8%), we integrated the data of the Austrian [16], German [17] and Swiss [18] floodplain inventories to delineate the distribution of floodplain forests.

Table 1. Criteria used for mapping the regional distribution of *Fraxinus excelsior* in the study region (Austria, Germany—Baden-Wurttemberg (BW) and Bavaria (BAV)—Switzerland, South Tyrol).

Criteria	Austria	Germany (BW/BAV)	Switzerland	South Tyrol	References
Proportion of *Fraxinus excelsior* in forests	2.7%	4.9%/1.1%	3.4%	<2%	[19–22], Buechsenmeister pers. comm.
Altitudinal distribution	<900: ~6%	<900: ~6%	<900: ~6%	<900: ~6%	[15]
	900–1200: ~2%	900–1200: ~2%	900–1200: ~2%	900–1200: ~2%	
	>1200: 0%	>1200: 0%	>1200: 0%	>1200: 0%	
Distribution of floodplain forests	Floodplain Inventory	Floodplain Inventory	Floodplain Inventory	Not available	[16–18]

3. Results

The distribution of broad leaved forests of different *F. excelsior* abundance is highly heterogenous on the landscape scale (Figure 3, Table 2). Highest abundances are found in extensive lowland floodplain forests along major rivers (e.g., Danube, Inn, Isar, Rhine), medium abundances are found in forests of the lowlands outside the Alps, whereas abundance in forests in the Alps is low.

The total area of broad leaved forest with *F. excelsior* occurrence in the study region—based on the second-level NUTS regions of the European Union (= sub-national socio-economic regions within Europe, [23])—varies notably (Table 2). Forests of medium *F. excelsior* abundance are most wide-spread, whereas forests of high and low abundance are more restricted.

Based on the NUTS2 regions we found that *F. excelsior* amounts to 2% of the total forest area in Austria, 1.9% in Switzerland and 1.8% in Southern Germany (Table 2). The proportions are considerably lower in Liechtenstein (0.7%) and South Tyrol (0.4%).

The digital high-resolution map of EAB invasion risk is available on request from the authors.

