Department for Environment Food & Rural Affairs

Rapid Pest Risk Analysis (PRA) for:

Popillia japonica

June 2015

Stage 1: Initiation

1. What is the name of the pest?

Popillia japonica Newman (Coleoptera: Scarabaeidae: Subfamily: Rutelinae: Tribe; Anomalini), the Japanese beetle.

Some sources regard the subfamily, Rutelinae, as a family in its own right, and thus the taxonomic placement may be reported as Scarabaeoidea: Rutelidae, for example in EPPO (2006).

2. What initiated this rapid PRA?

Following reports of the first incursion of this species in mainland Europe, consisting of large numbers of adults in an area near Milan, Italy in autumn 2014, a review of the UK Plant Health Risk Register scores was carried out. Discussions during this review concluded that a UK PRA was required to further assess the risk *P. japonica* poses to the UK now that it is present in mainland Europe, especially with regard to pathways, establishment and potential UK impacts.

3. What is the PRA area?

The PRA area is the United Kingdom of Great Britain and Northern Ireland.

Stage 2: Risk Assessment

4. What is the pest's status in the EC Plant Health Directive (Council Directive 2000/29/EC[1]) and in the lists of EPPO[2]?

Popillia japonica is listed in Annex IAII of the EC Plant Health directive as *Popilia japonica*, as an organism known to occur in the community, and relevant for the entire community. It is also on the EPPO A2 list of pests recommended for regulation.

5. What is the pest's current geographical distribution?

Table 1: Distribution of *Popillia japonica*

North America	USA:	Widespread in the eastern states (except Florida), with more scattered records in central states and outbreaks in some western states
	Canada:	Southern parts of the eastern states: Ontario, Quebec, New Brunswick, Prince Edward Island and Nova Scotia
Central America	No records	
South America	No records	
Europe	Azores:	Faial, Flores, Pico, São Miguel and Terceira
	Italy:	A limited area west of Milan (Province of Novara), in the communes (municipalities) of Bellinzago Novarese, Cameri, Galliate, Marano Ticino, Oleggio and Pombia
Africa	No records	
Asia	Japan:	Hokkaido, Honshu, Kyushu and Shikokui
	Russia:	Kunashir Island
Oceania	No records	

Popillia japonica is native to Japan, and is found on all four of the main islands including northern Hokkaido. Records of this pest in Russia refer to scattered and sporadic reports from Kunashir Island (e.g. EPPO, 2015; Nikritin & Shutova, 1969), this island being just off the eastern coast of Hokkaido, and which is disputed territory between Japan and Russia. Reports of *P. japonica* from the Korean peninsula almost certainly refer to the closely related species *P. quadriguttata* (EPPO, 2015). The status of records from the northern

[1] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:2000L0029:20100113:EN:PDF

[2] https://www.eppo.int/QUARANTINE/quarantine.htm

provinces in China is unclear, and at least some of these also appear to refer to *P. quadriguttata* (EPPO, 2015).

In 1916, *P. japonica* was discovered in eastern North America, where it was thought to have been present since around 1911 (Potter & Held, 2002). Since then, despite being subject to control measures, *P. japonica* has spread over much of the USA, and is now widespread in most of the eastern states (except Florida), with additional scattered records from many central and western states (APHIS, 2005-2014). In Canada, *P. japonica* is found in the southern parts of Ontario (where it can be a pest), southern Quebec, New Brunswick, Nova Scotia (Halifax) (Canadian Food Inspection Agency, 2000-2005) and Prince Edward Island (Canadian Food Inspection Agency, 2008). There are also reports of beetles from St John's in Newfoundland, though these are of only one or two individuals at a time, and beetles are not found every year (pers. comm. M. Damus (CFIA), 2015). All the Newfoundland reports are associated with urban areas or nurseries, no reports of any harm are known, and therefore it appears that these individuals are transient, sustained only by frequent entry events, rather than derived from an established population (pers. comm. M. Damus (CFIA), 2015).

Within the EU, *P. japonica* was first found in Terceira Island in the Azores (an autonomous region of Portugal) in the early 1970s (Simões & Martins, 1985), and is now also present in the islands of Faial, Pico, São Miguel and, most recently, Flores (Vieira, 2008). In 2014, *P. japonica* was reported for the first time from mainland Europe, with numerous adults caught near Milan (EPPO reporting service, 2014; Pavesi, 2014). The pathway of introduction to Italy is unknown, but the valley in which *P. japonica* has been found is adjacent to Milan's main international airport (Malpensa). A map of the 2014 findings, with details of trap catches, outbreak area and a buffer zone is available in Venanzio and Bosio (2015), showing the infested area is considered to extend around 15 km north to south, though only around 5 km east to west. Around 28,000 adults were trapped in this region between August and early October 2014, and larvae were found during soil sampling in the early winter (Venanzio & Bosio, 2015). Pavesi (2014) states that the density of the populations were very variable locally, with an apparent preference for sunny locations, and that the leaves of *Urtica* and *Rubus* (nettle and bramble) were particularly damaged by feeding, though the species of *Rubus* affected was not reported.

6. Is the pest established or transient, or suspected to be established/transient in the UK/PRA Area?

(Include summary information on interceptions and outbreaks here).

Only a few historical interceptions have been recorded in the UK, and no outbreaks or occurrences in the wider environment are known. All of the interceptions have been at ports of entry. Single adults were detected at Prestwick in Scotland, in association with military aircraft, in each of the years 1952, 1953 and 1954 (Cameron, 1954). Adults have been found at Avonmouth docks on two occasions in 1970, both associated with wheat from Virginia, USA: in October, 2 dead adults, and in November, 8 dead and headless adults (Fera, unpublished data). No more recent interceptions in the UK are known.

Additionally, an adult specimen of *Popillia* was found at Prestwick Airport in July 2003, this time associated with computer parts from Taipei, Taiwan. As *P. japonica* is not considered to be present in Taiwan (EPPO, 2015), this interception may have been of one of the very closely related species from eastern Asia. Germany has also reported the finding of a *Popillia* species, on *Cycas revoluta* from Costa Rica in August 1999 (EUROPHYT, 2015).

7. What are the pest's natural and experimental host plants; of these, which are of economic and/or environmental importance in the UK/PRA area?

Adults are highly polyphagous, with over 300 hosts in 79 plant families reported in the USA (Potter & Held, 2002), though the range of recorded hosts is smaller in Japan (Fleming, 1972). While they are best known as defoliators, skeletonising leaves, adults will also feed on fruit. Only a few of the recorded hosts are listed below, selected on the basis of those apparently favoured by the beetle, and of importance to the UK. More comprehensive adult host lists can be found in many places, such as Fleming (1972), CABI CPC (2014), Ladd (1987b) or Ladd (1989). Tree hosts include *Acer* (maples), *Betula* (birch), *Fagus* (beech), *Larix decidua* (larch), *Malus* (apples), *Populus* (poplars), *Prunus* (stone fruit), *Quercus* (oak), *Tilia* (limes) and *Ulmus* (elms). Shrubs and bushes commonly attacked include *Althaea rosea* (hollyhock), *Rhododendron*, *Rosa* (roses), *Rubus idaeus* (raspberry), *Vaccinium* (blueberry), *Viburnum* and *Vitis* (grapevine). Other hosts of economic importance to the UK include *Asparagus officinalis, Fragaria* (strawberry), *Trifolium* (clover) and *Zea mays* (maize). *Pelargonium domesticum* (geranium) appears to be toxic to *P. japonica*, though many beetles recover from the paralysis apparently induced by this host (in Fleming, 1972).

