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Invasion potential of *Agrilus planipennis* and other *Agrilus* beetles in Europe: import pathways of deciduous wood chips and MaxEnt analyses of potential distribution areas*

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Bark- and wood-boring beetles in the genus *Agrilus* (Coleoptera: Buprestidae) can survive wood-chipping, and *Agrilus planipennis* has established in North America and European Russia with devastating impacts on forest ecosystems. The work presented in this paper combined import statistics of deciduous wood chips, Maximum entropy modelling (MaxEnt) of climatic similarities, and the distribution of potential tree hosts to predict the likelihood of four selected North American *Agrilus* species to become introduced and established in Europe. In agreement with the EU's energy-policy target of increased use of wood chips, there was a linear or exponential increase in European imports of deciduous wood chips during the past 10 years from countries harbouring potentially harmful *Agrilus* species. MaxEnt showed high environmental suitability in Europe for the four selected *Agrilus* species, particularly in Eastern Europe and European Russia for *A. anxius*, *A. bilineatus* and *A. planipennis* and in southern Europe for *A. politus*. Documented susceptible host trees are widely distributed in the predicted areas of *Agrilus* distribution in Europe, and these areas receive large quantities of deciduous wood chips from countries where these and other *Agrilus* species are present. Thus, it was concluded that the fundamental conditions for introduction and establishment of *Agrilus* species in Europe are in place.

Introduction

Currently, EU-countries import deciduous wood chips from North America, European Russia and Asia. These wood chips can harbour tree-killing bark- and wood-boring beetles in the genus *Agrilus* (Coleoptera: Buprestidae) which are present in the area(s) of origin. The volume of such imports is expected to increase to satisfy future demands for renewable energy production in Europe (EU, 2005; UNECEFAO, 2009). A recent review (Flø *et al.*, 2013) of the literature on potentially invasive insect pests that may be introduced with wood chips from North America to northern Europe identified eight *Agrilus* species or subspecies that are likely to attack European trees. These *Agrilus* spp. have a broad distribution in North America, suggesting that they are pre-adapted to a wide range of climatic conditions and therefore may be able to colonize a wide geographic range in Europe if suitable host trees are present. High-risk *Agrilus* species that may be imported with deciduous wood chips were identified by considering (i) the likelihood that the species could arrive with the pathway of deciduous wood chips; (ii) the presence of susceptible host trees in Northern Europe; (iii) the climatic similarity between Northern Europe and the species' native range in North America; and (iv) the severity of the damage the species may cause in Northern Europe (Flø *et al.*, 2013).

Because deciduous wood chips may bring new and potentially very harmful *Agrilus* species into European forests this pathway needs to be assessed in more detail. Import of deciduous wood chips is mostly unregulated, even though wood chips are often large enough to allow survival of *Agrilus* and other potential pests (McCullough *et al.*, 2007). *Agrilus* is a hyperdiverse genus with nearly 3000 valid species and subspecies (Bellamy, 2008), but only three species appear on EPPO's Lists of pests recommended for regulation as quarantine pests or on the EPPO Alert list: *Agrilus anxius* (Gory 1841) is on the A1 List of pests absent from the EPPO region, *A. planipennis* (Fairmaire 1888) is on the A2 List of pests locally present in the EPPO region, and *A. auroguttatus* (Schaeffer 1905) is on the EPPO Alert list. Experience has shown that many high-impact invasive insects were not on phytosanitary lists prior to becoming invasive pests, and some were not even known to be significant pests in advance, such as the emerald ash borer *A. planipennis* that was detected in the USA in 2002 (Haack *et al.*, 2002). When pre-emptive quarantine measures fail and new species are introduced it is often too late to prevent further spread, and one must attempt to limit economic losses and there may be no choice but to accept the often devastating ecological impacts. Improved

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information about potential import pathways and candidate pest species ahead of any interceptions is essential to develop programs for early detection and eradication.

The goal of the present study was to determine if the fundamental conditions are in place to allow introduction and establishment of selected *Agrilus* species in Europe. The authors analysed import volumes of deciduous wood chips to 28 EU countries from North America, a region that harbours several *Agrilus* species that are documented to kill European trees (Flø *et al.*, 2013). Other areas in European Russia and Asia, where *A. planipennis* is present as an invasive (European Russia) or is native (Asia), were also considered. The potential distribution in Europe was explored using Maximum entropy modelling (MaxEnt) for three North American *Agrilus* species that are not yet present in Europe [*A. anxius* (bronze birch borer), *A. bilineatus* (two-lined chestnut borer), and *A. politus* (common willow agrilus)], as well as *A. planipennis* (emerald ash borer), which is present in North America, Asia and European Russia.

Methods

Data sources

Export/import data for deciduous wood chips

Import data for deciduous wood chips from 2004 until 2013 was collected for all 28 European Union member states using Eurostat's CN8-database (Eurostat, 2014). This database employs the 8-digit combined nomenclature (CN) and data collection follows a harmonized methodology. Other European countries, such as Norway, collect import data using other methodologies that are difficult to harmonize with the EU system. Export data to the EU was collected for the United States and Canada, which harbour several potentially invasive *Agrilus* species (Flø *et al.*, 2013), as well as European Russia, where *A. planipennis* has been introduced, and other countries in *A. planipennis*' native range (China, Taiwan, Mongolia, Japan, South Korea, North Korea) (Haack *et al.*, 2002). The target commodity was located under chapter '44 wood and articles of wood' in the World Customs Organization's harmonized system, more specifically under heading 44.01, code 44.01.2200 including non-coniferous wood in chips or particles (World Customs Organization, 2015). Data was converted from 100 kg units to tonnes (t). Mongolia was excluded from further analyses since the trade data showed that no wood chips were exported from Mongolia to the EU during the 10-year trade period under study.