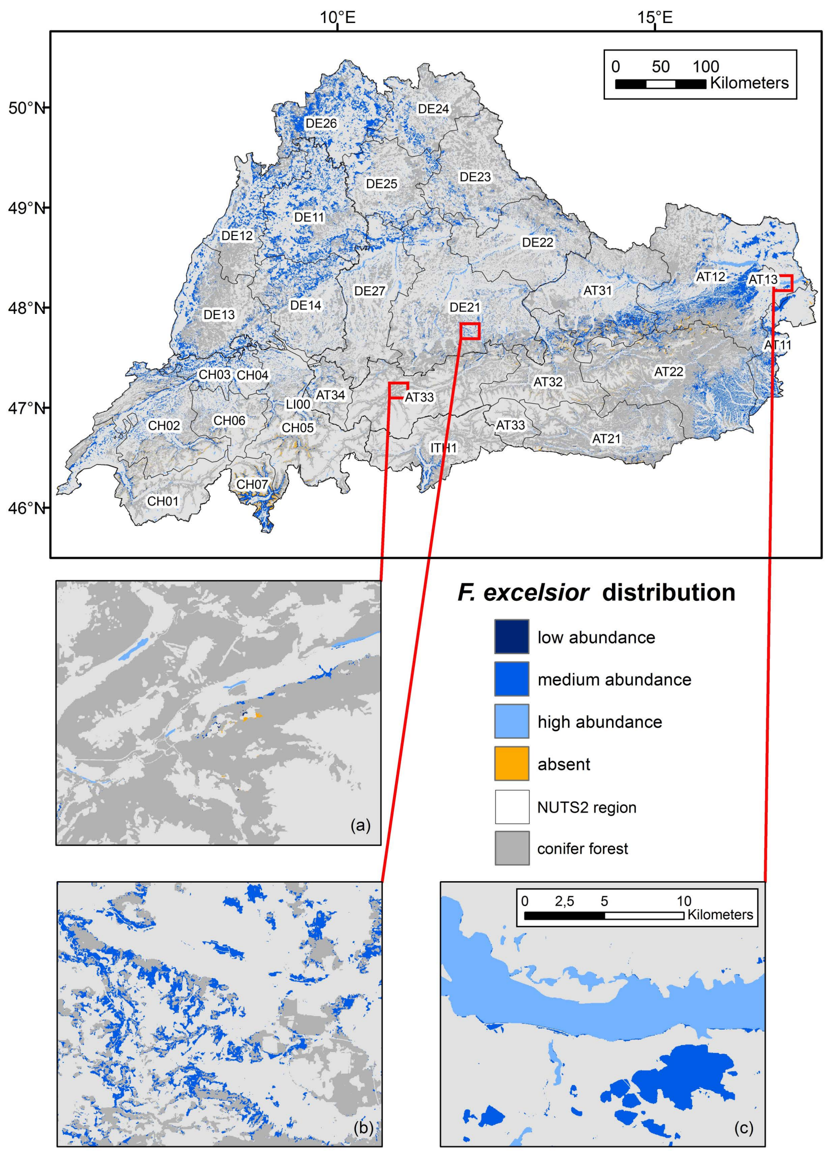

Figure 3. Risk map of future infestation by *Agrilus planipennis* based on *F. excelsior*-distribution for Austria, Bavaria, Baden-Wurttemberg, Liechtenstein, Switzerland and South Tyrol; with examples of landscapes differing in abundance of *F. excelsior* in the study region (see Table 2 for definitions): (**a**) mountainous landscape of the upper Inn Valley in Tyrol (near Innsbruck); (**b**) an agricultural landscape in the Bavarian Alpine Foothills (near Miesbach); (**c**) lowland floodplain forests along the Danube (east of Vienna) and adjacent remnant forests in a intensively used agricultural landscape. The acronyms and location of the NUTS2 (second-level Nomenclature of Units for Territorial Statistics) regions used in Table 2 are given. Study region: Austria (AT), Switzerland (CH), South Germany (DE), South Tyrol (ITH), and Liechtenstein (LI).

Table 2. Forest extent and distribution of *Fraxinus excelsior* in the NUTS2 (second-level Nomenclature of Units for Territorial Statistics) regions in the entire study region: Austria (AT), Switzerland (CH), South Germany (DE), South Tyrol (ITH), and Liechtenstein (LI). The total area of forest, broad leaved forests (BL) and the percentage of forested area of *F. excelsior* with different levels of abundance—low (~2%), medium (~6%) and high (~10%) are given. The total extent of *Fraxinus* forests and the proportions of different classes of *Fraxinus* forests on broad-leaved forest extent are also given. See Figure 3 for location of NUTS2 regions.

NUTS ID	NUTS Name	Nuts Region Area (km²)	Forest Area (km²)	BL Forest Area (km²)	Low *Fraxinus* Abundance, Forest (~2%) (km²)	Medium *Fraxinus* Abundance, Forest (~6%) (km²)	High *Fraxinus* Abundance, Forest (~10%) (km²)	Total *Fraxinus* Forests (km²)	Proportion Low Abundance, *Fraxinus* Forest on BL Forest Area	Proportion Medium Abundance, *Fraxinus* Forest on BL forest Area	Proportion High Abundance *Fraxinus* Forest on BL Forest Area	Percentage Fraxinus Forests in %
AT11	Burgenland	3944.1	1272.1	918.7	0.0	846.5	65.2	911.7	0	66.6	5.1	71.7
AT12	Lower Austria	19,184.7	7971.3	3143.0	80.4	2544.3	468.5	3093.2	1.0	31.9	5.9	38.8
AT13	Vienna	413.4	90.7	84.6	0.0	60.3	24.3	84.6	-	66.5	26.8	93.2
AT21	Carinthia	9525.7	5363.5	309.2	56.4	156.5	63.5	276.4	1.1	2.9	1.2	5.2
AT22	Styria	16,436.0	9748.8	1948.0	141.8	1627.6	71.7	1841.1	1.5	16.7	0.7	18.9
AT31	Upper Austria	11,966.4	5081.6	1408.7	171.3	1030.3	133.9	1335.5	3.4	20.3	2.6	26.3
AT32	Salzburg	7155.5	3168.6	416.1	87.8	232.9	28.4	349.0	2.8	7.4	0.9	11.0
AT33	Tyrol	12,644.2	4327.5	149.6	30.0	57.0	39.3	126.2	0.7	1.3	0.9	2.9
AT34	Vorarlberg	2591.7	860.8	152.3	30.1	89.3	23.4	142.8	3.5	10.4	2.7	16.6
AT total	**Austria**	**83,861.6**	**37,884.9**	**8530.3**	**597.7**	**6644.7**	**918.1**	**8160.6**	**1.5**	**24.9**	**5.2**	**31.6**
CH01	Lake Geneva region	8737.7	2327.5	481.7	57.9	323.0	58.0	438.8	2.5	13.9	2.5	18.9
CH02	Espace Mittelland	10,016.4	3454.3	1034.3	127.1	767.1	65.2	959.3	3.7	22.2	1.9	27.8
CH03	Northwestern Switzerland	1969.2	692.9	481.3	2.9	469.2	9.2	481.3	0.4	67.7	1.3	69.5
CH04	Zurich	1734.1	484.9	199.2	1.6	191.8	5.6	199.1	0.3	39.6	1.2	41.1
CH05	Eastern Switzerland	11,524.4	3483.0	715.4	124.4	395.1	70.3	589.8	3.6	11.3	2.0	16.9
CH06	Central Switzerland	4483.3	1324.1	199.4	26.8	140.7	17.9	185.4	2.0	10.6	1.4	14.0
CH07	Ticino	2831.6	1434.5	864.9	170.2	435.6	19.7	625.4	11.9	30.4	1.4	43.6

