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Alien forest insects in a warmer world and a globalised economy: impacts of changes in trade, tourism and climate on forest biosecurity†

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Abstract

This paper examines the effects of changing world trends on the introduction, establishment and spread of exotic insects associated with woody plants. Three aspects are considered: (i) commercial trade; (ii) tourism and consumer behaviour; and (iii) climate change.

The current literature indicates that there are two key pest pathways: movement of wood ((including solid-wood packaging), and the ornamental plant trade. The number of pests introduced along these routes is positively correlated with the volume and source of imports. It is likely, therefore, that improvements in regulation of the movement of wood will lead to a decrease in pest entry via this pathway. However, complexities associated with the ornamental plant trade will ensure that it remains a high risk route. There is evidence to suggest that numbers of interceptions at airports are positively related to the volume of air traffic from the countries from which passengers originate. Shifts in climatic conditions are likely to affect the survival, fecundity, development and dispersal of native insect species. However, it is difficult to entirely disentangle the effect of climate change from that of other physical or chemical factors, and/or other biotic causes.

Improved monitoring of imports/exports, more knowledge about possible pests, and the impacts of climate change are needed to prevent the arrival of foreign pests in the future.

Keywords: invasion; trade; climate change; forest; insect pests; wood; plants; bonsais.

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Introduction

Expanding world-wide trade, globalisation of economies and climate change are all factors that contribute to the international movement and establishment of exotic forest insects. Numerous examples already exist where commercial foreign trade has enabled pests to move from one continent to another. These include:

- Asian gypsy moth (*Lymantria dispar* (L.)) from Asia to North America (Liebhold et al., 1995);
- Asian long-horned beetles ((*Anoplophora glabripennis* (Motschulsky) and *A. chinensis* (Forster)), and emerald ash borer (*Agrilus planipennis* Fairmaire) from Asia to North America and Europe (Cavey et al., 1998; Colombo & Limonta, 2001; Dauber & Mitter, 2001; Poland & McCullough, 2006; Baranchikov et al., 2008);
- Eucalyptus long-horned beetles (*Phoracantha* spp.) and eucalyptus snout beetles (*Gonipterus* spp.) from Australia to Europe, Africa, South America, and other non-native regions (Marelli, 1928; Duffy, 1963; Kevan, 1964; Cadahia, 1980; Mansilla & Pérez-Otero, 1996, Barranco & Ruiz, 2003; EPPO, 2006);
- ambrosia beetle (*Megaplatypus mutatus* (Chapuis)) from South America to Europe (Alfaro et al., 2007);
- many species of bark beetles from Europe to New Zealand (Brockerhoff et al., 2006);
- red turpentine beetle (*Dendroctonus valens* LeConte) from North America to Asia (Britton & Sun, 2002); and
- pine shoot moth ((*Rhyacionia buoliana* (Denis & Schiffermüller) from Europe to North America and South America (Cerda et al., 1986; Mattson et al., 1994).

This usually unintentional, but human-assisted, movement of plant pests between countries has led to the establishment of the International Plant Protection Convention (IPPC; FAO, 1997) as an international agreement for preventing such movement. Since March 2005, (revised 2009), the International Standard for Phytosanitary Measures No. 15 has been adopted as a regulation specifically for preventing the movement of pests with wood packaging materials (FAO, 2009). Despite this, recent inventories of non-native insects established in another continent showed that alien species now establish at an ever-higher rate than previously. The European project Delivering Alien Invasive Species Inventories in Europe (DAISIE); Simberloff, 2009) revealed that the yearly establishment in Europe of alien insects associated with woody plants during the period 2000 - 2007 was nearly twice that from 1950 – 1974, the period just before the beginning of the globalisation process, the respective averages being 7.9 and 4.2 new species per year (Roques, 2008; Roques et al., 2009).

The current phytosanitary regulatory approach for detecting new pests primarily relies on inspection. However, the volume of international trade and travel is so great, and the modes of entry are so varied, that not all consignments or routes of entry can be screened, and usually the inspection capacity is completely overwhelmed. In the United States, inspectors examine up to 2% of cargo arriving at maritime ports, airports and border crossings (Work et al., 2005; Colunga-Garcia et al., 2009). Moreover, inspections are generally biased by focusing only on currently known quarantine pests and priority pathways (Haack, 2006). In fact, new threats may arise from unanticipated pest species via novel markets or commodities. Finally, weakening customs and quarantine controls at a continental level, such as in the European Union (EU), may allow alien species to spread between countries once they are successfully established in the region.

Trade patterns (types of products, trade routes and volume) are also quickly changing as a result of globalisation. As pointed out by Hulme (2009), new sea, land and air links in international trade and human transport have established novel pathways for the spread of alien species. Understanding how these factors may result in new introductions, obtaining sound estimates of the arrival rates of alien species, and assessing how new introductions may affect the native flora and fauna require the development of accurate risk assessments. Effective detection and mitigation measures for specific pathways or commodities also need to be formulated.

When alien phytophagous insects arrive at a location, their survival, establishment and spread depend on a number of factors including the availability of receptive host plants and on the suitability of the local climate (Elton, 1958). In fact, new immigrants are likely to arrive in areas where climatic conditions are markedly changing. The mean global temperature has increased by ca 1 °C since the pre-industrial era and has continued to accelerate. Eight of the ten years between 1996 and 2007 were among the warmest since 1850 (EEA, 2008). The Intergovernmental Panel on Climate Change (IPCC) models predict a further increase from 1.6 to 6.4 °C by 2100 (IPCC, 2007). We may expect similar ecological responses to climate change from alien pests as those already observed for some native species (see Parmesan & Yohe, 2003; Battisti et al., 2005; Parmesan, 2006). Climate change may directly allow some alien species to establish in areas where they could not survive before. Furthermore, an indirect effect of climate change may be that some native ecosystems become less resistant to invasion under future climates, especially if they are already stressed by other possible consequences of climate change,

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e.g. drought (see Rouault et al., 2006).

This paper examines: (i) the relationships between commercial trade and introduction of exotic insects associated with woody plants (including anticipated changes due to recent variations in volume, origin and variety of goods that may carry such insects; (ii) the possible effect of mass tourism and other new behaviours of consumers on such introductions; and (iii) the potential effect of climate change on establishment and spread of these insect species. It will present new data from two European projects, DAISIE and the European network on emerging diseases and invasive species threats to European Forest Ecosystems (called FORTHREATS).