Larval foodplants are less well studied, mainly because the larvae live and develop underground, feeding on roots, and are thus more difficult to study. As larvae are not especially mobile, their food source is mostly determined by which plants are growing in the area where the female beetle oviposited. Females usually lay eggs near the plant upon which they are feeding, though beetles feeding on trees and shrubs usually prefer to lay eggs in nearby grass, and turf and pasture seems to be the vegetation type with which most larval damage is associated (Fleming, 1972).

8. What pathways provide opportunities for the pest to enter and transfer to a suitable host and what is the likelihood of entering the UK/PRA area?

(By pathway)

Plants for planting (with roots) can be imported with enough soil to maintain the plant (both from within and outside the EU), and in practice, this can be a reasonable quantity of soil for larger plants. The larvae will have roots to feed on, though not necessarily of their preferred hosts, and the plants will be kept in conditions that are likely to be suitable for continued development of the beetle larvae. While larvae are most commonly found in association with pasture, they do feed on other hosts and there will be some chance of immature stages being associated with the rootballs of a wide range of plants. The pathway of introduction from Japan to the USA may have been on soil associated with iris roots (Dickerson & Weiss, 1918). Adults are reasonably large beetles that would be present on the foliage, not concealed in the roots, and it seems probable that they would be detected on the consignment, if they had not already flown off or dropped to the ground when the plant was disturbed during transportation. Therefore, this pathway was assessed mainly for larvae and eggs. To date, there have been no UK interceptions of *P. japonica* on growing plants from Japan or the USA, though it has been detected moving within the USA, e.g. in turf in California (Los Angeles County, 2003). While *P. japonica* is currently restricted to a small area of Italy, the amount of movement of plants within Italy (including around the infested area), is unknown. Additionally, plants moving in trade within the EU are subject to less inspection and regulation than those from third countries, with no intra-EU restrictions on many plant species, and of those hosts that do require plant passports, these are not routinely inspected. Overall, entry on this pathway is considered **moderately likely** within the next five years, based on the assumption the pest will continue to spread in Italy, though this rating will need to be kept under review in light of developments. If the pest was to spread to major Italian nursery production areas, then, due to the volume of imports of plants from parts of Italy to the UK and the more limited inspection on intra-EU trade compared to that from third countries such as the USA or Japan, then the prospects for UK exclusion would seem likely to diminish, and this entry rating would require revision. Confidence in this assessment is only **medium** as the beetle has such a wide host range, not all hosts will be subject to the same levels of inspection, and it is unknown how fast it may spread in Italy.

Soil as such could harbour eggs, larvae and pupae, with these life stages together accounting for the majority of time in the lifecycle. Late instar larvae are larger and more likely to be detected. Although eggs and early instar larvae are more likely to be overlooked, the soil would need to be kept in conditions that enabled development to continue (including roots to feed on). Soil is a prohibited commodity from outside the EU. Within the EU, *P. japonica* is only known from a tiny fraction of the total area, namely parts of the Azores and a valley to the west of Milan. Thus, although no data are collected on the volume of soil traded within the EU, the overall likelihood of association of any life stage of *P. japonica* with European soil is considered very small, while soil from North America and Japan is prohibited. Therefore, entry on this pathway is judged to be **very unlikely** with **high confidence**.

Harvested plant parts (cut flowers and branches, fruit, etc.) from a wide range of hosts could have adults associated with them, as the adults feed on both foliage and fruit. However, the adults are a reasonably large beetle (about 8-11 mm long), the damage they cause is leaf skeletonisation and surface damage to fruit, and hence is reasonably visible, and this is a well-known pest, regulated in the EU and elsewhere. Therefore, it seems likely that adults would be detected either during pre-export or import inspections, and action taken on the findings. Additionally, the adults are very mobile and are thus less likely to remain associated with many harvested products. When foliage is disturbed, for example by harvesting or packing, the beetles are likely to either drop to the ground or take flight, the response varying with temperature (Kreuger & Potter, 2001), and are thus less likely to remain associated with many harvested products. However, this dropping behaviour may actually cause some commodities to be contaminated as the adults may fall with the fruit into the collecting container, for example blueberries (Szendrei *et al.*, 2005). Adults will only be present during the warmer months of the year, and immature stages will not be associated with these commodities. Given that adults are very mobile and highly polyphagous, it seems likely that they could find a suitable host in the wider environment upon arrival. Given their polyphagous nature, a very wide range of imported material could be infested with beetles and the total volume of plant parts imported will be very considerable. However, adults will only be present during the warmer months of the year, and immature stages will not be associated with these commodities. Overall this pathway is considered **unlikely**, with **medium confidence**.

Hitchhiking is thought to be the means by which *P. japonica* entered the Azores, as it was first found in the vicinity of a US Air Force base and later moved into the fields adjacent to the airfield (Martins & Simões, 1988). The USA has measures targeted against accidental transport of adults in cargo planes to western states, as adults have been known to fly in while the planes are being loaded, though it is unclear what attracts them into the cargo holds (Hamilton *et al.*, 2007). A *Popillia* species was detected in Scotland, associated with computer parts from Taiwan, again indicating that the adults can be associated with non-host commodities. While either a male-female pair or a fertilised female would need to be transported in order to found a population, the adults are gregarious and use pheromones to attract one another. Other factors that may aid the beetle's ability to colonise a new area is that virgin females produce a pheromone highly attractive to males (Potter & Held, 2002) and thus there is a good possibility that hitchhiking females may already be fertilised. Older females can still lay reasonably large numbers of fertile eggs, though there is conflicting evidence over whether egg production is approximately constant throughout their lifespan (e.g. Van Timmerman *et al.*, 2001), or if there is a decline in the fertility of eggs from the oldest females (e.g. Ladd, 1987a). While *P. japonica* females usually mate before each oviposition period, continued mating is not required for the ongoing production of fertilised eggs (Ladd, 1987a) and thus a single female could theoretically lay a large number of fertile eggs over her lifespan. Regarding transfer to a suitable host, airports have large areas of grass which is a preferred habitat for egg-laying, though other factors such as the height of the grass and soil moisture and texture are important, for example the areas of grass between the runways at Indianapolis airport actually harboured few larvae, possibly due to the more rapid loss of moisture from the soil in these areas (Hamilton *et al.*, 2007). Overall, given the previous interceptions and known association of adult *P. japonica* with non-host commodities, hitchhiking is considered **moderately likely** with **medium confidence**, though adults are only present in the warmer months of the year and thus hitchhikers only pose a seasonal risk, in late spring through to early autumn.