Species presence data

Presence data for *Agrilus* species in North America was downloaded from the GBIF database (GBIF, 2014). Additional presence data for *A. planipennis* in European Russia was added from the literature (Orlova-Bienkowskaja, 2013). All synonym species names were included and all named presence locations and addresses were geo-referenced to acquire a sufficient number of presence points (Hijmans *et al.*, 2014). Only *Agrilus* species with more than 50 presence points were used for further analyses. These included the twolined chestnut borer *Agrilus bilineatus* (Weber 1801), the common willow agrilus *Agrilus politus* (Say 1825), the bronze birch borer *Agrilus anxius*, and the emerald ash borer *Agrilus planipennis* (Fairmaire). Distribution maps for potential host trees in Europe were downloaded from the EUFORGEN website (EUFORGEN, 2014). No GIS-data were available for *Betula pubescence*, but according to Hulte´n & Fries (1986) its distribution is similar to that of *B. pendula*, except that *B. pubescens* has a more northern distribution.

Meteorological data

High resolution meteorological data based on interpolations of observed data from 1950 to 2000 were downloaded from the WorldClim database (WorldClim, 2014). The data covered Europe (−10 to 40° longitude, 37 to 70° latitude) and North America (−170 to −55° longitude, 30 to 70° latitude) at a resolution of 30 arc-second grid cells (approximately 1 km^2). The 19 downloaded bioclimatic variables represented annual trends in temperature, precipitation and climate ranges. Further details on the meteorological data are reported by Hijmans *et al.* (2005).

Maximum entropy modelling (MaxEnt)

To explore the potential distribution in Europe species distribution models (SDMs) were built for the four selected *Agrilus* species. Maximum entropy modelling (MaxEnt) (Phillips *et al.*, 2004, 2006) was chosen as the SDM tool because it has been shown to outperform other SDM methods, and because it will accept presence only data and a small number of presence points (Elith *et al.*, 2006).

Since the primary interest was not in pinpointing which environmental variables were most important in determining species distributions, MaxEnt was treated as a machine learning process. All 19 bioclimatic variables from the WorldClim database were used as predictors and the algorithm chose the most important variables through the default regularization settings. For replicate runs of the SDMs the default setting 'cross-validation' was chosen, as it utilizes all the available data and thus makes better use of the limited data (Phillips, 2014).

Model performance

Model performance was measured using the area under the curve (AUC) parameter of the receiver operator characteristic (ROC). AUC can be interpreted as the probability of correctly predicting species presence in a randomly selected geographic grid cell. In the ROC analysis, each grid cell in the predictor data set receives scores from the independent testing data set, the relationship between the true positive rate and the false positive rate is plotted, and the AUC is calculated. If the AUC of the test data run is close to 0.5

the model performs no better than a random model, and if AUC is 1.0 the model provides a perfect fit with no false negatives (van Erkel & Pattynama, 1998; Phillips, 2014). The average AUC value of 10 independent cross-validation runs is presented for each *Agrilus* species.

Background point selection
MaxEnt was not run entirely in its default mode (Table 1). For two of the selected species (*A. anxius* and *A. bilineatus*), background points (or pseudo-absence points = the absence of observations) were not selected from the entire geographical area covered by the North American bioclimatic variables, as is default. This was done to avoid creating an artificially high AUC caused by a large number of true negatives (grid cells where both the predicted and the actual value are negative). Instead, background points were selected randomly from within circles of a given radius created around presence points (Table 1). The circle radius was set to fall within the limits of the known distribution of the host tree, because the targeted *Agrilus* species were assumed to be uniformly distributed throughout the range of its host tree (or trees). This approach ensured that the background points included in the MaxEnt analyses only included the range of environmental conditions the authors wanted MaxEnt to distinguish between. The penalty function (the beta multiplier or regularization multiplier) was downsized in order to restrict the distribution predictions and to get a more conservative, localized prediction map, even though this may cause a somewhat over-fitted model (Phillips, 2014). The SDMs were fitted to the known North American distribution of each *Agrilus* species and the prediction maps were inspected visually to ensure that the predicted species distribution approximately matched the distribution of the native host tree, before projecting the model onto Europe. If the SDM did not match the host tree distribution in North America the model settings were adjusted to improve the match. The settings used in the MaxEnt models and summary statistics for the tree *Agrilus* species are given in Table 1. For all three species omission rates showed a close fit to predicted omissions, indicating that the test and training data sets were independent.

Analysis software
All data was downloaded and handled in R version 3.1.1 (R Core Team, 2014). MaxEnt version 3.3.3k (Phillips *et al.*, 2004) was run through R using the dismo-package version 1.0-5 (Hijmans *et al.*, 2014).

