Drivers and pathways of forest insect invasions in Europe, can we predict the next arrivals?

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DRIVERS AND PATHWAYS OF FOREST INSECT INVASIONS IN EUROPE, CAN WE PREDICT THE NEXT ARRIVALS?

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A total of 385 alien insect species established on woody plants in Europe since 1800. Along with globalization, the rate of arrival of new species exponentially increased during the second half of the 20th century to reach an average of 6.7 species per year during the period 2000-2012. This trend mirrors the rapid increase in the import of live woody plants. Very large discrepancies were observed between alien establishments and interceptions at borders. An analysis of the temporal changes in colonization of trees species growing in Europe revealed that since 2000 the recruitment of alien herbivores increased more rapidly on deciduous trees and shrubs, especially of tropical/ subtropical origin such as palms and eucalypts, whereas this recruitment has decreased in Gymnosperms and slowered in fruit trees. Identifying appropriate and effective tools for the prior warning and early detection of alien insect arrivals is urgently needed but extremely challenging because most potential invaders do not cause significant damage in their native range, and even could be yet unknown to Science. A novel method consisting in sentinel plantings in other continents to detect potential invaders is discussed from the results of recent experiments carried out in China.

KEY WORDS: Invasions, Insects, Forests, Europe, Pathways.

AN EXPONENTIAL ACCELERATION OF THE ARRIVAL OF EXOTIC INSECT SPECIES IN EUROPE

The globalization of economies, expanding world-wide trade, and climate change are all factors that contribute to the accelerated international movement and establishment of alien organisms, allowing them to overcome geographic barriers. Therefore, the rate at which humans translocate species beyond their native ranges has substantially increased during the last decades. The analysis of the data compiled in two recent databases devoted to alien species established in Europe, the DAISIE database (Delivering Alien Species Inventories in Europe; www.europe-aliens.org) launched in 2008, and the more recent EASIN catalogue (European Alien Species Information Network; Katsanevakis et al. 2015; www.easin.org) updated for insects by late 2014, revealed that the establishment rate of alien insects in Europe has increased from an average of 9.7 species per year for the period 1950-1974 to an estimated 14.9 species per year for 1990-2014. Most alien insect species in Europe were introduced accidentally, with only 14% of introductions being intentional, most of these for biological control (RABITSCH, 2010).This recent influx of alien insects appears to mainly due to the arrival of herbivores rather than to the introduction of parasitic and detritivorous species (ROQUES, 2010a). Thus, phytophagous species represented 69.8 % of the alien insects newly established in Europe since 2000. Moreover, these species were mostly associated with woody plants (76.5% of the total herbivores), those related to agricultural plants and products being a minority (Fig. 1). This is probably related to recent changes in trade practices, especially the increased magnitude in the movement of live woody plants for ornamental purposes (LIEBHOLD *et al.*, 2012; ESCHEN *et al.*, 2015). Along with globalization, the rate of arrival of species associated with woody plants thus exponentially increased from ca. 1.8 new species first observed per year during the first half of the 20th century to 6.7 per year during 2000-2014 (Fig. 1). As a result, a total of 385 alien insect species are at present reported as established on woody plants in Europe (ROQUES, 2010b; ESCHEN *et al.*, 2015). Therefore, identifying their pathway of arrival in order to prevent new introductions presents a significant challenge to researchers as well as to government agencies.

NOT SO EASY TO IDENTIFY A PATHWAY!

International trade in live woody plants, such as nursery stocks or bonsais, is widely recognized as a major pathway of introduction for alien insect pests