Plants for planting with roots	Very unlikely ☐	Unlikely ☐	Moderately likely ☑	Likely ☐	Very likely ☐
Confidence	High Confidence ☐	Medium Confidence ☑	Low Confidence ☐		

Soil	Very unlikely ☑	Unlikely ☐	Moderately likely ☐	Likely ☐	Very likely ☐
Confidence	High Confidence ☑	Medium Confidence ☐	Low Confidence ☐		

Harvested plant parts	Very unlikely ☐	Unlikely ☑	Moderately likely ☐	Likely ☐	Very likely ☐
Confidence	High Confidence ☐	Medium Confidence ☑	Low Confidence ☐		

Hitchhikers	Very unlikely ☐	Unlikely ☐	Moderately likely ☑	Likely ☐	Very likely ☐
Confidence	High Confidence ☐	Medium Confidence ☑	Low Confidence ☐		

9. How likely is the pest to establish outdoors or under protection in the UK/PRA area?

(*The likelihood rating should be based on the area of potential establishment, e.g. where hosts are present and the climate is suitable, within the UK/PRA area)*

The northern limits of the current distribution of *P. japonica* are Hokkaido in Japan, and parts of Nova Scotia in Canada, though, at least in Japan, the larvae require two years instead of one in order to complete development in these northerly locations. This suggests that some areas of the UK may be suitable for outdoor establishment as parts of Hokkaido, in particular, are usually considered to be climatically similar to parts of the UK. Previous attempts have been made to model the potential distribution of *P. japonica* in Europe. Bourke (1961) created a "rough model", where suitable climates for establishment were those that met all three of the following criteria: (1) the total of mean rainfall in June, July and August exceeded 250 mm, (2) the mean July soil temperature (5-10 cm depth) was between 20 and 28°C and (3) the mean January soil temperature exceeded -2°C. As a result, the UK was judged to be at low risk, as the summer temperature was too low, while much of central Europe, including most of France and Germany, was considered suitable for establishment (though moisture could be limiting in areas that are not irrigated), and only a comparatively small part of central Europe was considered to be highly suitable (Bourke, 1961). Using the climate mapping programme CLIMEX, Allsopp (1996) used the existing range of *P. japonica* to map potential areas of establishment in regions including North America and Europe. This work considered the UK to be marginal for establishment, with Bristol being most suitable (Allsopp, 1996). However, CABI CPC (2014) notes that after only 12 years, the current distribution of *P. japonica* in North America meant that it had already spread to regions outside those predicted by Allsopp (1996).

As the existing data is not clear on whether the UK would be suitable for establishment of *P. japonica*, therefore some preliminary climate risk mapping was carried out using interpolated climate data for the UK, as well as Belgium, France, Italy and the Netherlands. Details of the analysis, datasets used, assumptions and limitations, and the maps generated are presented in Appendix 1. From the maps presented here, based on day degrees, it appears that parts of the UK are potentially suitable for the outdoor establishment of *P. japonica*, though southern England is most likely to be at risk and the majority of larvae seem likely to require two years to complete development (Figs. 3-6). However, if summers temperatures are limiting, those experienced in the UK are unlikely to prove warm enough, except, perhaps, on south facing slopes or similar locations (Figs. 7-8). Based on these preliminary maps, establishment of *P. japonica* is considered **likely** in the warmer parts of the UK, particularly on south facing slopes, but with **medium confidence**, as many climatic factors have not been included in this preliminary mapping, as the data are not readily available, or require substantial analysis and interpretation. For example, these maps are based on climate as measured at weather stations above ground level, from which there are a great deal of data, but much of the life cycle of *P. japonica* is spent underground. However, preliminary analysis, using data from one site in London, suggests that degree day accumulations from air temperatures are a reasonable first approximation of soil temperatures (data presented in Appendix 1: table 3 and Figure 9).

Establishment under protection is also uncertain. Multiple generations within a year have not been recorded, and it is not known if the larvae require a period of cooler temperatures in order to proceed with their development. There have been published reports of *P. japonica* from glasshouses, though these are very old. The available data were from Pennsylvania, where 20 out of 30 rose-growers, who grew their crops in greenhouses, noted injury due to *P. japonica*, with one site collecting tens of thousands of adult beetles (Metzger, 1933). Therefore, it is evidently possible for *P. japonica* to enter glasshouses and the ensuing larvae to develop to adults. However, it is unclear if these populations could persist and establish, i.e. if the emerging greenhouse adults were able to lay a new generation of eggs and thus truly establish, or if the glasshouses were re-infested by beetles from outdoors every autumn, so that the glasshouse records are only of transient populations. Adults are reasonably large (8-11 mm long) insects, gregarious, and cause visible defoliation. Populations therefore seem unlikely to be overlooked, at least while there are adults, and controls applied against the infestation would reduce the chances of establishment. Additionally, no recent reports of *P. japonica* in protected cultivation have been found. Therefore, establishment in protected cultivation is overall considered **unlikely** with **medium confidence**, but if there were outdoor populations there is a possibility of individuals moving into glasshouses, laying eggs, and a transient population developing.

Semi-protected cultivation, as increasingly used in the UK for soft fruit and cherry production, will have different establishment risks associated with it, compared to the risks from either outdoors or under fully protected cultivation. The polytunnels used in semi-protected cultivation are typically open-sided, therefore there are few barriers to insects arriving from outside, while the temperatures inside may be more favourable to insect development than the surrounding area. This combination of factors means that assessing potential establishment in such semi-protected environments is extremely difficult and subject to a very high level of uncertainty, and as such, no separate rating for semi-protected cultivation is given here.

Outdoors	Very unlikely	☐	Unlikely	☐	Moderately likely	☐	Likely	✓	Very likely	☐
Confidence	High Confidence	☐	Medium Confidence	✓	Low Confidence	☐				

Under Protection	Very unlikely	☐	Unlikely	✓	Moderately likely	☐	Likely	☐	Very likely	☐
Confidence	High Confidence	☐	Medium Confidence	✓	Low Confidence	☐				

10. If the pest needs a vector, is it present in the UK/PRA area?

This beetle is a free-living organism, and no vector is required.

11. How quickly could the pest spread in the UK/PRA area?

In the USA, adults are quite mobile, moving within and between plants frequently, with marked beetles found up to 2.75 miles away from their original point of capture (Fleming, 1972). Beetles have been detected on boats over 5 miles out at sea (Fleming, 1972), though this is an artificial situation, because the beetles could not land on the water, but had to continue flying. Fleming (1972) also gives a useful summary of the spread of *P. japonica* in the USA from its time of introduction, with yearly data of the area infested between 1916 and 1952 in his Table 7 (pages 100-101), though this is the actual area occupied by *P. japonica*, and as such includes both natural and human-assisted causes of spread. In the Azores, *P. japonica* spread relatively slowly for the first few years, possibly hampered by high ground, but in 1984 and 1985, the infested area increased by a minimum of 2 km in each year (Martins *et al.*, 1988). However, warm temperatures are required for the beetles to take flight with an optimum temperature range of 29–35°C (Kreuger & Potter, 2001), though when disturbed they will take flight at temperatures exceeding 21°C (Fleming, 1972). Other factors promoting flight include relative humiditybelow 60% (Fleming, 1972), little cloud cover, wind speeds below 20 km h^{-1} (Lacey *et al.*, 1994), and time of day between about 9am and 3pm (Kreuger & Potter, 2001). The temperatures required for flight are those experienced by the beetle, which may be significantly higher than the ambient temperature or those recorded by meteorological stations (for example, if the insect was on a sunny, sheltered leaf). However, summers in the UK are cooler than those in much of the current range, and so in the UK there may be fewer days that allow *P. japonica* to take flight and, depending on the month of adult emergence, considerably fewer days might prove optimal for flight. A reduced number of days where flight is possible would decrease the overall rate of spread. Overall, the potential rate of natural spread is considered to be **moderate**, with **medium confidence**.