Results

Trade data on deciduous wood chips

Trade data for the period 2004–2013 indicated a linear increase in total yearly quantities of deciduous wood chips exported to the EU from eight selected countries where potentially invasive *Agrilus* species were present (Fig. 1A). The total yearly amount of wood chips exported from the eight countries to the EU (Table 2) showed a gross increase of 64% from 2004 to 2013, with a mean yearly increase of 9.8%. However, although the overall analysis suggested a linear increase in total yearly trade volumes individual countries showed considerable year-to-year variation in exported quantities (Fig. 1).

Export volumes from individual countries
The Russian Federation, Canada, the USA and China exported wood chips to the EU in all of the 10 years under study (Table 2). Russia was consistently the largest exporter and shipped 84% of the total quantity of wood chips from the selected countries to the EU. Russian exports to the EU increased exponentially from 2004 to 2013 (Fig. 1B). Export from Canada to the EU was generally low, except for the years 2007–2010, while USA had a relatively low export all years except 2004 (Fig. 1C). Export from Asia to the EU was very low: the Republic of Korea exported small quantities of wood chips most years, Japan exported small quantities for 4 years, whereas exports from China increased rapidly until 2011 and then dropped to very low levels

Table 1 Maximum entropy modelling (MaxEnt) settings and summary statistics for analysis of potential distribution areas in Europe for four North American *Agrilus* species

MaxEnt settings and results	*A. politus*	*A. anxius*	*A. bilineatus*	*A. planipennis*
Beta/Regularization multiplier	0.5	0.5	0.5	1
Doclamp	TRUE	TRUE	TRUE	TRUE
Circle radius for background point selection	FALSE	700 km	300 km	FALSE
Mean no. of training points	111.6	40.5	43.2	33.3
Regularized training gain	1.951	1.884	1.200	2.145
Unregularized training gain	2.777	2.627	1.887	2.833
Iterations	500	500	500	500
Training AUC	0.975	0.968	0.932	0.981
Mean test sample	12.4	4.5	4.8	3.7
Test gain	1.235	1.561	1.073	1.709
Mean no. of background points	10111.6	7934.5	9189.2	10033.3

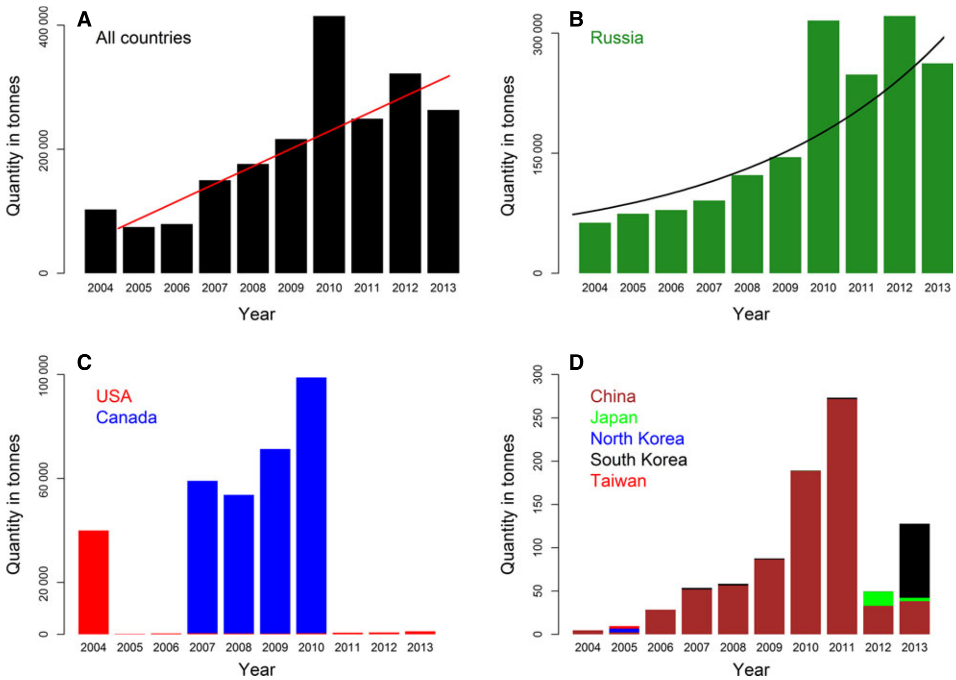

Fig. 1 Annual quantities of deciduous wood chips exported from eight selected countries outside Europe to the EU over the 10-year period 2004–2013. The trend line in (A) indicates a linear increase for all countries combined (Import Quantity = 42 860 + 29 472 (YEAR), R^2 = 0.64). Export from Russia (B) showed an exponential increase in the same period (Import Quantity = 31 488 + a (b^{YEAR}); where a = 631 610 with SE 17 930, t = 2.34 and $P < 0.048$; and b = 1.217 with SE 0.062, t = 19.61 and $P < 0.0001$). Note that the y-axis is scaled differently between figure panels.