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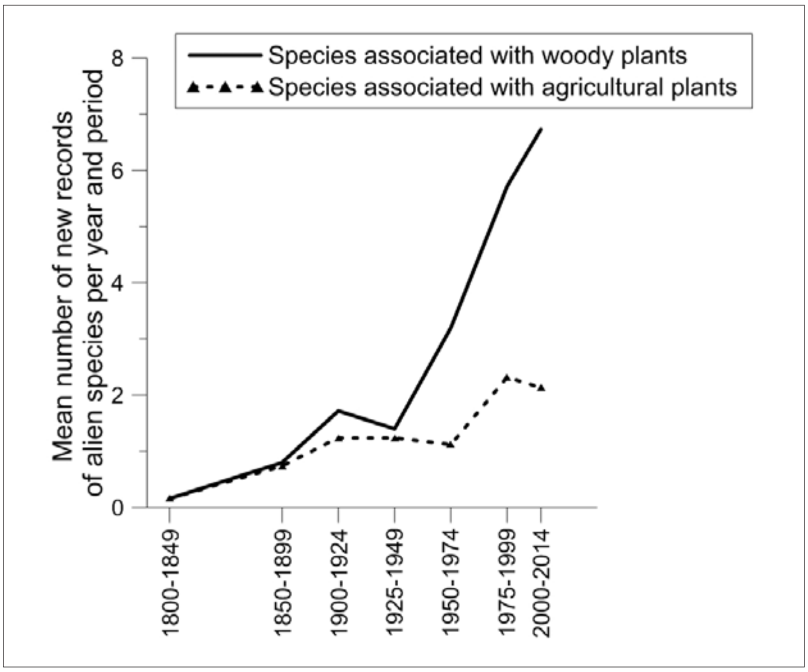

Fig. 1
Temporal changes in the introduction of alien phytophagous insect species in Europe, based on year of first record figured in the DAISIE and EASIN databases.

(Smith *et al.*, 2007; Rabitsch, 2010; Liebhold *et al.*, 2012). Pests arriving via this trade can relatively easily establish because they arrive on their host, which is often planted outside (Eschen *et al.*, 2015). However, a major problem is that the exact pathway responsible for a particular introduction is usually unknown. In most databases, these species are assigned post hoc by the assessor to the most likely introduction pathway or pathways, often more on the basis of assumptions of the assessor or from inference on the basis of a species' ecology than on hard evidence (Kenis *et al.*, 2007; Essl *et al.*, 2015). Practically, the interceptions by phytosanitary services at the borders of European Union could not really help in assessing introduction pathways because huge discrepancies exist between interceptions and establishments of alien insects (Kenis *et al.*, 2007; Bacon *et al.*, 2012). Eschen *et al.* (2015) thus noticed that among the 117 alien species established during the period 1995- 2012, only 7 were intercepted (the Asian long-horned beetles *Anoplophora chinensis A. glabripennis* on plants for planting and bonsais and on wood package material and bonsais, respectively; the box moth *Cydalima perspectalis*, the palm moth *Paysandisia archon*, the midge *Horidiplosis ficifolii,* and the aleyrodid *Singhella citrifolii* on plants for planting; and the conifer seed bug *Leptoglossus occidentalis* as a stowaway). Thus, most of the alien species reported in Europe since the late 1990s, and which have spread extremely rapidly, invading most of the continent within a few years, were never detected before their establishment; e.g. the chestnut gall wasp, *Dryocosmus kuriphilus* (Hymenoptera: Cynipidae; first detected in 2002 in Italy; Avtzis and Matošević, 2013), the honeylocust gall midge, *Obolodiplosis robiniae* (Diptera: Cecidomyiidae; detected in 2003 in Italy; Skuhravá and Skuhravý 2009), or the elm zig-zag sawfly, *Aproceros leucopoda* (Hymenoptera: Argidae; detected in 2003 in Poland; Blank *et al.*, 2010).

Another way to identify the introduction pathways: looking at the temporal changes in colonization by exotic insects of the tree species growing in Europe

A comparison of the richness in alien insect species recruited by the woody plants growing in Europe revealed that the exotic trees planted in Europe have recruited much more species than the native ones (Fig. 2). The top ten especially includes *Citrus*, palms and eucalypts. It is also worth noticing that about a half (51%) of the alien insect species did not switch onto natives woody hosts yet but stick to their original, exotic host with which they probably arrived.