Spread in trade is considered to include hitchhiking on non-host commodities. The situation in North America would seem to suggest that, while controls against spread of the beetle may have some effect, they do not entirely mitigate the risk. Rooted plants are a pathway and are commonly moved around the UK in trade, the larvae are cryptic (living in the soil), and *P. japonica* larvae and adults are very similar to the native garden chafer *Phyllopertha horticola*. Therefore, it is considered that there would always remain a significant risk of *P. japonica* moving in trade even with controls in place, and a single adult female is capable of founding a new population, as she is likely to have been fertilised very soon after emergence. Therefore, the potential rate of spread in trade in the UK is judged to be **quickly**, with **high confidence**.

Natural Spread	Very slowly	☐	Slowly	☐	Moderate pace	✓	Quickly	☐	Very quickly	☐
Confidence	High Confidence	☐	Medium Confidence	✓	Low Confidence	☐				

With trade	Very slowly	☐	Slowly	☐	Moderate pace	☐	Quickly	✓	Very quickly	☐
Confidence	High Confidence	✓	Medium Confidence	☐	Low Confidence	☐				

12. What is the pest's economic, environmental and social impact within its existing distribution?

Popillia japonica is a major pest in parts of North America, though impacts in Japan are usually less severe. However, as the UK summers are cooler than those experienced in many parts of *P. japonica*'s current range, detailed information on impacts will focus on reports from the north of its current range, as these are of most relevance to the UK. For example, while this can be a major pest of soybean (*Glycine max*) (e.g. Sara *et al.*, 2013) this crop is not discussed further here, as soya is not currently a major crop in the UK, though its importance may increase in the future (Soya UK, 2015).

Reports of impacts on specific crops abound in the literature, though it should be noted that all of the examples in this paragraph come from the USA, where temperatures are more favourable for *P. japonica*. Impacts on maize are caused by the adults' preference for feeding on the silks, leading to reduced pollination and hence number of kernels (Steckel *et al.*, 2013). Impacts on pasture and other grassed areas such as golf courses and lawns are due to larval feeding on the roots, and are reported by very many authors, such as Dalthorp *et al.* (2000) or Hamilton *et al.* (2009). There are even more papers available detailing adult damage to a very wide range of plants, for example percentage skeletonisation on *Betula* spp. (birch) was reported by Gu *et al.* (2008), with susceptibility varying with birch species and cultivar: average defoliation was around 25-30%, but *B. pendula* did not show any damage, while *B. papyrifera* and *B. utilis* were >70% defoliated in each of the three years of the study. Defoliation levels on assorted trees including *Malus* (crab apples), *Rosa* and *Tilia* were detailed by Potter *et al.* (1998): the crab apples' susceptibility varied by cultivar, with a range of 10-95% defoliation, while all *Tilia* and *Rosa* cultivars were severely damaged in years with high numbers of beetles, though some cultivars were less damaged in years when beetle populations were lower.

On a geographical basis, impacts in Canada appear to be sporadic, other than in parts of southern Ontario where *P. japonica* is regarded as more of a serious pest. Although the pest is present in Montreal serious damage is reported is only in warm summers such as 2012 (e.g. CBC News, 2012; Sutherland, 2012). The infestation in Halifax, Nova Scotia, was first detected in 2001 due to visible adult damage on ornamental plantings in a city park, but in 2003, while adults were detected during visual surveys, there was "little evidence" of feeding damage (Canadian Food Inspection Agency, 2000-2005). In southern Ontario, two of the nectarine cultivars tested by Cline and Norton (2012) had poor overall performance in trials; this was largely attributed to the higher amounts of damage inflicted upon them by *P. japonica*. The Ontario Hop Grower's Association considers *P. japonica* to be a serious pest, especially on organic sites as control options are more limited (Anonymous, 2013).

In Japan, *P. japonica* is usually considered to be a pest of relatively little importance, though there are occasional reports of damage. For example, Ando (1986) reported that it was not a significant pest in Hirosaki (situated in the far north of the main island of Honshu) prior to about 1975, but, possibly due to the increasing areas of grass being grown, it became more serious over the next ten years, with damage to various crops including peach and cherry. *Popillia japonica* is mentioned as one of the pests of pasture in Hokkaido during experimental work on the influence of nitrogen fertiliser on the pest population, but is only mentioned as one species in a long list (Kikuta & Yokoyama, 1985).

In the Azores, the main hosts are *Rubus ulmifolius*, *R. hochstetterorum* (blackberry), *Pteridium* (bracken), *Mentha* (mint) and *Trifolium repens* (white clover) (Simões & Martins, 1985), though many other hosts have been recorded, including crop species such as *Phaseolus vulgaris* (bean) and *Prunus* spp. (stone fruit) (Martins & Simões, 1988). However, no sources that detail damage due to *P. japonica* in the Azores have been found. In Italy, to date, little damage other than to *Rubus* sp. and *Urtica* sp. has been observed (Pavesi, 2014), though it has been detected on at least 18 species of plant (Venanzio & Bosio, 2015). It should also be noted that *P. japonica* was first observed in the Parco del Ticino, which is a large area of over 90,000 hectares along the river Ticino, and is a UNESCO Man and Biosphere site (Parco Lombardo del Ticino, 2015). As parts of this site are a nature reserve, monitoring of damage levels is likely to be less than on agricultural land, and so it may be that damage due to *P. japonica* in Italy is currently under-recorded.

In summary, the impacts in the native range of Japan are considered to be **small**, with **medium confidence**. Impacts in the northern part of the invasive range (parts of southern Canada) appear to be sporadic and restricted to warmer years, though local damage can be quite severe. Overall, the impacts in southern Canada are judged to be **small** but with **medium confidence**, as they do vary in severity. In most states in the USA, especially those with warm or hot summers, its impact is considered to be **large** with **high confidence.**

Impacts (Japan)	Very small	☐	Small	✓	Medium	☐	Large	☐	Very large	☐
Confidence	High Confidence	☐	Medium Confidence	✓	Low Confidence	☐				

Impacts (southern Canada)	Very small	☐	Small	✓	Medium	☐	Large	☐	Very large	☐
Confidence	High Confidence	☐	Medium Confidence	✓	Low Confidence	☐				

Impacts (USA, especially southern and central states)	Very small	☐	Small	☐	Medium	☐	Large	✓	Very large	☐
Confidence	High Confidence	✓	Medium Confidence	☐	Low Confidence	☐				

13. What is the pest's potential to cause economic, environmental and social impacts in the UK/PRA area?

Summer temperatures in the UK are lower than those in many parts of the beetle's current range, and this would be expected to limit the amount of defoliation caused by the adults. Larvae are expected to have a predominantly 2-year lifecycle in the UK (see Figs. 4–6 in Appendix 1). This would mean the population build-up would be slower and hence damaging numbers may only occur in the warmest years. Due to the wide host range, many crops and fruit trees, turf and ornamental garden species and plants of environmental importance to the UK (such as *Vaccinium*) could potentially be affected, though impacts in North America do seem to be largely social and economic, rather than environmental. Areas of high-maintenance turf, such as golf courses and ornamental turf in parks may be most at risk, as the damage would be very noticeable on these manicured areas of turf. Additionally, larvae will experience less extreme temperatures in the soil, and thus some of the potential temperature limitations on adult damage will not apply. Overall, the potential impacts across all sectors in the UK are considered to be broadly similar and **small** with **medium confidence**.