Table 2 Export of deciduous wood chips, from countries outside Europe and European Russia that harbour *Agrilus* spp., into EU in the 10-year period 2004–2013. All trade data are given in tonnes. *N* denotes the number of years with export from each country during 2004–2013. The total exported volume was 2 049 538 t

Country	*N*	Min	Mean	Max	Sum	SD	% of total
Russia	10	0.3	14 355	314 057	1 722 559	54 214	84.05
Canada	10	0.5	2817.4	98 511	281 740	13 779	13.75
USA	10	0.1	193	39 909	44 357	21	2.16
China	10	0.1	5	221	761.3	87	0.04
South Korea	7	0.2	3	85.6	92.6	16	0.005
Japan	4	0.1	0.5	16.5	20.6	2.6	0.001
North Korea	1	0	0.4	4.4	4.4	1.4	0.0003
Taiwan	1	0	0.3	3	3	0.9	0.0001
Total					2 049 538		100

(Fig. 1D). The Democratic People's Republic of Korea and Taiwan exported only a single shipment each during the 10-year period (Table 2), to Denmark and Austria, respectively.

Import volumes into individual EU countries

Of the 28 EU countries, Finland, Germany, Italy, Sweden, and Estonia imported 99.5% of all deciduous wood chips imported into the EU (Table 3). Finland alone imported

Table 3 Import of deciduous wood chips to the five EU countries with the largest imports during the 10-year period 2004–2013. All import data are given in tonnes. *N* denotes the number of years with import to each country during 2004–2013

Country	*N*	Min	Mean	Max	Sum	SD	% of EU total
Finland	10	0.5	48 100	314 057	1 923 987	87 642	93.90
Germany	10	0.1	1052	41 123	42 099	6498	2.05
Italy	9	0.2	2018	39 909	40 362	8919	1.97
Sweden	9	0.1	447	14 347	22 368	2083	1.10
Estonia	5	0.1	474	7334	9479	1651	0.50
Total					2 038 295		99.52

93.9% of all deciduous wood chips to the EU and was the only country that had a consistently high import every year. Most of Finland's import (1 683 530 t; 88%) came from Russia. Finland also imported 240 443 t from Canada between 2005 and 2010 and small amounts from China (0.9 t), and USA (12.9 t). Germany, the second largest importer, imported 41 124 t of wood chips from Canada over three years, 886 t from the USA over nine years, and small quantities from China (74 t over eight years) and Russia (14 t in 2010). Italy imported 40 203 t over nine years from the USA, and 159 t from China over seven years. Sweden imported 22 286 t over five years from Russia, 79.4 t over six years from the USA, 2.4 t over six years from China, 0.2 t from Canada in 2011, and 0.1 t from Japan in 2011. Estonia imported 9479 t from Russia over four years and 0.1 t from the USA in 2007.

Potential distribution estimated by Maximum entropy modelling

Agrilus anxius

MaxEnt modelling of potential distribution of *A. anxius* in Europe showed a high probability of distribution in European part of Russia, Finland, Belarus and Ukraine, especially in areas with a humid continental climate (Fig. 2). In addition, the probability of distribution was high in the Alps, in Eastern Denmark, and in coastal areas of Western Norway. MaxEnt predicted the potential distribution of *A. anxius* with excellent accuracy (in terms of prediction of true positives and true negatives), giving an average test AUC value of 0.903, with a standard deviation of 0.085. Over the 10 cross-validation runs the total contribution of the four most important environmental variables to the MaxEnt model was on average 57.7%, with mean temperature of the wettest quarter of the year contributing 21.2%, mean temperature of the coldest quarter 13.2%, minimum temperature of the coldest month 12.1%, and mean temperature of the driest quarter 11.2%. The mean temperature of the wettest quarter was also the strongest contributor in the test of individual variables, based on jackknife resampling of training and test results (i.e. leaving out one variable at a time and re-estimating bias and standard error).

Agrilus bilineatus

Similar to *A. anxius*, the MaxEnt model prediction of potential distribution of *A. bilineatus* in Europe showed a high probability of distribution in areas with a humid continental climate in Finland, European Russia, Estonia, Latvia, Moldova, Belarus, Ukraine, and Poland (Fig. 3). In Scandinavia and other parts of Western Europe, the probability of distribution was higher in some coastal areas than further inland. MaxEnt predicted the potential distribution of *A. bilineatus* with moderate model accuracy, giving an average test AUC value of 0.829, and a standard deviation of 0.115. Over the 10 cross-validation runs five variables contributed on average >10% to the MaxEnt model, and their total contribution to the model averaged 59.3%. Annual mean temperature contributed on average 15.3%, and mean temperature of the warmest quarter of the year,

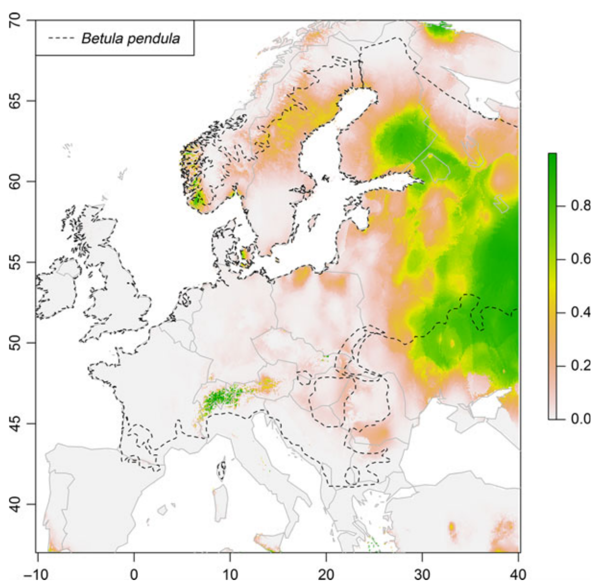

Fig. 2 Potential distribution of the bronze birch borer *Agrilus anxius* in Europe predicted by Maximum entropy modelling (MaxEnt). Colours indicate probability of occurrence of *A. anxius* (green = high, white = low) and dashed lines show the distribution of the host tree silver birch *Betula pendula.*