The temporal changes in the colonization by alien insects of tree species growing in Europe has been hypothesized to reflect the invasive processes

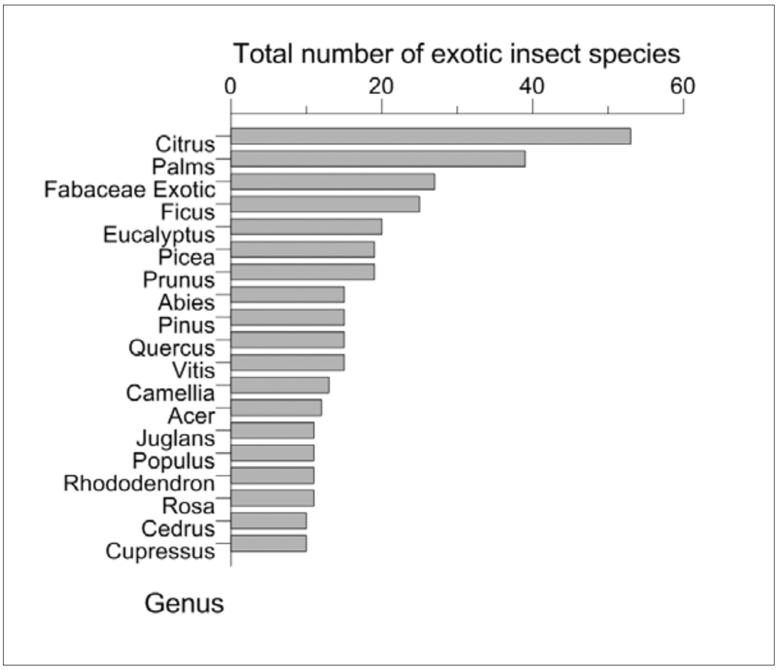

Fig. 2
Tree genera growing in Europe ranked by the total number of associated exotic insect species.

(ESCHEN *et al.*, 2015). During the recent decades, the colonization trends largely differed between large taxonomic host groups such as Angiosperms (then sub-divided into deciduous trees, fruit trees and shrubs), Gymnosperms and palms. During the period 2000-2011, the rate of increase in the number of newly recorded alien insects has thus increased more rapidly on deciduous trees, shrubs and palms whereas it has decreased in Gymnosperms and slowered in fruit trees (Fig. 3). At the family level, it appeared that the recruitment of alien insects had a recent fast increase in Myrtaceae (eucalypts), Fabaceae (exotic legume trees), Rutaceae (*Citrus*), Arecaceae (palms) but a decrease in Pinaceae and Fagaceae (ESCHEN *et al.*, 2015).

More globally, the recent period corresponded to a much faster increase in the recruitment of alien herbivores by trees of tropical/ subtropical origin planted in Europe than by native conifer and broadleaved trees (Fig. 4). This pattern is clearly illustrated by the eucalypts which recruited 7 new species since 2000 (*Ophelimus maskelli*, 2000: *Ctenarytaina spatulata*, 2002*; Leptocybe invasa,* 2003*; Blastopsylla occidentalis,* 2006:*; Ctenarytaina peregrina,* 2006*; Glycaspis brimblecombei,* 2007*; Thaumastocoris peregrinus,* 2011; Hurley et al., 2016) whereas only 2 and 4 species were recruited during 1950-1974 and 1975-1999, respectively. The situation is quite similar for palms (10 new alien insect species since 2000) and exotic Fabaceae (*Acacia, Albizzia* and others; 7 new species since 2000) whereas only 4 new alien species established on *Acer* and *Quercus* during the same period. It probably reflects that the trade of ornamentals, including bonsais, turned to be the major pathway of invasion by forest insects whereas timber trade and wood packaging contributes much less at present. For instance, it is noticeable that the recent introductions of eucalypt pests corresponded to tiny foliage feeders (e.g. the psyllids *Acizzia jamatonica* and *Glycaspis brimblecombei*; MIFSUD *et al.*, 2010; BELLA and RAPISARDA, 2013) and gall-makers (e.g. the eulophids *Ophelimus maskelli* and *Leptocybe invasa;* HURLEY *et al.*, 2016) whereas the previously established species were xylophagous insects (*Phoracantha* long-horned beetles; COCQUEMPOT *et al.*, 2010) and large foliage feeders (*Gonipterus* weevils; SAUVARD *et al.*, 2010). It is hypothesized that the newly arrived species proceeded from the trade of eucalypt seedlings or foliage for ornamental purposes whilst the former ones resulted from the trade of eucalyptus wood.