Increased global trade and invasions of forest insects

Variations in trade volume

The volume of trade in manufactured goods grew at an average annual rate of 7.5% from the early 1950s until 2006, outperforming agricultural products which nevertheless grew at 3.5% (WTO, 2007). Currently, all forecasts predict a significant increase in global trade over the next 20 years, despite the present economic crisis. Such growth in international trade is likely to result in an increased arrival of alien organisms. This is clearly important in determining the probability of a pest becoming established. Unfortunately, there is limited information on the relationship between "propagule pressure"[1] and successful establishment of exotic forest insects unlike for other groups such as birds (Kolar & Lodge, 2001).

There is considerable evidence that the greater the level of international trade, the higher the number of alien species established in areas such as the United States, China and Europe.

Strongly positive (although nonlinear) correlations have been established between the volume of international trade and the accumulation of exotic species for groups as diverse as insects, molluscs and plant pathogens in the United States (Levine & D'Antonio, 2003). Both manufactured goods and agricultural products can harbour alien forest insects (Work et al., 2005; Haack, 2006; McCullough et al., 2006; Colunga-Garcia et al., 2009). Species associated directly or indirectly with traded products are more likely to be dispersed to new regions. Levine and d'Antonio (2003) suggested that it is not the type of trade *per se* (e.g. the amount of agricultural goods), but the overall level of trade that seems to be important. Using the Global Invasive Species Database (GISD) of the International Union for Conservation of Nature (IUCN), Westphal et al. (2008) also concluded that the best predictor of the number of invasive alien species in a country is the level of international trade. Haack (2001) reported that the number of bark beetle interceptions from foreign countries was related to the value of imports from those countries.

Lin et al. (2007) found that the rapid increase in the number (per decade) of newly introduced invasive species in China since the 1970s coincided with the sharp economic growth (as represented by Gross Domestic Product, GDP) experienced by the country during the same period. Significant variations in the number of invasive species were detected among Chinese provinces in relation to the economic development and trade, the more economically developed provinces in southern China and the coastal areas of eastern China having higher abundances of invasive species than provinces in inland and western China. Foreign exchange earnings, as indicated by the import and export values of commodities, have a significant linear relationship with the number of invasive species per province.

The DAISIE and FORTHREATS projects are specifically considering alien insects related to woody plants in Europe. They have revealed strong positive correlations between the number of alien species per European country and the volume of both manufactured (r^2 = 0.776; p = 0.000) and agricultural imports (r^2 = 0.757; p =0.000) of the country. More limited correlations were also shown with the road network size (r^2 = 0.717;p = 0.003), the GDP (r^2 = 0.531; p = 0.042), and the geographic size (r^2= 0.521; p = 0.046) of a given country. In contrast, the alien species richness was not correlated with the total forest cover (p = 0.14) nor with the percentage of forest cover (p = 0.78) (Roques, 2008).

The overall conclusion from the above studies is that the number of established alien species is expected to grow exponentially with the increase in trade volume. This can be demonstrated for Europe at least, where nearly twice as many new species were observed per year during the period 2000 – 2007 (6.3 species) compared to 1960 – 1979 (3.4 species; Roques, 2008; Figure 1).

However, even if the arrival rate is accelerating, as shown by the incidence of interceptions (e.g. see McCullough et al., 2006; Roques & Auger-Rosenberg, 2006), there may be other factors involved which make the overall process of alien establishment much more

[1] *A composite measure of the number of individuals of a species released into a region to which they are not native. It incorporates estimates of the absolute number of individuals involved in any one release event (propagule size) and the number of discrete release events (propagule number).*

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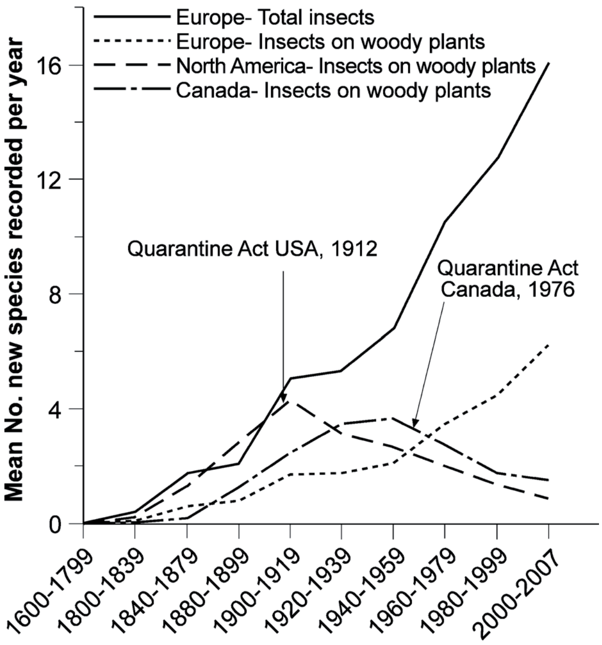

FIGURE 1: Comparison of the establishment rates of total alien insect species in Europe and of alien insects associated with woody plants in Europe and North America. Values are expressed as mean numbers of new insects recorded per year. (European data from DAISIE and FORTHREATS; North American data from Langor et al., 2009).

complex. Figure 1 compares the yearly establishment of alien forest insects in Europe, Canada and the whole North America, using data presented by Langor et al. (2009). The disestablishment of internal customs processes (such as quarantine procedures) as a result of the formation of the EU in 1993 has probably made it easier for alien species to be introduced and further spread once established in an EU country. Also, the quarantine legislation of the European Union is less stringent than that in North America for some groups of organisms. For example, alien species of *Megastigmus* seed chalcids have repeatedly established in Europe since the beginning of the 20th century and currently represent 43% of the total fauna of tree seed chalcids (Roques & Skrzypczynska, 2003). This magnitude may reflect the lack of regulatory measures for seed imports in continental Europe as was shown for *M. schimitscheki* Novitzky, the latest species to arrive with seeds from Asia Minor during the 1990s (Roques et al., 2008). In contrast to Europe, the establishment rate of alien species in North America increased from the late nineteenth century until about the 1920s then declined rapidly thereafter. When considered separately, the same trend was observed for Canada but the decline occurred later (1960s – 1970s). Langor et al. (2009) attributed these two declines to the quarantine legislations enacted in the United States in 1912 and in Canada in 1976, respectively. This explanation seems too limited, however, as new species of alien forest insects are still being reported from North America, e.g. the siricid *Sirex noctilio* F. in 2004, the bark-beetle *Xyleborus maiche* (Stark) in 2005, and the buprestid *Agrilus subrobustus* Saunders in 2006 (Colunga-Garcia et al., 2009).