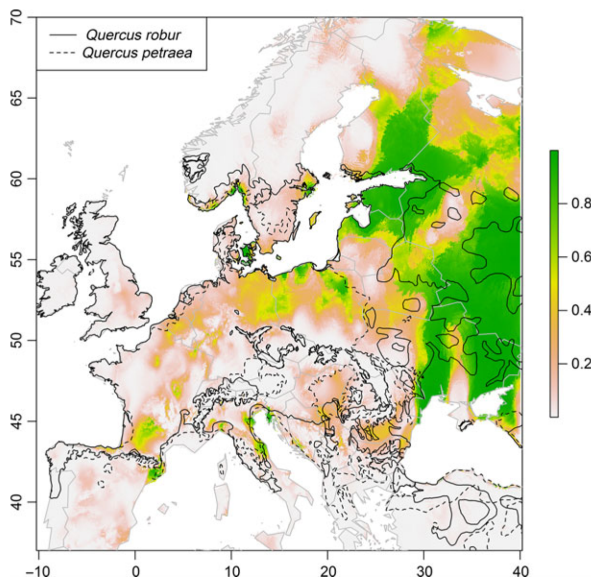

Fig. 3 Potential distribution of the twolined chestnut borer *Agrilus bilineatus* in Europe predicted by Maximum entropy modelling (MaxEnt). Colours indicate probability of occurrence of *A. bilineatus* (green = high, white = low). The solid and dashed lines show the distribution of two potential host trees (pedunculate oak *Quercus robur* and sessile oak *Q. petraea*) respectively.

temperature seasonality (the difference between annual maximum and annual minimum temperature), mean temperature of the coldest quarter, and isothermality (mean diurnal temperature range divided by the annual temperature range) all contributed between 10.8% and 11.2%.

Agrilus politus

In contrast to the other three species, the MaxEnt model prediction for *A. politus* showed a high probability of potential distribution in southern areas of Europe around the Mediterranean Sea and elsewhere in areas dominated by a temperate climate. MaxEnt predicted the potential distribution of *A. politus* with moderate model accuracy, giving an average test AUC value of 0.872, and a standard deviation of 0.062. Over the 10 cross-validation runs four variables contributed on average >10% to the MaxEnt model, and their total contribution to the model averaged 52.2%. Precipitation of the coldest quarter of the year contributed 16.1% to the model, annual mean temperature contributed 12.5%, maximum temperature of warmest month 11.9%, and mean temperature of warmest quarter 11.7%. Precipitation of coldest quarter of the year had a permutation importance in the jackknife resampling test of 22.9%, which indicates that the model depends heavily on this variable.

Agrilus planipennis

The MaxEnt model prediction for *A. planipennis* showed a high probability of potential distribution immediately surrounding its current distribution in European Russia, as well as in Finland and Belarus, areas dominated by a continental climate. MaxEnt predicted the potential distribution of *A. planipennis* with excellent model accuracy, giving an average test AUC value of 0.933, and a standard deviation of 0.088. Over the 10 cross-validation runs three variables contributed on average >10% to the MaxEnt model, and their total contribution to the model averaged 73%. Precipitation of the driest month of the year contributed 45.9% to the model, minimum temperature of coldest month contributed 16.7%, and temperature seasonality 10.4%. Precipitation of the driest month of the year had a permutation importance in the jackknife resampling test of 16%, which indicates that the model depends heavily on this variable.

Discussion

The species distribution models presented in this paper show that large areas in Europe have high environmental suitability for the four selected *Agrilus* species, mainly in the continental climate zone. The model predictions of potential *Agrilus* distribution in Europe also overlap with the distribution of known and potential host trees in Europe, suggesting that these beetles would be able to establish in Europe if they were introduced with e.g. imported wood chips. *Agrilus anxius, A. bilineatus* and *A. planipennis* have a high potential distribution in Eastern Europe including European Russia, Ukraine, Belarus and Moldova, but can also find suitable climate and host trees in parts of Western Europe. The risk of accidentally introducing *A. anxius* and *A. bilineatus* is increased by the substantial import of deciduous wood chips to the EU from Canada and USA (326 000 t in total from 2004 to 2013, 15.9% of total EU import of deciduous wood chips; Table 2). Import of deciduous wood chips from North America could also bring *A. planipennis* to Europe, as this species is well established in the eastern parts of USA and Canada. Because most deciduous wood chips imported to the EU come from Russia, there is also a risk of importing *A. planipennis* from the east, as this species expands westwards from its present distribution around Moscow. The greatest risk of importing *A. planipennis* with wood chips to the EU is probably associated with the high volumes of deciduous wood chips shipped from Russia to Finland, and to a lesser degree to Germany, Italy, Sweden, and Estonia (Table 3). Finland's high import volumes probably reflect the country's role as a leading pulp and paper producer in Europe (Lamers *et al.*, 2012).