This kind of analysis may thus help targeting the commodities at risk in the ornamental trade. However, this significant, and very rapid, increase since the beginning of the 21st century in the establishment of new alien insect species related to trees originating from areas with warm climates also suggests a relationship with the current climate warming up in Europe which may help the alien species to establish.

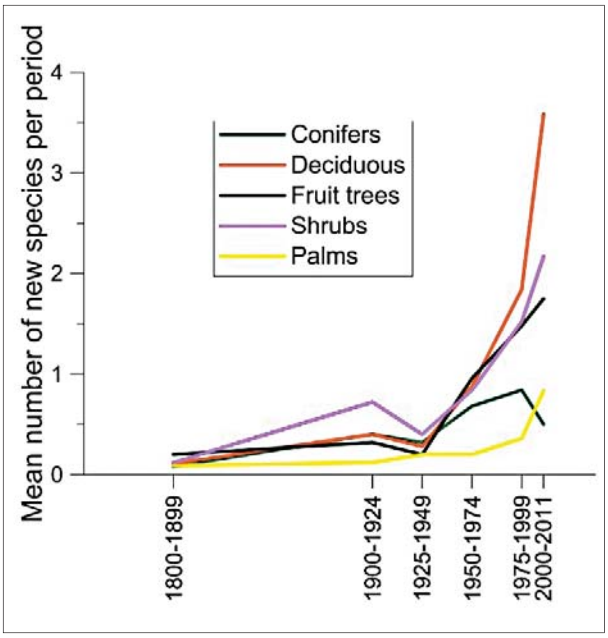

Fig. 3
Temporal changes in the mean number of alien insects recruited by broad taxonomic groups of trees growing in Europe (from ESCHEN *et al*., 2015, modified).

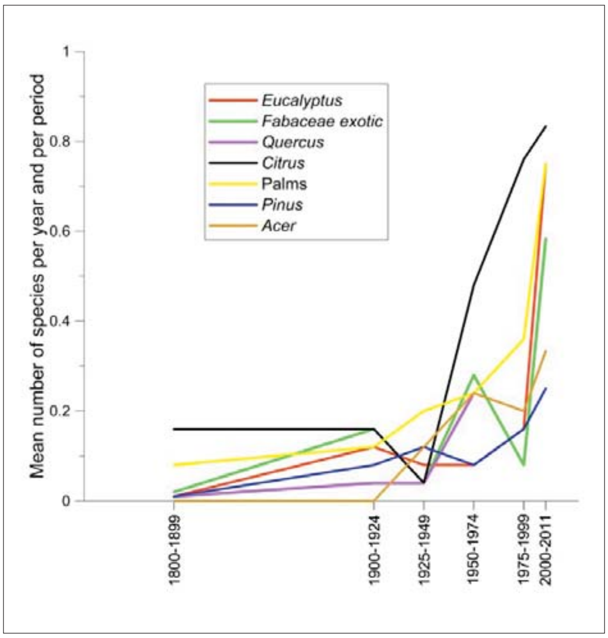

Fig. 4
Temporal changes in the mean number of alien insects recruited by different genera of trees growing in Europe (from ESCHEN *et al*., 2015, modified).

If the trade of plants for planting tends to constitute a major invasive pathway, it is not precluding the trade of wood and derivates as a pathway. Wood packaging is still an issue as shown by the recent invasion of the long-horned beetle *Aromia bungii* in Germany and Italy (GARONNA *et al*., 2013) and the new outbreaks of the Asian long-horned beetle *Anoplophora glabripennis* in Italy (FACCOLI *et al*., 2015), Switzerland (FORSTER and WERMELINGER, 2012) and Corsica (EPPO, 2013). Trade of timber, roundwood and other raw forest products also remain a pathway. Several exotic ambrosia beetles (*Ambrosiodmus rubricollis, Cyrtogenius luteus, Xylosandrus crassiusculus*) were thus trapped in Italian ports importing such material (RASSATI *et al*., 2014). Finally, the real importance of hitchhiking in containers remains difficult to be assessed but it is probably higher than currently considered (e.g., the probable multiple introductions of the western conifer seed bug, *Leptoglossus occidentalis*; LESIEUR, 2014).