Speed of trade

The increasing speed of intercontinental transportation for commodities as well as for individual passengers also allows exotic organisms to survive longer-distance travel than in the past with slower maritime transport (Humble & Allen, 2001). At present, a container of ornamental plants leaving Singapore reaches London in ca 14 hours by air cargo and 22 days by sea ship (source: http://www.cma-cgm.com) whereas such transport took several months of maritime shipping in the past.

Changing trade routes

The large increase observed in the different kinds of freight traffic (airborne, seaborne, railway) must also be analysed with respect to changes in trade routes. Between 1990 and 2008, container traffic grew from 28.7 million TEU (Twenty-foot Equivalent Units; i.e. 6.1 m-long shipping containers) to 152.0 million TEU, an increase by about 430% (Rodrigue et al., 2009). With the opening of new markets during the last twenty years, Asia has become the focal point of maritime container movements far beyond Europe and North America (Table 1). The situation was somewhat similar for air cargo traffic over a similar period. From 2000 to 2007, this traffic increased for the top 30 airports by 23% for those in Asia, by 20% for those in Europe but only by 12% for those in North America (Airports Council International, 2008). Overall, the number of airports in the top 30 for cargo traffic increased from 10 to 12 in Asia but decreased from 14 to 11 in North America. In addition, 15 Asian airports were among the 25 that grew most rapidly in 2007. This is likely to modify the list of potential invaders to be expected as Asia plays a key role as a source of alien species for other world regions. Nowadays, species of Asian origin represent more than one-third (34.6%) of the 412 alien insects presently recorded on trees and shrubs in Europe (Roques, 2008). This is much greater than for those from North America (25.4%) and other continents (Africa: 10.2%; Central and South America: 8.6%; Australasia: 7.6%; undefined subtropical/tropical areas: 8.2%; cryptogenic: 5.4%), (Roques, 2008). It is noticeable that the contribution of Asia is more important for insects related to woody plants than for total alien insects (29%), (Roques et al., 2009). Mattson et al. (2007) reported that North America was a bigger source of alien insect species than Asia but

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their analysis was based on a truncated list of only 109 species. McCullough et al. (2006) similarly reported that improved relations and increased trade between the United States and countries such as Vietnam and China were mirrored by notable increases in pest interceptions over time. Thus, interceptions of both insect pests and plant pathogens from China were roughly ten-fold greater from 1995 to 2000 than from 1985 to 1990. However, other, well-established, major trade routes are also important transport corridors for pests. Langor et al. (2009) stated that almost all alien species of forest insects in Canada originate from the Palaearctic ecozone, especially Europe, reflecting historical trade patterns. Similarly, a survey of exotic beetles that attack trees or shrubs in New Zealand found 51 species of mainly Australian (58%) and European (25%) origin (Brockerhoff & Bain, 2000). Thus, it appears that the origin of these exotic beetles reflects the proximity of Australia as well as Australian and European trade relations which traditionally predominated in that country.

Lin et al. (2007) also pointed out that the likelihood that a Chinese plant community will have received alien species is greatly due to its proximity to a seaport or other major point of entry besides the frequency, speed, and mode of dispersal of the aliens themselves. Thus, they suggested that the inspection regimes at important areas of import and export, such as Shanghai, Hong Kong, Beijing and Guangdong, be intensified.

Changes in the variety of exchanged goods and related pathways

There have been significant changes during the last ten years in the variety of plant material being traded in relation to consumer demand. There was a steep increase in the international trade of horticulture products over this period, which resulted in a continuous movement of such plants all over the world (CBI, 2006). A number of specific pathways for the horticultural trade (e.g. ornamental plants for planting, bonsais, Christmas trees, large potted trees, seed trade) have been identified, which can directly bring about the translocations of alien insects likely to affect trees and shrubs as discussed in the next section. These types of plant constitute ‘miniature’ ecosystems, which may host a large variety of insects that have the potential to damage other woody plants (Roques & Auger-Rozenberg, 2006). Ornamental plants also pose a particular risk because they tend to be transported swiftly, with contaminants intact, into suitable receptor habitats (Smith et al., 2007). For example, more than 73000 plant types are currently cultivated in the UK, which includes only a negligible number of native species (ca 1500 spp.) (Perrings et al., 2005). Recent consumer demand for particular items, such as bonsais and Christmas trees, has reinforced the importance of this pathway. The development of trade in plant material through the Internet is also significant because there is less control, especially for tree seeds which can be moved quite freely all over the world

TABLE I: World Port Ranking for container traffic in 2005 (in millions of Twenty-foot Equivalent Unit-TEU) and total cargo volume (in millions of tons) (from American Association of Port Authorities, 2007).

Port (Country)	**Container traffic** (millions of TEU)	Rank	Port (Country)	**Total Cargo volume** (millions of tons)	Rank
Singapore (Singapore)	23.192	1	Shanghai (China)	443.0	1
Hong Kong (China)	22.427	2	Singapore (Singapore)	423.3	2
Shanghai (China)	18.084	3	Rotterdam (The Netherlands)	376.6	3
Shenzhen (China)	16.197	4	Ningbo (China)	272.4	4
Busan (South Korea)	11.843	5	Tianjin (China)	245.1	5
Kaoshiung (Taiwan)	9.471	6	Guangzhou (China)	241.7	6
Rotterdam (The Netherlands)	9.287	7	Hong Kong (China)	230.1	7
Hamburg (Germany)	8.088	8	Busan (South Korea)	217.2	8
Dubai (United Arab Emirates)	7.169	9	South Louisana (USA)	192.5	9
Los Angeles (USA)	7.485	10	Houston (USA)	192.0	10