Table 2. *Cont.*

NUTS ID	**NUTS Name**	**Nuts Region Area (km²)**	**Forest Area (km²)**	**BL Forest Area (km²)**	**Low *Fraxinus* Abundance Forest (~2%) (km²)**	**Medium *Fraxinus* Abundance Forest (~6%) (km²)**	**High *Fraxinus* Abundance Forest (~10%) (km²)**	**Total *Fraxinus* Forests (km²)**	**Proportion Low Abundance *Fraxinus* Forest on BL Forest Area**	**Proportion Medium Abundance *Fraxinus* Forest on BL forest Area**	**Proportion High Abundance *Fraxinus* Forest on BL Forest Area**	**Percentage Fraxinus Forests in %**
CH total	**Switzerland**	**41,296.7**	**13,201.1**	**3976.3**	**510.9**	**2722.4**	**245.9**	**3479.2**	**3.5**	**28.0**	**1.7**	**33.1**
DE11	Stuttgart	10,568.2	3402.8	2127.0	0.0	2126.2	0.8	2127.0	-	62.5	0.0	62.5
DE12	Karlsruhe	6909.7	2948.4	1088.0	0.0	1004.2	83.8	1088.0	-	34.1	2.8	36.9
DE13	Freiburg	9493.2	4343.8	995.5	9.2	897.3	88.6	995.1	0.2	20.7	2.0	22.9
DE14	Tübingen	9093.9	2897.0	1088.8	16.8	1059.1	13.0	1088.8	0.6	36.6	0.5	37.6
DE21	Oberbayern	17538.4	6076.4	1090.8	45.7	824.0	209.9	1079.6	0.8	13.6	3.5	17.8
DE22	Niederbayern	10,332.3	3551.0	510.2	44.5	394.5	65.0	503.9	1.3	11.1	1.8	14.2
DE23	Oberpfalz	9663.3	3952.5	384.4	0.6	382.0	1.7	384.4	0.0	9.7	0.0	9.7
DE24	Oberfranken	7224.3	2744.3	570.6	0.0	565.8	4.9	570.6	-	20.6	0.2	20.8
DE25	Mittelfranken	7286.6	2439.6	543.6	0.0	542.7	1.0	543.6	-	22.3	0.0	22.3
DE26	Unterfranken	8542.5	3392.0	2161.8	0.2	2157.6	4.0	2161.8	0.0	63.6	0.1	63.7
DE27	Schwaben	10,030.2	2794.6	577.6	9.1	423.3	143.0	575.5	0.3	15.2	5.1	20.6
DE total	**Germany**	**106,682.6**	**38,542.2**	**11,138.3**	**126.1**	**10,376.6**	**615.5**	**11,118.2**	**0.3**	**28.2**	**1.5**	**29.9**
ITH1	**Bolzano**	**7425.0**	**2680.5**	**225.2**	**35.8**	**178.4**	**0.0**	**214.2**	**1.3**	**6.7**	**0.0**	**8.0**
LI00	**Liechten-stein**	**163.7**	**66.9**	**8.2**	**0.5**	**7.4**	**0.1**	**7.9**	**0.7**	**11.0**	**0.1**	**11.8**

4. Discussion

4.1. Distribution and Abundance of F. excelsior

Fraxinus excelsior is able to grow under highly different environmental conditions, from riparian zones to mountains forests and on nutrient-rich and poor soil [24]. In addition, *F. excelsior* has been widely planted in cities, parks and along roads as shade or ornamental trees. Its native range in Europe is limited by cold winter temperatures, late spring frosts and dry, hot summers [1,3]. Common Ash has an intermediate status between pioneer species and old-growth forest components. It usually occurs in groups within broad leaved forests, is often a dominant species in juvenile forest stands, but rarely attains dominance in older forest stages [1,24].