SENTINEL PLANTINGS AS AN EARLY WARNING TOOL TO IDENTIFY POTENTIAL INVADERS

Besides pathway analyses, predicting which of the many potentially invasive species are most likely to establish in a particular region or country is mainly done for plant pests through pest risk analyses (PRAs), which are generally based upon expert opinion and thus can lead to misleading prioritizations. Other methods based on modelling (climate envelope, niche), hierarchical cluster analysis (ESCHEN *et al*., 2014) or self- organizing maps (SOM; WORNER *et al*., 2013) all have an intrinsic weakness because they are only considering the species known as plant pests in the countries of origin, or the invasive species that have already established in the countries of introduction. Actually, a large proportion of the recent insect invaders throughout the world were not known to cause significant damage in their country of origin because they coevolved there with their hosts and were under control of natural enemies, both conditions being released in the invaded areas (LIEBHOLD *et al*., 2012). A notorious example is the emerald ash borer (*Agrilus planipennis*) that is relatively harmless in its native Far-Eastern Asia but is now one of the most important tree pests in North America (BARANCHIKOV *et al*., 2008).

A novel method to detect potential invasive threats consists in sentinel plantings. Growing plants in continents where they are non-native and studying their subsequent colonization by indigenous insects enables to detect potential invaders, even those that are not known anywhere else as pests, before they are introduced into a new continent. Since Asia is currently considered to be the main supplier of forest insect invaders to

Europe (Roques, 2010b), such an experiment was carried out in China during 2007-2011 using seedling plantations of five broadleaved (*Quercus petraea, Q. suber, Q. ilex*, *Fagus sylvatica*, and *Carpinus betulus*) and two conifer species (*Abies alba* and *Cupressus sempervirens*) native to Europe. The trial resulted in a first list of Asian insects potentially threatening European trees. A total of 104 insect species, mostly defoliators, were observed to be capable of switching onto these new hosts (Roques *et al.*, 2015). Among them, a total of 38 species showed more than five colonization events, mostly infesting *Q. petraea*, and 6 of them presented a high likelihood of introduction to Europe. Most of these species were unknown as tree pests, and a majority of the identified species appeared to have switched from agricultural crops and fruit trees rather than from forest trees. Three years was shown to be an appropriate duration for the experiment, since the rate colonization then tended to plateau. Although these results are promising, the use of seedlings generally prevented the rapid colonization of groups like xylophages. Apart from the logistical problems, the identification to species level of the specimens collected was also a major difficulty but the situation could be improved in the future by the development of molecular databases.

A complementary, and more recent, experiment used sentinel nurseries. After having identified the Chinese trees the most exported to Europe during the recent years, experimental nurseries of these species were settled in China without any pest control measures in order to follow the development of insect damage and identify the corresponding species. Five Chinese tree species were considered, including *Buxus microphylla*. A major result was the observation of heavy damage by the box moth, *Cydalima perspectalis,* in all of the sentinel nurseries (Kenis *et al.*, unpublished observation). It is likely that such an observation obtained 10 years ago would have pointed out the threat constituted by the box moth before its first record in Europe in 2006, and therefore would have suggested to implement measures in order to prevent its introduction and subsequent rapid spread in Europe (Bella, 2013).

Botanical gardens and arboreta may also constitute excellent tools in this objective because they exist all over the world and, by collecting and planting large numbers of introduced and native plant species together, they make it possible to survey for possible shifts of phytophagous species from the natives to the exotics. However, these collections often include only a few specimens of each plant species, with a limited genetic variability, and are thus not suitable for statistical analyses.

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