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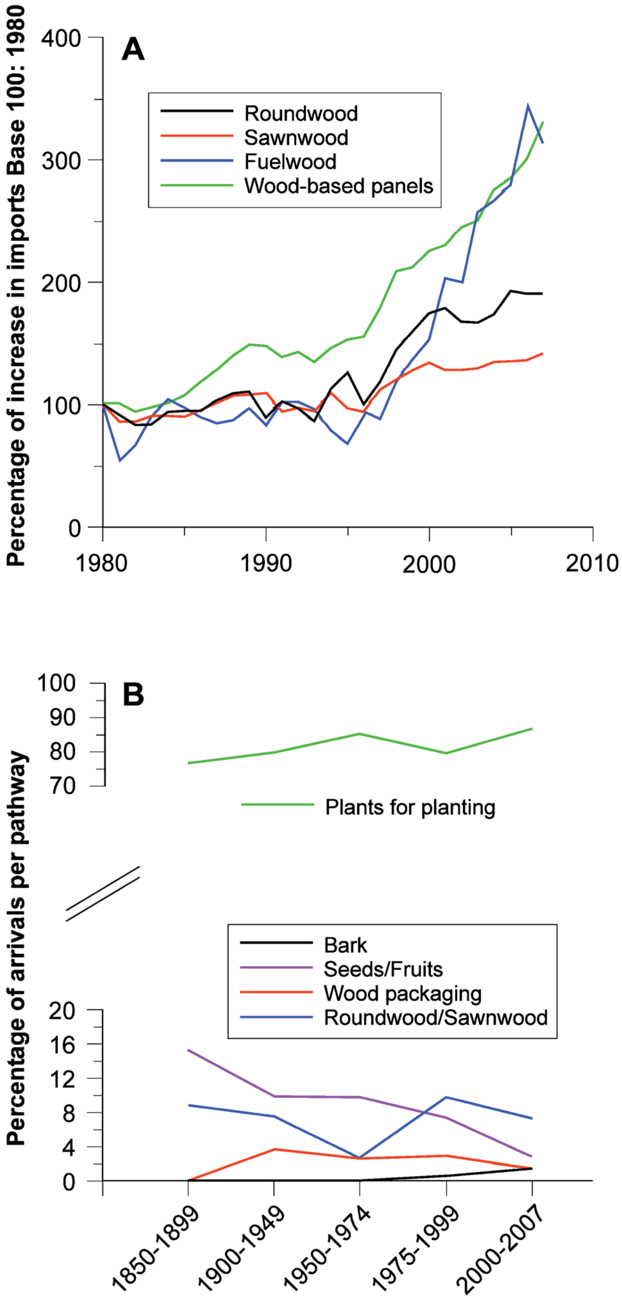

FIGURE 2: Variation over time in trade of wood and derivates and arrival of alien insects associated with woody plants.

A: Change in world trade of wood and derivates at world level between 1980 and 2007 (data from FAOSTAT, 2008);

B: Variation in the relative contribution of the different pathways for the introduction of alien insects associated with woody plants in Europe from 1850 to 2007 (data from DAISIE and FORTHREATS).

although some countries have adopted regulations (e.g. New Zealand).

Simultaneously, changes are also occurring to the wood-trade sector. Insects are increasingly transported via derived wood products, especially solid-wood packaging, pallets and plywood compared with raw logs, which were a major source of alien insects in the past (Cock, 2003; Humble 2010). Each importation of living or untreated material constitutes a potential source for introduction of alien species (Krcmar-Nozic et al., 2000). Meanwhile, the wood and wood products market has shown greater global variations (Figure 2a). The movement of derived wood products, especially wood packaging, pallets and plywood, has increased rapidly, together with that of firewood while the trade in roundwood and sawnwood has increase more slowly (FAOSTAT, 2008). Regional variations do not necessarily show clearly in this global data. For example, there was a dramatic increase in the importation of timber from Russia and the Baltic States to a number of European and Asian countries from 1996 onward. In Belgium, it was shown that such imports not only allowed new opportunities for exotic bark-beetle introductions but created a trade pathway offering high mobility and low traceability (including the possibility of illegal trade) (Piel et al., 2008).

Other pathways, not directly related to plants and plant products, must also be mentioned because alien forest insects may use them for hitchhiking. Thus, containers, used cars, and ships are well known to host a variety of insect material, including hidden adults, larvae and egg masses, such as those of Asian gypsy moth (Wallner et al., 1995). In New Zealand, Ridley et al. (2000) indicated that almost 40% of all containers examined from a random sample have some type of external contaminants, either insects, fungi spores or plant debris. Thus, the huge increase in container movement (cf above) is likely to result in a higher frequency of alien pest arrival.

It is not easy to identify either vectors or pathways because most of the introductions are accidental. Deductions or assumptions based on species' biology, plant host, and other characteristics can be made, however (Kenis et al., 2007). Thus, plants for the ornamental trade seemed to contribute significantly more than forestry products to the establishment of alien forest insects in Europe at least. This tendency appears to have increased since 2000 as the amount of woody material traded as well as that of seeds and fruits decreased (Figure 2b). Similarly, Smith et al. (2007) showed that plant trade, particularly in ornamental plants, accounted for nearly 90% of human-assisted introductions of phytophagous insects in the UK, which include mostly species associated to woody plants. Similar high proportions have been found in France (Streito & Martinez, 2005), Italy (Pelizzari et al., 2005), and Serbia and Montenegro (Glavendekić et al., 2005).

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Subsequent changes in alien entomofauna composition

The section above highlighted the potential of both ornamental plants and wood derivatives to act as pathways for introducing pests. The trade of ornamental plants for planting is considered to be responsible for the introduction of insect species as diverse as:

- cycad scale, *Aulacaspis yasumatsui* Takagi, introduced to Florida and Hawaii on imported cycads (Howard et al., 1999);
- silver fir woolly adelgid, *Adelges nordmannianae* (Eckstein) (synonym *Dreyfusia nordmannianae* (Eckstein)), and hemlock woolly adelgid, *Adelges tsugae* Annand, introduced on conifer nursery stock from Asia to Europe and North America, respectively (Binazzi & Covazzi, 1988; McClure, 1988);
- *Cinara cupressi* (Buckton) aphids introduced to Africa with cypress plants (Ciesla, 1991);
- chestnut gall wasp, *Dryocosmus kuriphilus* Yasumatsu, introduced from China to the United Statees and Europe (Bosio, 2004);
- black locust leaf miner, *Phyllonorycter robiniella* (Clemens), introduced from North America to Europe (Marek et al., 1991); and
- black locust midge, *Obolodiplosis robiniella* (Haldemann), also introduced from North America to Europe (Glavendekić et al., 2010).

In addition to these defoliators, sap suckers and gall-makers, such ornamental plants may also host xylophagous species. A total of 46000 potted plants of maple, *Acer palmatum* Thunb. were thus destroyed at a nursery in the south of England during 2005 because of the large presence of Asian citrus long-horned beetles, *Anoplophora chinensis* (Evans, 2008). A special mention must be made of the bonsai trade, which nowadays constitutes a high risk pathway for alien forest pests. It is responsible for the introduction into Europe of *A. chinensis* (Hérard & Roques, 2009) but may also carry other xylophagous beetles, aphids, scales and other defoliators and leaf miners. Roques and Auger-Rozenberg (2006) reported nearly twice as many interceptions on bonsais as on timber at the European borders from 1995 onwards.