In southern Central Europe, *F. excelsior* occurs in a range of habitats and thus it is the 4th most common broadleaved tree species ([25], Büchsenmeister pers. comm.). We found that *F. excelsior* amounts to 1.8%–2.0% of the total forest area in Austria, Switzerland and Southern Germany, while proportions are considerably lower in the smaller regions Liechtenstein (0.7%) and South Tyrol (0.4%). However, recent forest inventory data report somewhat higher proportions of *F. excelsior*, maybe due to differing inventory methods: It is assumed that the proportion of *F. excelsior* in Austria is ca. 2.7% of all forest trees, 3.4% in Switzerland, 4.9% in Baden-Wurttemberg and 1.1% in Bavaria [19–21]. No data are available for South Tyrol and Liechtenstein.

4.2. EAB Invasion Risks into Central Europe

The spread of *A. planipennis* is facilitated by two spread mechanisms—*i.e.*, endogenous spread (by flight) and human-assisted transportation [7]. Whereas the first mechanism is most relevant for short-range dispersal and range-infilling, the second one is particularly so for long-distance dispersal. Given observed average velocities of spread in Russia (13–31 km year^{-1}) and North America (2.5–80 km year^{-1}) [7], it is likely that EAB will cover the distance (1500 km) between its current range edge in western Russia and the eastern border of the study region within a few decades. In addition, spread of EAB in the study region will be facilitated by the rather continuous distribution of *F. excelsior*. In the study region, potential corridors for spread can be found particularly along rivers and more generally in the lowlands (Figure 2), while the higher elevations of the Alps may serve as a barrier slowing or halting regional spread. Given the high connectivity of occurrences of *F. excelsior* in low and medium altitudes, it seems unlikely that the availability of host trees will be a major factor for limiting spread outside the Alps.

Human-assisted secondary long-range dispersal is most likely with infested wood and wood products. Although import restrictions of ash wood products from infested regions into the European Union have been introduced (e.g., [26,27]), secondary spread (e.g., by infested wood products) into Central Europe is increasingly likely to occur, the larger the infested area in Eastern Europe becomes. Thus, introduction into Central Europe may occur at any time. Invasion history shows that ports and trade centers are main gateways for such accidental introductions of alien species through international trade [28]. As EAB is able to cope with wide range of climatic condition [29,30], it is likely that it will be able to colonize the full range of *F. excelsior*-habitats in Central Europe.

We note that although the results of this study are not based on modeling the spread of EAB using habitat characteristics and the species' ecological needs as has been done for North America [31,32], our study is the first one which provides a spatially explicit analyses of the invasion risks posed by EAB into a European region. Due to the high-resolution habitat distribution map [8] as the foundation of our analyses, we were able to regionalize invasion risks to a high extent. This information provides a basis for quantifying the scale of the likely impacts caused by EAB, and it identifies likely corridors of spread once EAB spreads into the study region

5. Conclusions

The high susceptibility and mortality of *F. excelsior* to infestations of EAB in Russia [7] leave no doubt that this beetle will become a major forest pest once it reaches Central Europe. This will put additional pressure on *F. excelsior*, which is also suffering from a fungal disease for several years, leading to wide spread ash dieback [24].

Although experience from the spread of EAB in North America has shown that halting its spread is difficult (reviewed by [7]), developing and testing management approaches with the aim to halt or at least slow down the invasion of EAB in Europe must be pursued with great urgency. Therefore, Central European countries not yet infested should develop dedicated precautionary measures to prevent inadvertent import of EAB into their territory. Additional education campaigns will help to raise awareness of the potential risk of *A. planipennis* invasions with the wider public, forest managers, and also in the scientific community.

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Author Contributions

V.V., F.E. and D.M. led the analyses and writing. M.K. and J.P. contributed land cover data, discussed the results and commented on the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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