Economic Impacts	Very small ☐	Small ☑	Medium ☐	Large ☐	Very large ☐
Confidence	High Confidence ☐	Medium Confidence ☑	Low Confidence ☐		

Environ - mental Impacts	Very small ☐	Small ☑	Medium ☐	Large ☐	Very large ☐
Confidence	High Confidence ☐	Medium Confidence ☑	Low Confidence ☐		

Social Impacts	Very small ☐	Small ☑	Medium ☐	Large ☐	Very large ☐
Confidence	High Confidence ☐	Medium Confidence ☑	Low Confidence ☐		

14. What is the pest's potential as a vector of plant pathogens?

Popillia japonica is not known to vector any plant pathogens.

15. What is the area endangered by the pest?

Southern parts of the UK, especially sheltered parts of southern England and urban heat islands are most at risk. However, in any but the warmest years, damaging populations may not be able to develop in the UK.

Stage 3: Pest Risk Management

16. What are the risk management options for the UK/PRA area?

(Consider exclusion, eradication, containment, and non-statutory controls; under protection and/or outdoors).

Exclusion: *Popillia japonica* is listed in Annex IAII of the EU Plant Health directive, and as such any detection of the insect on consignments would be subject to statutory action. There have been relatively few interceptions of *P. japonica* in the UK, and only one other notified interception of a *Popillia* species was found from Germany, indicating these beetles are not currently commonly moving in trade. Though the cryptic larvae are more likely to be undetected in rootballs, there haven't been any notified findings of adults emerging from imported rooted plants. Overall, until the pest had been found in Italy, the prospects for exclusion were favourable. However, it is likely that the pest will spread in Italy to nursery production areas, then, due to the volume of imports of plants from parts of Italy to the UK and the more limited inspection on intra-EU trade compared to that from third countries such as the USA or Japan, then the likelihood of an outbreak and eventual establishment of the pest in the UK will increase significantly.

Eradication and containment: Previous eradication and containment strategies in newly infested areas have not always been successful. For example, following the finding in around an air base in Terceira in the Azores in the early 1970s, eradication was attempted (Martins & Simões, 1985). This failed, the beetle continued to spread in Terceira (Martins *et al.*, 1988), and has now been detected on four other islands in the archipelago (Vieira, 2008). On the other hand, eradication in California has been successful, on 3 separate occasions in the 1960s, 70s and 80s (Potter & Held, 2002), though this may be, at least in part, due to the climatic unsuitability of parts of California for *P. japonica* (for example, the soil being too dry).

An additional problem for eradication strategies is that the native garden chafer (*Phyllopertha horticola*) is widespread in the UK (and Europe), has a similar lifecycle and biology, and the adults are easily confused with *P. japonica* without close examination. There is thus a possibility that initial infestations of *P. japonica* could be misidentified as the native chafer, potentially allowing the establishment of larger populations before detection. This would make eradication or containment more difficult.

In summary, the difficulties of detecting an outbreak of *P. japonica* at an early stage, the very broad host range of the pest and the limited options for treating larvae in the soil mean that once established outdoors, eradication is likely to be very difficult to achieve.

Non-statutory controls: Control options for *P. japonica* include insecticide applications against the adults and soil treatments to target larvae. Chlorpyrifos and pyrethroid insecticides are used to target adults in some parts of the USA and these are registered for some crops in the UK. However, chemical options for treating larvae in the soil are likely to be restricted to a small proportion of the plants and situations of which they may be needed. Experiments on the effectiveness of a variety of larval control methods (both chemical and biological) in Tennessee have been investigated, with the majority of the tested treatments being most effective on younger larvae (Mannion *et al.*, 2001), though not all the control methods included will be available for use in the UK. In addition to chemical options, there has been work on the effectiveness of various species of entomopathogenic nematodes, including *Steinernema kushidai* in Japan (Hatsukade, 2001), or *S. scarabaei* and *Heterorhabditis bacteriophora* in New Jersey, USA (Elmowitz *et al.*, 2013). Of these three species, only *H. bacteriophora* is currently available for use (under licence) in the UK. Pheromone traps for *P. japonica* are available and are commonly used in North America, though Switzer *et al.* (2009) notes there can be problems with trap spillover, where beetles are attracted to the trap but not captured by them, instead landing on, then causing damage to, nearby foliage. Existing control methods against the native chafer *P. horticola* might prove effective against *P. japonica*, such as entomopathogenic nematodes (e.g. Smits *et al.*, 1994; Sulistyanto & Ehlers, 1996) or various designs of traps and lures (Ruther, 2004). However, the timing of vulnerable stages in the lifecycle between the two species is likely to be different, which would impact on the effectiveness of the control measures applied.

There is a great deal of literature from the USA on damage thresholds and sampling methods: Potter and Held (2002) provide a summary and further references for these, as well as other aspects of cultural controls such as minimising irrigation during egg-laying periods to make the soil less attractive to the beetles, increasing cutting height of turf, and strip-intercropping. For smaller scale infestations, removing adults by hand reduced the amount of damage seen on grapevines (Switzer & Cumming, 2014).

17. Summary and conclusions of the rapid PRA

Provide an overall summary and conclusions and then short text on each section:

This rapid PRA shows that: *Popillia japonica* is a highly polyphagous scarab beetle with root feeding larvae and foliage feeding adults. It is native to Japan, and has been an invasive alien pest in North America for around 100 years. In Europe, it has been present in the Azores since the 1970s. In the summer of 2014, *P. japonica* was reported for the first time in mainland Europe, from a valley in Italy near Milan, where it is present in very high numbers. Following this finding in mainland Europe, this PRA was requested to reassess the potential risk *P. japonica* poses to the UK.

Risk of entry

Plants for planting and hitchhiking were considered the pathways of highest risk, supported by these being suspected as the pathways for previous introductions to the Azores and to some parts of North America. Overall, hitchhiking was considered to be moderately likely with medium confidence, while entry in association with plants for planting with roots were considered to be moderately likely, also with medium confidence, as the larvae are cryptic and will be hidden in the soil. Entry in association with harvested parts of plants, such as fruit or cut foliage, is considered unlikely with medium confidence: while adults are relatively conspicuous, their behaviour (at cooler temperatures) of dropping to the ground when disturbed may contaminate products such as harvested fruit. Soil on its own was considered very unlikely with high confidence, as soil from outside the EU is prohibited, and *P. japonica* is only present in a tiny area within the EU.