More generally, there is a large discrepancy between interceptions and establishments of alien species (Figure 3). A comparison at family level during the period 1995 – 2005 for the alien insects and mites associated with woody plants in Europe revealed that the major groups of invaders were largely undetected (e.g. aphids, midges, scales, leafhoppers and psyllids). Species in these groups are usually more related to the vegetative parts of plants other than wood. In contrast, the groups which were predominantly intercepted (e.g. long-horned and bark-beetles), actually made little contribution to the established alien entomofauna. Similar results were obtained at country level for Austria, the Czech Republic, and Switzerland (Kenis et al., 2007). This pattern may reflect the increasing importance of the ornamental plants pathway although it is also possible that some of these pest species may have arrived as stowaways, e.g. on containers or vessels. Other than wood, there are few controls on plant imports, especially plants for planting. It is probably for this reason that Hemiptera largely dominate the alien insects related to woody plants in Europe and Canada, where they represent 55% and 53% of the total, respectively (Roques, 2008; Langor et al., 2009). On the other hand, it cannot be concluded that the inspection emphasis on long-horned and bark-beetles has effectively restricted the introduction of such species. Work et al. (2005) estimated that even rigorous inspections probably detected only 19 – 50% of the imported species, depending on the pathway. In New Zealand, a survey of exotic bark beetles carried out by Brockerhoff et al. (2006) also revealed that three of the five true bark beetles that have become established were intercepted reasonably frequently but the two others (*Cryphalus wapleri* Eichhoff and *Phloeosinus cupressi* Hopkins) were not intercepted at all. Similarly, only two (*Xyleborinus saxesenii* (Ratzeburg) and *Coccotrypes dactyliperda* (F.)) of the six other Scolytinae that have become established in New Zealand, were intercepted whereas the four others (*Amasa truncata* (Erichson), *Ambrosiodmus compressus* (Lea), *Coptodryas eucalyptica* (Schedl), and *Xylosandrus pseudosolidus* (Wood & Bright) were not. A possible reason for these interception differences may be that some species established a long time ago through a different route so they may not arrive at current ports.

Finally, ornamental plants are generally used in man-made habitats such as nurseries, parks and gardens and roadside plantings and shelter belts. At present, most alien species imported via ornamentals are confined to such habitats. In Europe, 68.7% of the species related to woody plants still live in such habitats whereas only 15.1% have moved to forests (Roques, 2008). However, it is unclear whether the reason for this phenomenon is due to a lower resistance of disturbed urban and semi-urban areas or to the time lag necessary for accumulation before spreading in natural habitats. Another probable reason is that most alien species (46.4% in Europe), (Roques, 2008) remained strictly associated with their original, exotic host and have not so far infected native trees.

Fresh wood as well as wood derivates usually host only xylophagous species, mostly bark- and ambrosia-beetles (Curculionidae, Scolytinae, Platypodidae, Bostrychidae) and long-horned beetles

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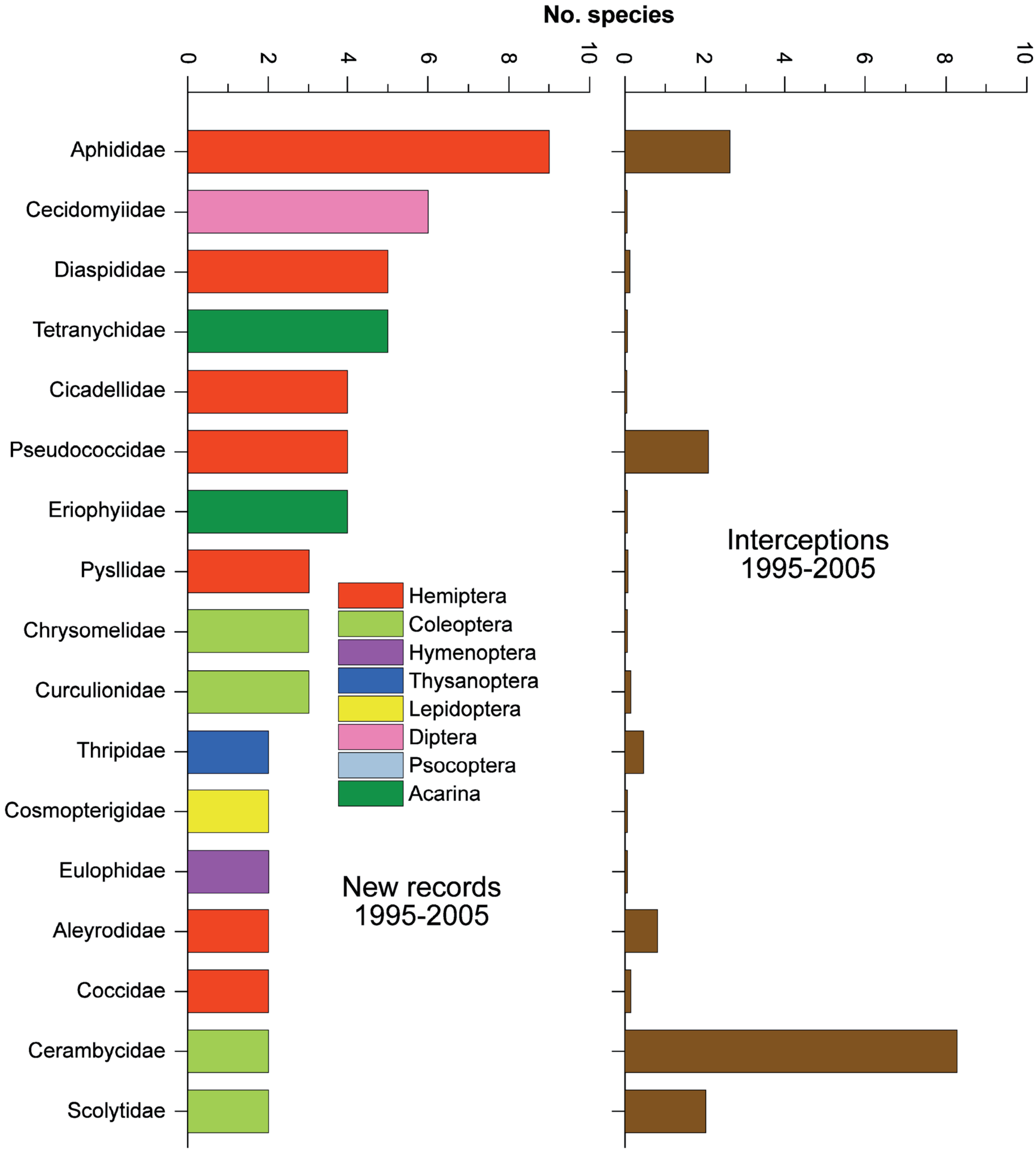

FIGURE 3: Comparison of the number of alien insect and mite species on woody plant hosts established in Europe during 1995-2005, with the number of interceptions during the same period, by family (interception data from Roques & Auger-Rozenberg, 2006; establishment data from DAISIE and FORTHREATS).