Trade statistics and risk of introduction

The risk of introducing new and harmful *Agrilus* species to Europe may continue to increase in the coming years. Over the last decade, there has been a significant increase in EU imports of deciduous wood chips from countries where high-risk *Agrilus* species are present, and from Russia, the largest trade partner, the increase has been exponential (Fig. 1). A further increase in import of wood chips to the EU may be expected, as the EU aims to use more bioenergy to satisfy future energy demands (EU, 2005; UNECEFAO, 2009). One fundamental problem with using trade data to identify high-risk imports and quantify risks is that the biological resolution of the Eurostat data tends to be low. Wood chip consignments often include a mixture of tree species with different probabilities of containing harmful *Agrilus* species, but unfortunately there is no information about tree species composition in the trade data and it is difficult and time-consuming to obtain such data upon inspection (Økland *et al.*, 2012). The biological state of the wood used for chipping may also vary much between consignments, but again it is impossible to separate high- and low-quality wood chips based on the trade data alone. Wood chips for bioenergy purposes are typically made from low-quality wood from damaged trees, salvage harvesting, or logging residues that do not meet the quality demands for sawn wood and are more likely to contain bark- and wood-boring insects (Hall, 2002). Wood chips intended for pulp and paper production are generally of better quality, but most consignments may still include some low-quality wood chips. Wood chip consignments may also contain wood chips of varying sizes, including fractions that exceed maximum size limits (Roberts & Kuchera, 2006; Kopinga *et al.*, 2010) and thus have a larger probability of harbouring live *Agrilus* beetles (McCullough *et al.*, 2007).

The geographical resolution of the trade data is usually quite crude, and insufficient to determine the location of the trees used for wood chip production. Russia, the USA and Canada are vast countries, but the trade data does not give the precise area of origin of the wood chips or the trees used in wood chip production.

Potential distribution area and climate

Agrilus anxius, A. bilineatus A. politus, and *A. planipennis*
According to the species distribution models presented in this paper *A. anxius, A. bilineatus* and *A. planipennis* have the highest probability for potential distribution in the European part of Russia and neighbouring areas, in areas with a humid continental climate. *Agrilus politus* was predicted to have the highest potential distribution in southern parts of Europe around the Mediterranean, in areas dominated by a more temperate climate.

The climatic niche of *A. anxius* seems to encompass dry and cold winters and warm and wet summers (Fig. 2). The potential distribution of *A. anxius* in Europe was largely determined by temperature. Low temperatures are not believed to be a limiting factor for *A. anxius* in Europe, since *A. anxius* needs to be subjected to freezing temperatures to complete its life cycle (Barter, 1957).

The MaxEnt model for potential distribution of *A. bilineatus* (Fig. 3) was determined by winter and summer temperatures, but also by temperature seasonality and isothermality. High temperature seasonality and isothermality is characteristic for the humid continental climate type.

Agrilus planipennis (Fig. 4) is already established in European Russia and is spreading towards the eastern parts of Europe (Orlova-Bienkowskaja, 2013, 2014b). The MaxEnt model for potential distribution of *A. planipennis* is localized around its current distribution area in European Russia, but also shows a potential distribution northward to Finland and Sweden, westward to the Baltic countries, and southward towards Belarus and Ukraine – mainly areas within a continental climate type. This coincides with the climate in other parts of *A. planipennis'* invasive range: the Northern United States and Southern Canada has a humid continental climate, according to the Köppen-Geiger climate classification maps (Peel *et al.*, 2007). A similar climate is also found in *A. planipennis'* native range in Far East Asia (Peel *et al.*, 2007).

In the MaxEnt model for potential distribution of *A. politus* (Fig. 5), precipitation of the coldest quarter was the most important variable, together with annual mean temperature of warmest month and mean temperature of warmest quarter. In *A. politus'* potential distribution area in Europe the coldest quarter (i.e. the winter months) are normally also the driest months. *Agrilus politus* seems to prefer a considerably drier and warmer climate than *A. anxius*, *A. bilineatus*, and *A. planipennis.*

Pest significance of Agrilus anxius, A. bilineatus A. politus, *and* A. planipennis
Agrilus anxius is documented to kill the two most important birch species in Europe, *Betula pendula* and *B. pubescens*, as well as the two Asian species *B. maximowicziana*, and *B. szechuanica* (Nielsen *et al.*, 2011). *Betula pendula* and *B. pubescens* are widely distributed in the modelled distribution area of *A. anxius* in Europe. At present *B. pendula* and *B. pubescens* have very few insect pests that can kill