Risk of establishment

The climate mapping based on degree days undertaken in this PRA suggests that *P. japonica* may be able to establish outdoors in southern parts of the UK, though it is likely to require two years to complete a generation and there is some uncertainty over whether summer temperatures will be warm enough. Overall, establishment outdoors is considered likely with medium confidence. There have been some very old records of this beetle in glasshouses, but overall establishment in protected cultivation is considered unlikely with medium confidence. Semi-protected cultivation of soft fruits is also potentially at risk.

Economic, environmental and social impact

Within the current range, impacts in southern parts of the USA were considered large, with high confidence. Impacts in cooler parts of North America, such as southern Canada, were considered small, and *P. japonica* is usually not considered to be a significant pest in Japan. Due to the climatic limitations the beetle is likely to face in the UK, all potential impacts were considered small with medium confidence.

Endangered area

Southern parts of the UK, especially sheltered areas and urban heat islands, though damage might only be seen in the warmest years.

Risk management options

The prospects for continued exclusion were previously considered to be good. However, now *P. japonica* is present in Italy, and that it seems likely to spread in future years, the likelihood of this species entering and establishing in the UK is considered to have significantly increased, given the volume of trade in plants between the UK and Italy. If *P. japonica* were to become established outdoors, the prospects for eradication are considered poor, due to the broad host range and difficulty of controlling the soil-dwelling larvae. Non-statutory control options include insecticide treatments and pheromone traps against the adults, and for the larvae, soil treatments (though these could only be used on some crops) and possibly entomopathogenic nematodes.

Key uncertainties and topics that would benefit from further investigation

The climatic suitability of the UK for *P. japonica*. The preliminary work on risk mapping for this rapid PRA suggests that parts of the UK are suitable for establishment, but there have been many simplifications and assumptions made. As well as creating uncertainties over the likelihood of establishment, this also affects the judgements on potential impacts. A more detailed analysis including more factors, such as an approach using CLIMEX, or further comparison of soil and air data, may help to resolve some of these uncertainties.

18. Is there a need for a detailed PRA or for a more detailed analysis of particular sections of the PRA? If yes, select the PRA area (UK or EU) and the PRA scheme (UK or EPPO) to be used.

(For completion by the Plant Health Risk Group) ✓ (put a tick in the box)

No	✓				
Yes		PRA area: UK or EU		PRA scheme: UK or EPPO	

19. Images of the pest

Adult *Popillia japonica*, showing white tufts of hairs along the sides of the abdomen. Adults are up to 11 mm long. © Kansas Department of Agriculture Archive, Bugwood.org

Damage to grass turf by *Popillia japonica* larvae, including damage by predators digging up the larvae to feed on. © M.G. Klein, USDA Agricultural Research Service, Bugwood.org

20. Given the information assembled within the time scale required, is statutory action considered appropriate / justified?

[*For completion by the Plant Health Risk Group*] *(put a tick in the box)*

Yes Statutory action	✓	No Statutory action	

Popillia japonica is listed in Annex IAII of the EC Plant Health directive, and as such, statutory action will be taken against this species if it is detected.

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Name of Pest Risk Analyst(s)

Anastasia Korycinska, incorporating text and comments by Richard Baker, Dominic Eyre and others

Appendix 1. Preliminary work on climate mapping for *Popillia japonica*

Review of thermal requirements from literature

Published thermal requirements for the development of *P. japonica* were sought in the literature and elsewhere. Ludwig (1928) undertook a series of rearing experiments at 17 temperatures between 10 and 40°C (though not all life stages were studied at each temperature). Egg and pupal development showed a linear response to temperature between certain limits, though larval development appeared to be affected by factors such as food, as well as an apparent capacity for the third larval instar to vary in duration dependent upon the length of the first two instars, as well as on temperature. Overall, the number of degree days required for the development of *P. japonica* was not found to be constant, but varied with temperature (data shown in Table 2) (Ludwig, 1928). In later work, Ludwig (1932) hypothesised that there may be several physiological "varieties" of *P. japonica* which have differing growth rates when reared under the same conditions, and that while the majority of individuals develop at approximately the same time, a small number have significantly longer development periods. In more recent work, Régnière et al. (1981) created a model for the temperature response of *P. japonica*. In order to test the model, they reared larvae at differing temperatures, from which the minimum threshold temperature for development and accumulated degree days can be calculated, and these are given in Table 2.

Table 2. Published thermal requirements for the development of *Popillia japonica*. The three italicised entries indicate they refer (or seem likely to refer) to the prediction of the date of adult emergence, and do not cover the full lifecycle.

Minimum threshold for development	Degree days	Details	Source
Between 13 and 15°C (depending on life stage)	1317.1	At a temperature of 20°C, egg-adult	Ludwig (1928)
	1596.5	At 22.5°C, egg-adult	
	1970.9	At 25°C, egg-adult	
10°C	1305	Egg-adult	Régnière *et al.* (1981)
10°C	1422	Egg-egg	Régnière *et al.* (1981)
50°F (= 10°C)	*1030*	*From Jan 1, cumulative degree days before adult emergence in Iowa*	*Hodgson and Kuntz (2013)*
50°F (= 10°C)	*970*	*From Jan 1, cumulative degree days before adult emergence in Ohio*	*Herms (2004)*
Not stated	*Min: 1029 Max: 2154*	*"Growing degree days" but no details of what is being measured, or the threshold temperature. Location: Long Island, New York using a 20-year dataset.*	*Johnson (2000)*

Fox (1939) studied thresholds for various biological aspects of *P. japonica.* He found that minus 9.4°C was the lowest temperature at which larvae can survive, though he noted that winter air temperatures are much lower than the soil temperatures experienced by the larvae, especially if there is significant snow cover. For successful egg hatching and early larval development, mean summer soil temperatures suitable for development were considered to be in the range of 17.5–27.5°C (Fox, 1939). Fox (1939) also gave details of the distribution of *P. japonica* in Hokkaido, stating that it was scarce or possibly absent in northern and north-eastern areas, but "generally prevalent" throughout most of the rest of the island. Following on from this provisional distribution in Hokkaido, Fox (1939) suggested that summer temperature might be the key factor limiting the distribution of *P. japonica*, and that the potential distribution in North American could extend from northern Maine and adjoining regions of Canada, to southern parts of Ontario. Over seventy years later, this does approximate to the current distribution of *P. japonica* in the north-eastern area of the continent. The ability of the larvae to dig deep down (up to 25 cm) into the soil, thus avoiding exposure to more extreme cold temperatures in the surface layers, was considered to be one of the factors that enables its survival in Hokkaido, as the larvae have few physiological adaptations for freezing tolerance (Hoshikawa *et al.*, 1988). However, while some larvae do burrow deeply into the soil, the figures reported are usually the maximum depth attained. Under permanent turf in New Jersey and Pennsylvania, less than 3% of *P. japonica* larvae were found at a depth of 15 cm or more between December and February, 31% were between 10 and 15 cm below the surface, 62% between 5 and 10 cm, with the remaining 5% being found in the top 5 cm of soil (Fleming, 1972).