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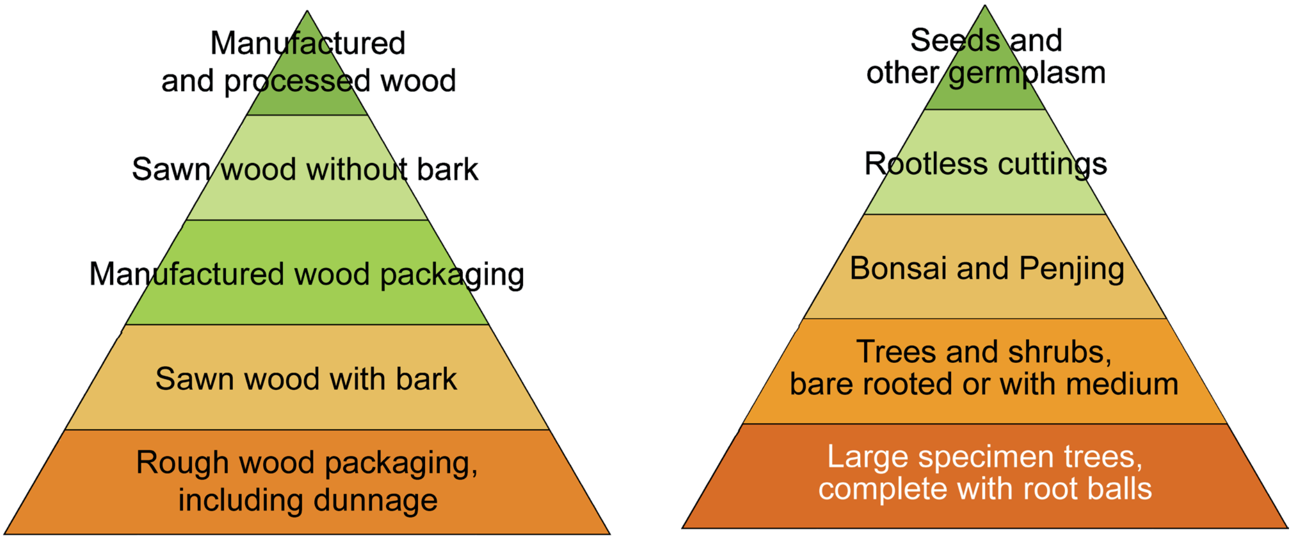

FIGURE 4: Comparison of the risk profile for different pathways involving untreated wood (left) and living plants (right) for the introduction of alien insects. The risk decreases from the base to the top (modified from Evans, 2008).

(Cerambycidae). Thus, Haack (2006) pointed out that wood packaging material was the likely pathway by which almost all of the recently observed 28 exotic insect borers first entered the United States. This subject was reviewed recently by Humble (2010).

Recently, Evans (2008) published a generalised comparison of the risk profile of untreated wood with that of plants for planting (Figure 4). An additional point to be considered is that the effectiveness of detecting and eradicating alien pests also differs between the ornamental-plant and wood-derivative pathways. Since wood-derivative treatments associated with ISPM 15 are expected to be effective, the probability of eliminating both quarantine species and as yet unknown ones travelling with wood and derivates is high. In contrast, checks of ornamental plants usually target only quarantine invertebrates whilst non-quarantine invertebrates along with other, as yet unknown, species are left free to enter new regions. Moreover, in this case, direct treatments are either not efficacious or not practical with increasing size of planting material.

Risks associated with the development of mass tourism and changing consumer behaviour

According to the international association of the world's airports, the Airports Council International (http://www.aci.aero), world-wide traffic in air passengers has increased by 34.4% since 2000 to reach 4.8 billion in 2007. This increase involved both international and domestic travel. In China, the number of passengers on international flights represented 16.9 million passengers in 2004, almost tripling the number from 1995. On domestic flights, the number was 138.3 million in 2005 compared to 2.3 million in 1978 (Ding et al., 2008). Although periodic fluctuations may be expected due to various economical, political and sanitary crises, such as a reduction in 2001 – 2002 due to flight restrictions following terrorist attacks in the US on 11 September 2001, this general trend is likely to be sustained. Statistics on passenger rail traffic also showed continued growth, with a doubling of traffic levels on both the Indian and Chinese railway networks in less than twelve years (International Union of Railways, 2008).

It has been known for a long time that international travellers can deliberately or accidentally introduce species that later prove to be invasive, while domestic travellers can contribute to the spread of already established alien species. Ridley et al. (2000) reviewed a series of studies carried out in various airports of New Zealand during the 1960s to 1980s where clothing, shoes and luggage of air passengers were carefully vacuumed. Mostly spores from pathogenic fungi were recovered but live insects were also found, especially from tents brought by travellers. The risk was assumed to be particularly relevant to indigenous forests, since the tents were probably transported in order to camp in national parks. Liebhold et al. (2006) analysed historical records of interceptions of alien insects in air passenger baggage by United States Department of Agriculture inspectors, and concluded that baggage is a significant invasion pathway. The most commonly infested commodity intercepted by inspectors was fruit (mainly tropical fruits), and the

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most commonly intercepted insects were *Homoptera* spp. and *Diptera* spp. Numbers of interceptions from passengers originating from different countries were positively related to the volume of air traffic from that country. This probably reflects the emphasis placed on the inspection of fruits at airports. However, very few of these species appeared to be relevant to forest trees, except for some scale insects.