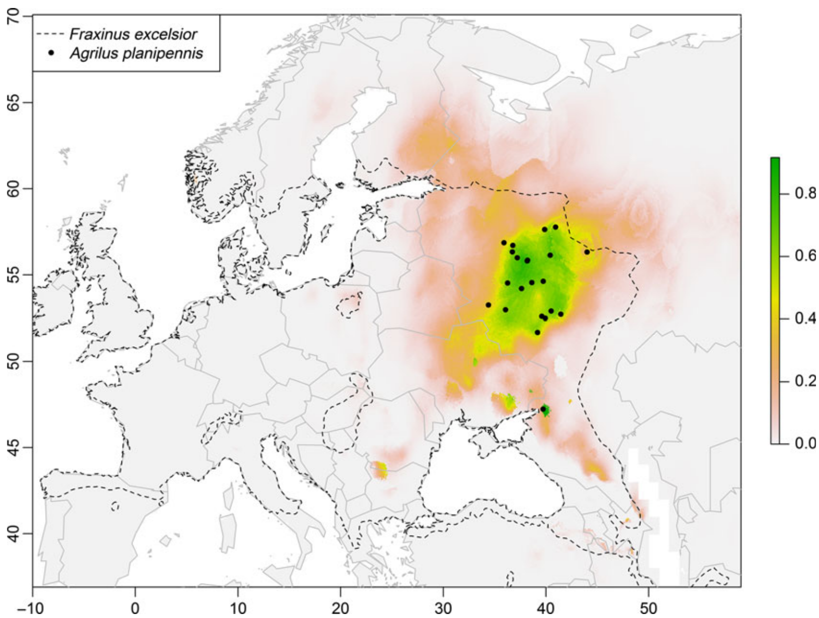

Fig. 4 Potential distribution of the emerald ash borer *Agrilus planipennis* in Europe predicted by Maximum entropy modelling (MaxEnt). Colours indicate probability of occurrence of *A. planipennis* (green = high, white = low). Dashed lines show the distribution of the host tree European ash (or common ash) *Fraxinus excelsior*. Black dots show the presence of *A. planipennis* according to Orlova-Bienkowskaja (2014a).

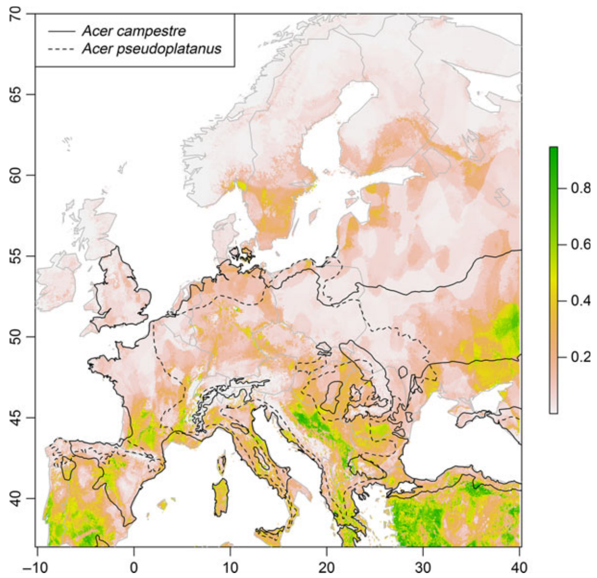

Fig. 5 Potential distribution of the common willow agrilus *Agrilus politus* in Europe predicted by Maximum entropy modelling (MaxEnt). Colours indicate probability of occurrence of *A. politus* (green = high, white = low). The solid and dashed lines show the distribution of two potential host trees (field maple *Acer campestre* and sycamore maple *A. pseudoplatanus*) respectively.

them, and introduction of *A. anxius* could have dramatic effects on extensive areas of birch forests in Eurasia.

Agrilus bilineatus has been documented to kill the European species *Quercus robur* in North America (Muzika *et al.*, 2000), and it has many other potential host species in Europe, including the common and widespread *Q. petraea*. The predicted distribution area of *A. bilineatus* in Europe overlaps to a large extent with the distribution of *Q. robur*. Introduction to Europe, and subsequent attack on the highly valued *Q. robur* could be costly, as this species is used in forestry and is highly valued as an ornamental tree. *Quercus robur* is also ecologically important because of its high number of associated species (Southwood *et al.*, 2004).

Agrilus politus is distributed throughout the United States (including Alaska) and most Canadian provinces (Bright, 1986) and attacks several species of maple (*Acer*) and willow (*Salix*) in this extensive distribution area. An ability to kill European host trees has not been documented for *A. politus*, but several potential host species are available in Europe. These include *Acer campestre, A. platanoides, A. pseudoplatanus*, *Salix alba, and S. caprea*, which are some of the most common maple and willow species across Europe.

Agrilus planipennis was detected in North America 13 years ago (Haack *et al.*, 2002), and has become one of the most devastating tree-killing insect pests ever introduced. North American ash species show very little documented resistance (Whitehill *et al.*, 2014) and mortality rates approach 100% in some areas. European ash species are also expected to be highly susceptible to *A. planipennis*, and the beetle appears to thrive in its invasive range in Russia (Orlova-Bienkowskaja, 2014a). The Eurostat trade data suggests that Finland, Germany, Italy, Sweden and Estonia run the highest risk of introducing this *Agrilus* species with imported wood chips from Russia (Table 3). The main European host of *A. planipennis*, *Fraxinus excelsior*, is present in all these countries. On the other hand, the model prediction for potential distribution of *A. planipennis* is centred within the continental climate area, suggesting a low probability of establishment in countries located in the oceanic climate zones, such as Great Britain, parts of France and Germany, or countries in the Mediterranean climate zone, for example Italy and Spain.