While *P. japonica* has a 1-year lifecycle in much of its range, the ability to extend this to two years has been documented. In Honshu (the largest island in Japan), at a location just south of Tokyo, larvae complete development within a year, but in the north of Honshu, around a quarter of the larvae have a 2-year lifecycle (King, 1931). In Hokkaido, most larvae appear to have a 2-year life cycle, with higher numbers of adults emerging in alternate years (Clausen *et al.*, 1927). In the USA, King (1931) noted that 2-year life cycles occurred in Pennsylvania and New Jersey, but that this was "exceptional". In Massachusetts, about 10% of larvae in were considered to take two years to complete development, though most individuals completed development within one year (Vittum, 1986).

Of the more recent literature, all published thermal research appears to be based on adult activity, and is not relevant to larval development (e.g. Kreuger & Potter, 2001; or Lemoine *et al.*, 2013). Several agricultural extension programmes in the USA give assorted values for degree days required for *P. japonica*, but on closer examination many, if not all, of these have degree day accumulations starting on the first of January, i.e., the degree day value given is used to predict the date of adult emergence, and does not apply to the full larval development period. Some examples are provided in Table 2. NAPPFAST has modelled emergence dates of *P. japonica*, using data for the whole life cycle sourced from Ludwig and Régnière (Borchert *et al.*, 2003).

Climate data and mapping

Two datasets were used for obtaining climate data, using daily minimum and maximum air temperatures. Global data are available from the Climatic Research Unit at the University of East Anglia, interpolated at a resolution of 10 minutes latitude and longitude, for the period 1961-1990 (New *et al.*, 2002). European data, interpolated to 25 km grid squares, were obtained for the period 2000-2014 for eleven countries (namely Austria, Belgium, Denmark, France, Germany, Ireland, Italy, Luxembourg, the Netherlands, Switzerland and the UK) (dataset described in Biavetti *et al.*, 2014; available from MARS-AGRI4CAST, 2014). Additionally, to compare day-degree accumulations between soil and air, MIDAS (Met Office Integrated Data Archive System) data from a weather station at Kew Gardens were obtained for a ten-year period between 2003 and 2012 (Met Office, 2012). For the MIDAS air temperatures, the minimum of the twice-daily minimum measurements and the maximum of the twice-daily maximal temperatures were used. The soil temperatures were taken at a depth of 10 cm. Since hourly data were available, the daily minimum and maximum daily values were used directly in the calculations. Two years (2006 and 2007) were excluded from the analysis due to the very large number of missing values for these years.

The minimum threshold temperature for development at 10˚C and accumulated degree days for development at 1422 days were based on Régnière et al. (1981). During the lifecycle of *P. japonica*, there is a “callow” period during which the newly emerged adults remain in the soil, harden their cuticles, and mature (Régnière *et al.*, 1981), and it appears that the calculations that Borchert *et al.* (2003) carried out on Régnière’s data included this maturation period for the egg-egg values, but not the egg-adult values. As the adults remain in the soil and are unable to lay eggs during the callow period, the egg-egg values are considered to better represent the lifecycle, and so were used here. Degree days were calculated, using the average of the daily minimum and maximum temperatures, minus the threshold temperature. Where the maximum temperature was above the threshold, but the average was below, the correction described in Baker (1980) was applied, to allow for the fact that some development can still take place under these conditions.

For the global dataset (New *et al.*, 2002), maps showing degree days for a threshold temperature of 10˚C had previously been created by Baker (2002). This map was copied, and boundaries set in the mapping programme ArcGIS® 10.2 at 1422 and 711 degree days, i.e., the development period for one generation in a calendar year, or half a generation (thus allowing for 2-year development). Maps were created for Japan where *P. japonica* is native (Fig. 1), North America, where it is invasive (Fig. 2), and for Europe to map the potential distribution (Fig 3). These degree-day boundary values were also used for the 15-year mean of the accumulated degree days for the MARS data, generating comparable maps to the global dataset for the eleven countries in Europe included (Fig 4). Individual years of the MARS dataset were also analysed. The number of years out of the 15-year time series where the accumulated degree days were ≥ 1422 were mapped (Fig. 5), i.e., the proportion of years where development within 1 year was possible. Additionally, the proportion of the 2-year time periods where the cumulative degree-days over 2 consecutive years were ≥ 1422 were also mapped (Fig. 6), i.e. the proportion of 2-yearly periods where development over 2 years was possible. It should be noted that the calculations of 2-year generations between figures 4 and 6 are not directly comparable. In figure 4, half the value of the accumulated degree days for *P. japonica* is based on the 15-year mean accumulated degree days for each grid square. In Figure 6, the actual accumulated degree-days for consecutive years were summed and compared to the total accumulated degree days required by *P. japonica*.

Fox (1939) regarded mean summer soil temperatures of between 17.5 and 27.5°C as suitable for egg-hatching and early instar development, and therefore mean summer temperatures (using air temperature data) were also examined using the MARS data. First the maximum and minimum daily temperatures were averaged, and then the mean summer temperature for the months June, July and August for each grid cell was calculated. Two maps were produced, the first showing the suitable grid cells for *P. japonica* using a 15-year average and appropriate class boundaries (Fig. 7), and the second map showing the number of years out of the 15-year time period where each grid cell was suitable, i.e., temperatures were within the range specified by Fox (Fig. 8).

A comparison of degree day accumulations over 10°C at Kew Gardens in London, for air and soil over 8 years between 2003 and 2012, show that there are differences in the date by which a threshold of 711 day degrees are accumulated above and below ground (see Table 3 and Figure 9). In half of the years, thermal accumulation was faster in the soil, while in the other half, the threshold was reached first by the air temperatures. The difference varied between 5 and 24 days. In cooler years, the threshold is reached first by the soil, suggesting that the capacity of *P. japonica* to establish in marginal areas (such as the UK) may be enhanced, as the buffering effect of the soil is likely to facilitate larval survival in cooler years. This suggests that using air temperatures to model the development of a soil-dwelling insect is an acceptable compromise for a preliminary analysis such as this. In addition, the soil temperatures were measured under grass, a typical habitat for *P. japonica* larvae.

Table 3. Comparison of degree-day accumulations base 10°C between soil (10 cm depth) and air from a weather station in Kew Gardens. The start date was 1 January of each year, with a threshold of 711 days representing half the total degree days required for *Popillia japonica* to complete its development, i.e. the value needed to complete its life cycle in two years. Data were obtained from Met Office (2012) between 2003 and 2012, though the values for 2006 and 2007 were omitted as there were a large number of missing values for each year.

Year	Date 711 accumulated day degrees reached Soil (10 cm depth)	Air	Difference (days)	Which earlier?
2003	07 August	25 July	13	Air
2004	07 August	02 August	5	Air
2005	09 August	29 July	11	Air
2008	19 July	06 August	18	Soil
2009	13 July	06 August	24	Soil
2010	25 July	07 August	13	Soil
2011	11 August	05 August	6	Air
2012	25 July	15 August	21	Soil

Distribution data for *P. japonica* were collected from a variety of sources (data not shown), though much of these data are at quite a coarse resolution (e.g., the level of US or Canadian states). The theoretical generation time maps for Japan and North America generated here and the known distribution of the Japanese beetle do generally correspond, for example Hokkaido and parts of Nova Scotia are known to have breeding populations of *P. japonica*, and both islands have areas that are shown here to be theoretically suitable for the 2-year development of the beetle.