International exhibitions are another important potential hazard. Such exhibitions act as 'hubs' by concentrating the arrival of alien forest insects before dispersal, because they usually involve mass planting of exotic trees and shrubs for decorative purposes. The 1992 Universal Exhibition which took place in Seville (Spain) led to the planting of 267 plant species of which 26% were planted for the first time in the country (Durán et al.,1994). A total of 496 pest diagnostics were undertaken on these plants. The tests revealed mostly alien aphids, scales and mites, with the first record of the North American leafhopper *Tinocallis saltans* (Nevsky) on *Ulmus pumila* L. Polyphagous species of aphids such as *Aphis gossypii* Glover and *Myzus persicae* Sulzer (synonym *Nectarosiphon persicae* Sulzer) predominated but some were specialists such as *Appendiseta robiniae* (Gillette). It is likely that this exhibition has triggered the spread of exotic species throughout Spain at least. A similar situation was observed during the 2004 Olympic Games in Athens where imported palm trees were widely planted. This coincided with the first arrival of the red palm weevil, *Rhynchophorus ferrugineus* (Olivier), which subsequently colonised the entire Eastern Mediterranean region within the following two years (Kontodimas et al., 2006). As a result of this disaster, a concerted campaign was launched in 2006 against the introduced North American fall webworm (*Hyphantria cunea* Drury), to prevent its possible impact on Beijing's urban landscape trees during the 2008 Olympic Games (Ding et al., 2008). However, a large tree planting campaign, including exotic trees and shrubs, was initiated by the Chinese President on that occasion and may have resulted in further insect introductions (People's Daily On-line, April 6, 2008).

The translocation of large, potted trees with soil attached to their rootstock also appears to constitute a pathway for international movement of a number of forest insects. Relying on so-called 'green' alibis (i.e. to achieve instant woody landscapes without having to wait for the trees to grow), this fashionable behaviour has led to the introduction of larvae and pupae from foreign species that develop in the soil in addition to those developing on tree structures. This is probably the pathway by which processionary moths (such as oak processionary moth, *Thaumetopoea processionea* L. in the UK (Evans, 2008) and pine processionary moth, *T. pityocampa* (Denis & Schiffermüller) in Alsace (Robinet et al., 2009b)) have expanded far beyond their native range.

With the escalating prices of fuel oil and gas, wood use as both a secondary and primary heating fuel is on rise. In the United States, a high level of risk for spreading of emerald ash borer, *Agrilus planipennis*, has been associated with individuals moving firewood for such purposes or for making barbecues at campgrounds (Buck, 2008). It has been determined that sales of firewood from quarantine areas to homeowners for heating create a potential spread of emerald ash borer of up to 240 to 320 km per movement of firewood. Moreover, plotting parks and campgrounds at one-day (800 km) or two-days (1600 km) driving distances from the quarantine area showed that most of eastern North America is potentially as risk, as far south as Florida.

Changing climate and forest insect invasions

Shifts in climatic conditions may affect the survival, fecundity, development and dispersal of native insect species, and signs of their response to global warming have already been detected (Parmesan & Yohe, 2003; Battisti et al., 2005; Parmesan, 2006). In the same way, climate change may directly influence the introduction, colonisation and rate of establishment of alien insect species into new territories, and may also facilitate the spread of alien species already present in the environment, increasing or decreasing their impact.

In recent years, there has been an increase in the number of reported case studies showing that a wide range of alien taxa introduced from warmer climes reproduce and establish in previously unsuitable areas and as a result enlarge their range of distribution (Walther et al., 2009). In Europe, a total of 186 alien insect species affecting trees and shrubs were identified that originated from areas with a subtropical and/or tropical climate. Their presence in Europe indicates that they are capable of surviving European winter conditions at least locally, e.g. along the Mediterranean coast (Roques et al., 2009; Roques, unpublished data). Moreover, interceptions by quarantine services at European borders from 1995 to 2005 revealed 38.7% of intercepted species arrived from tropical Asia (18.2%), tropical and Southern Africa (15.2%), South America (5.1%), and Australasia (0.2%) (Roques & Auger-Rozenberg, 2006). The recent arrival and establishment of several tropical species associated with palms is illustrative of this process. Since 1993, 31 palm pests have been recorded, among them a Castniidae moth from South America, *Paysandisia archon* (Burmeister) (Montagud Alario & Rodrigo Coll, 2004) and the red palm weevil, *Rhynchophorus ferrugineus*, from Melanesia. The latter successfully colonised southern France, Corsica, Italy, continental Greece, Crete and Cyprus from 2004 to 2006 (Rochat et al., 2006). More generally, the insect fauna recorded on palms, eucalypt and tropical legume trees planted in Europe significantly increased during the period 2000 – 2007 as a result of colonisation of specific,

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exotic insects whereas infestations of broad-leaved trees remained stable and that of conifers decreased (Roques, unpublished data).

Such a climatically triggered invasion process often starts with a few precursor individuals, which only temporarily occur in a site during short favourable climatic periods or, in this early stage, are spatially restricted to favourable micro-habitats. Continued climate change may prolong the duration of these occasional occurrences of initial introductions, increase their frequency or enlarge the range and area of suitable habitats, thus, making it more likely for these species to persist, to occur more frequently and to develop larger populations. With further global warming, alien species originating from warmer regions may build up larger populations that may spread to wider areas. Global warming may also provide new opportunities for introductions to areas where, until recently, introduced species were not able to survive. A first key point is the effect of climate on the thermal thresholds constraining survival. For example, the climatic conditions occurring in winter during the 1990s did not allow larvae of pine processionary moth, *Thaumetopoea pityocampa* (Denis & Schiffermüller), to survive when accidentally introduced beyond its natural range, because larval development is limited by not only by temperatures below -16 °C (which are lethal) but also temperatures that prevent feeding (i.e. night air temperature below 0 °C and temperature inside the nest below 9 °C on the preceding day), (Battisti et al., 2005). With the northwards shift of climatic isotherms, self-sustaining moth populations have been able establish far beyond previous boundaries (Robinet et al., 2010). Similarly, former greenhouse inhabitants, such as the exotic scale-species *Coccus hesperidum* L. and *Icerya purchasi* Maskell that affect ornamental shrubs have recently been found outdoors in Switzerland (Kenis, 2005).