Management implications

The analyses of wood chip import pathways reported in this paper and the modelled distribution areas of selected *Agrilus* species in Europe strongly suggest that the fundamental conditions are in place for introduction and establishment of *Agrilus* species in Europe. This new information about potential import pathways and candidate pest species calls for adjustments to current management procedures to reduce the risk of species introductions. These include efforts to reduce the likelihood that *Agrilus* will be present in wood chips. Establishment of new *Agrilus* species in Europe could potentially be extremely damaging and costly. Eradication will probably be impossible, or if possible, the management costs would be very high. In the United States, management of *A. planipennis* alone has an estimated annual cost of 1.7 billion USD (Aukema *et al.*, 2010). Most of these costs are related to removal and replacement of dead trees.

Because eradication is usually impossible the best options are pre-emptive measures, such as reducing the risk of entry of *Agrilus* species through phytosanitary regulations. *Agrilus planipennis* may survive the wood chipping process (McCullough *et al.*, 2007), and since it is the largest of the *Agrilus* species discussed in this paper it is very likely that other *Agrilus* species also may survive chipping. *Agrilus planipennis* is believed to have been introduced to North America with wood packaging material (Herms & McCullough, 2014), and to Russia through plants for planting or wood packaging material (EPPO, 2007; Orlova-Bienkowskaja, 2013). Reducing the maximum permitted diameter of wood chips is not alone considered a sufficient pre-emptive measure, for two main reasons. First, the actual chip dimensions tend to be highly variable and to exceed the dimensions specified by producers and regulators (EPPO, 2013). Second, very little is known about the survival of pests in wood chips of different sizes and qualities. Alternative pre-emptive measures to reduce the occurrence of viable beetles in wood chips could be disinfection of wood chips with ionizing radiation or heat treatment. However, there is currently no information about the effectiveness of these measures (EPPO, 2013).

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Potentiel d'invasion d'*Agrilus planipennis* et d'autres *Agrilus* en Europe: filières d'importation de copeaux de bois de feuillus et analyses MaxEnt des zones de répartition potentielles

Les coléoptères de l'écorce et du bois du genre *Agrilus* (Coleoptera: Buprestidae) peuvent survivre aux processus de fabrication des copeaux de bois, et *Agrilus planipennis* s'est établi en Amérique du Nord et dans la partie européenne de la Russie avec des impacts dévastateurs sur les écosystèmes forestiers. Le travail présenté dans cet article combine des statistiques sur l'importation des copeaux de bois de feuillus, la modélisation du maximum d'entropie (MaxEnt) des similitudes climatiques, et la répartition des arbres-hôtes potentiels pour prévoir la probabilité d'introduction et d'établissement en Europe de quatre espèces d'*Agrilus* d'Amérique du Nord. L'objectif de la politique énergétique de l'UE d'accroissement de l'utilisation des copeaux de bois s'est accompagné d'une augmentation linéaire ou exponentielle des importations européennes de copeaux de bois de feuillus au cours des 10 dernières années en provenance de pays dans lesquels des espèces d'*Agrilus* potentiellement nuisibles sont présentes. La modélisation MaxEnt a montré que les conditions environnementales en Europe sont très favorables aux quatre espèces d'*Agrilus* étudiées, notamment en Europe de l'Est et dans la partie européenne de la Russie pour *A. anxius*, *A. bilineatus* et *A. planipennis*, et dans le sud de l'Europe pour *A. politus*. Les arbres-hôtes sensibles connus sont largement répandus dans les zones de répartition potentielle de ces *Agrilus* en Europe, et ces zones reçoivent de grandes quantités de copeaux de bois de feuillus provenant de pays où ces espèces et d'autres espèces d'*Agrilus* sont présentes. Ainsi, il est conclu que les conditions fondamentales de l'introduction et de l'établissement d'espèces d'*Agrilus* en Europe sont réunies.

Инвазивный потенциал *Agrilus planipennis* и других жуков рода *Agrilus* в Европе: пути распространения с импортом щепы древесины лиственных пород и анализы MaxEnt зон потенциального распространения

Развивающиеся под корой и в древесине жуки рода *Agrilus* (Coleptera: Buprestidae) способны выжить при переработке древесины в щепу. Златка *Agrilus planipennis* уже акклиматизировалась в Северной Америке и Европейской части России с разрушительным воздействием на лесные экосистемы. Работа, представленная в статье, сочетает статистику импорта щепы древесины лиственных пород, моделирование максимальной энтропии (MaxEnt) климатических аналогий и распространенность потенциальных деревьев-хозяев для спрогнозирования вероятности завоза и акклиматизации в Европе выбранных четырех североамериканских видов *Agrilus*. В соответствии с задачей увеличения использования древесной щепы, в рамках энергетической политики ЕС, на протяжении последних 10 лет отмечается линейное или экспоненциальное увеличение импорта в ЕС щепы лиственных пород из стран, в которых имеются потенциально вредные виды рода *Agrilus*. Анализ MaxEnt показал высокую экологическую пригодность среды в Европе для четырех видов *Agrilus*, особенно в Восточной Европе и в Европейской части России, для *A. anxius*, *A. bilineatus* и *A. planipennis* и, в юж ной части Европы, для *A. politus*. Зарегистрированные восприимчивые деревья-хозяева широко распрост ранены в спрогнозированных зонах потенциального распространения видов рода *Agrilus* в Европе, и именно в эти зоны завозятся большие объемы щепы лиственных пород из стран, где присутствуют эти и другие виды *Agrilus*. Таким образом, авторы приходят к выводу, что основные условия для интродукции видов рода *Agrilus* в Европу уже существуют.

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