The arrival of a non-native species does not automatically lead to a successful establishment, especially if the usually small founder populations are subject to a strong Allee effect (Liebhold & Tobin, 2008; 2010). However, changes in climatic conditions that result in a prolonged growing season and reproductive period of the host often provide conditions that alien species may exploit. Species introduced from warmer regions to temperate areas have, until recently, been constrained by local growing seasons too short to allow them to reproduce and establish, but this may change. There is evidence of a strong association between patterns of emergence by the invasive gypsy moth, *Lymantria dispar,* and climatic suitability in Ontario, Canada (Régnière et al., 2009). This alien moth has been trapped more frequently in this region since 1980. However, between 1992 and 1997, a temporary decline in climatic suitability occurred, which resulted in a pronounced reduction in the area of defoliation by this species. Since 1998, the trend has again reversed with a consequent resurgence in defoliation and increased frequency of moths in pheromone traps to the north and west in Ontario. In organisms for which population dynamics are mainly controlled by temperature, climate change may increase development rates and lead to the production of an additional yearly generation. An example of this is the American fall webworm, *Hyphantria cunea*, an invasive in Japan, which shifted from a bivoltine to a trivoltine life-cycle in at least a part of its range (Gomi et al*.,* 2007). Another key point is the synchrony between the development of an insect and its host plant. Studies done on native species showed that climate change may lead to a mismatch between the two processes because of different thermal thresholds, e.g. bud burst and egg hatching between oak (*Quercus* sp.) and winter moth, *Opheroptera brumata* (L.) (Visser & Both, 2005), and between sycamore (*Acer* sp.) and sycamore aphid, *Drepanosiphum platanoidis* (Schrank) (Dixon, 2003). It is likely that the same process is affecting introduced species but it is not yet documented.

These examples show that some alien species profit from improved conditions, mainly from warmer temperatures. Much less is known of introductions that fail or species that show range contractions as a consequence of climate change (Parmesan et al., 1999). Moreover, besides temperature, other aspects of climate change, such as changes in precipitation regimes, are also likely to influence invasion processes, but little is known about their possible effect. It is difficult to entirely disentangle the effect of climate change from that of other physical or chemical factors, and/or other biotic causes, however, especially man-mediated changes in land use and habitat modification. Much more research is required to establish whether the observed changes can really be attributed to a variation in climatic conditions. Also, only limited information is currently available about climate-driven invasions.

What of the future? A number of studies have attempted to predict the suitability of ecosystems for invaders under potential climate change scenarios (e.g. Wharton & Kriticos, 2004; Vanhanen et al., 2008). Using the climatic modelling program CLIMEX, Vanhanen et al. (2008) simulated the potential distribution ranges in Europe of three species of long-horned beetles from Asia, *Tetropium gracilicorne* Reitter, *Xylotrechus altaicus* (Gebler) and *Aeolesthes sarta* (Solsky). The results showed that the first two species could become established practically anywhere in Europe except the south, while it was predicted that *A. sarta* would have difficulty in establishing populations in central and northern parts of Europe. A separate simulation, using the IPCC climate change scenario A1B (IPCC, 2001), forecast expansions of 200 to 1100 km at both the northern and southern edges of the distribution range for the studied species. However, other modelling studies have shown a rather limited influence of global

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warming on the expansion of invasive organisms compared to other factors. A relevant example here is the pine wood nematode, *Bursaphelenchus xylophilus* (Steiner & Buhrer), whose spread in China is mostly related to dissemination through domestic trade of wood (Robinet et al., 2009).

Finally, the introduced insect species must find an acceptable host and one at the right development stage. Apparently, that is not so easy. About half of the exotic insect species of woody plants that have been introduced to Europe are still confined to the original, exotic host tree and have not switched to another host plant (Roques et al., 2009). A challenge for further studies is to document the capabilities of exotic insects to switch to native plants with respect to the response of these plants to global warming, in terms of phenological development, physical properties and chemical composition.

Conclusions: How to mitigate the risks?

Recommendations can be formulated at a number of different levels. Basic knowledge of the exotic entomofauna already established is fragmentary in most continents and countries even where the potential impact of invasions has been considered for a long time. The DAISIE results have shown the value in having global inventories at both a continental and country level. All relevant variables in discriminating specific taxa or groups and new risk pathways need to be more carefully surveyed in order to provide an understanding of the effects of temporal changes on faunal composition, the relative importance of each feeding guild, and/or the relative colonisation of the host plants. Simultaneously, the exact importance of each pathway must be evaluated by effectively assessing the arrival rates of alien species. The collection of negative records of the absence of an alien species in a commodity should also be undertaken in addition to those of positive interceptions as was done by Work et al. (2005) and McCullough et al. (2006).

The development of early warning systems is also essential. In the present situation where ornamental trade is the dominant pathway for invasion by insects related to woody plants, a more thorough survey of parks, gardens and nurseries may function as an early warning system. This could also be accompanied by the installation of more sophisticated quarantine and control measures at invasion 'hubs' for the ornamental plant trade (e.g. in the Netherlands) (Roques et al., 2009). However, the lack of knowledge about potential invaders indicates a need for more sophisticated experiments. One approach is to establish sentinel trees in other regions in order to evaluate the impact of local indigenous insects should they become introduced as exotics at a later date. This is currently carried out in China for potential pests of European tree species (Baker et al., 2009). The implementation of surveillance programmes using traps baited with host-produced volatile chemicals and/or species-specific pheromones in forest habitats in and around port facilities also allowed an early detection of non-indigenous xylophagous insects in the United States and Canada (Humble, 2010). However, Skarpaas and Økland (2009) noticed that new introductions often may go undetected by pheromone traps or will require a high trapping intensity.

The pathway framework model developed by Skarpaas and Økland (2009) for assessing the risk of forest pest introductions with timber imports predicts that the most effective measures for actively reducing the risk of exporting pests are those that involve isolating produce when stored (e.g. storage enclosure, location), followed by removal of suitable habitats (e.g. debarking, timber irrigation, rapid processing), whereas delayed import seems least effective. Improvements in techniques used to apply ISPM15 will probably lead to a greater decrease in the probability of pest entry via wood-trade and solid-wood packaging in the near future. However, ornamental trade will still remain a high risk pathway. Thus, regulatory systems could incorporate a pathway approach that ensures that imported plant material is free of all quarantine and regulated non-quarantine pests but also practically free of non-regulated pests as suggested by Evans in a recent IUFRO concept paper (n.d.). This would require that the place of production, rather than that of reception, develops standardised pest managements practices, such as pre-export treatments and preventive measures to clean growth media. Such practices would eventually be transcribed into pre-certification programmes.

However, such pre-emptive measures are obviously not sufficient to completely prevent all new introductions of alien insect species in the context of rapidly expanding global trade. Prevention of establishment through the eradication of newly established populations and containing the spread of introduced species are, therefore, likely to play increasingly important roles. Thus, Liebhold and Tobin (2010) propose the manipulation of Allee effects, in order to eradicate small populations of introduced pests. By enhancing Allee effects or suppressing populations below Allee thresholds, population extinction may be achieved without further intervention. Another approach to containing the spread of invading species is locate and eradicate isolated colonies that establish by long-distance translocation ahead of the range boundary.

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