Assumptions and limitations

It should be noted that several assumptions and approximations were made for this preliminary analysis, and these should be remembered when consulting the maps given here. Only air temperatures were considered, as, though soil moisture is important for larval development, it was judged that the UK had sufficient rainfall during all months of the year. This will not be the case for non-irrigated parts of, for example, Mediterranean Europe, though females do appear to select damper soils (e.g., irrigated or poorly drained areas) in times of drought (Fleming, 1972) and thus may be able to partially compensate for drier regions. Air temperatures were used as they are easily obtainable from climatic datasets, though the larvae live in the soil, and in reality will experience less extreme temperatures (lower in summer, higher in winter). However, the comparison of soil and air temperatures carried out here, albeit only for a single site, suggests air temperatures are in fact a reasonable first approximation for assessing accumulated day degrees within the soil. While the maps make a clear distinction between 1 and 2 year lifecycles, in reality a mix of lifecycle lengths may be seen in some locations, with some larvae taking one and some 2 years to develop in a given marginal site (Fox, 1939).

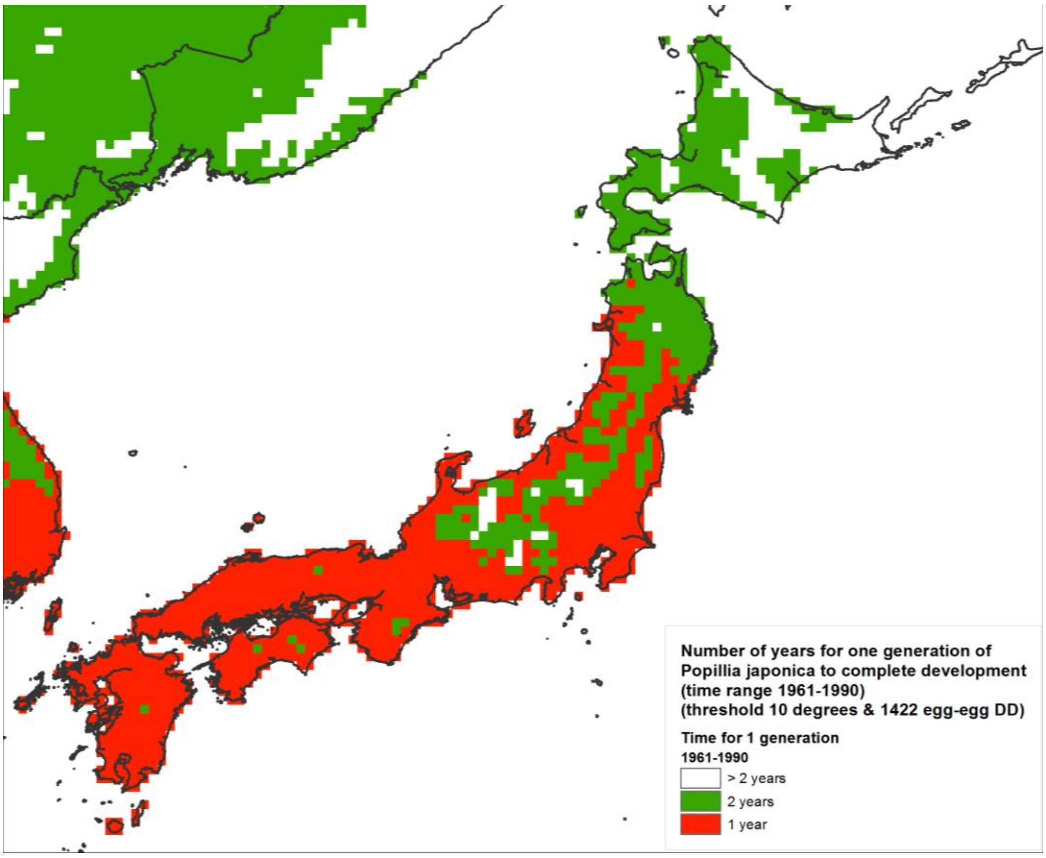

Figure 1. Potential distribution of *Popillia japonica* in Japan based on the number of years needed to complete one generation, using data from New *et al.* (2002) (time period 1961-1990, with a spatial resolution of 0.5° latitude and longitude).

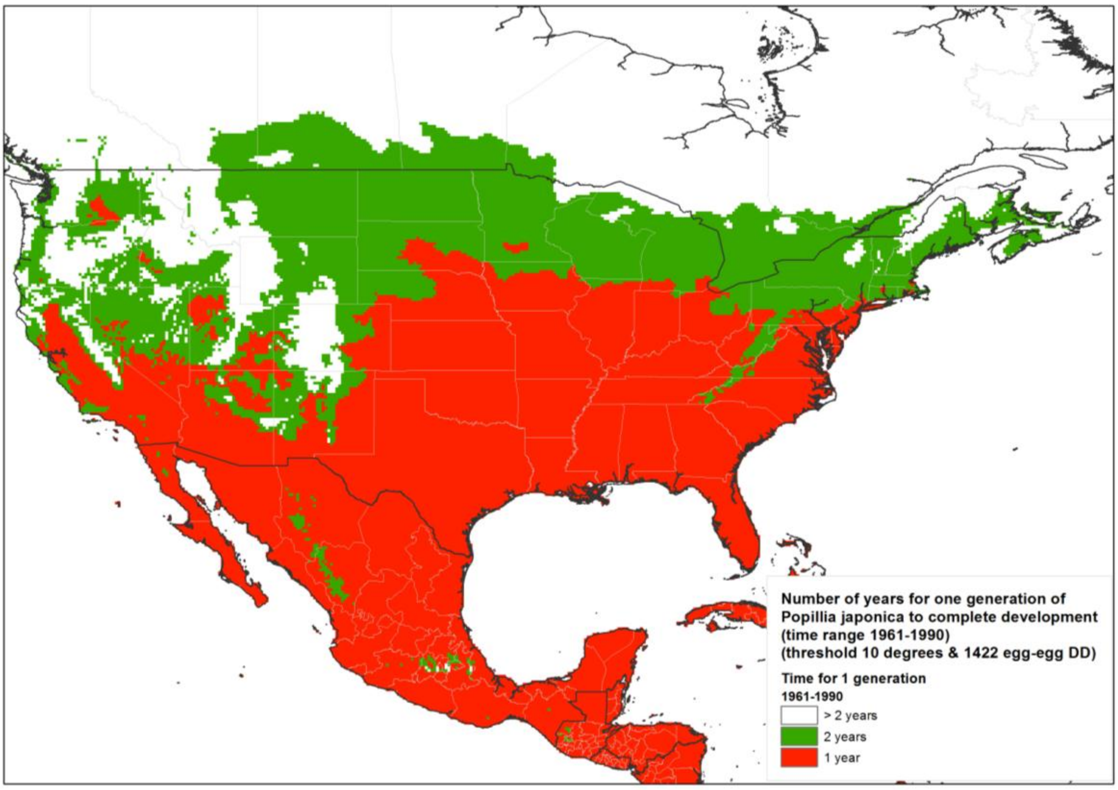

Figure 2. Potential distribution of *Popillia japonica* in North America based on the number of years needed to complete one generation, using data from New *et al.* (2002) (time period 1961-1990, with a spatial resolution of 0.5° latitude and longitude).

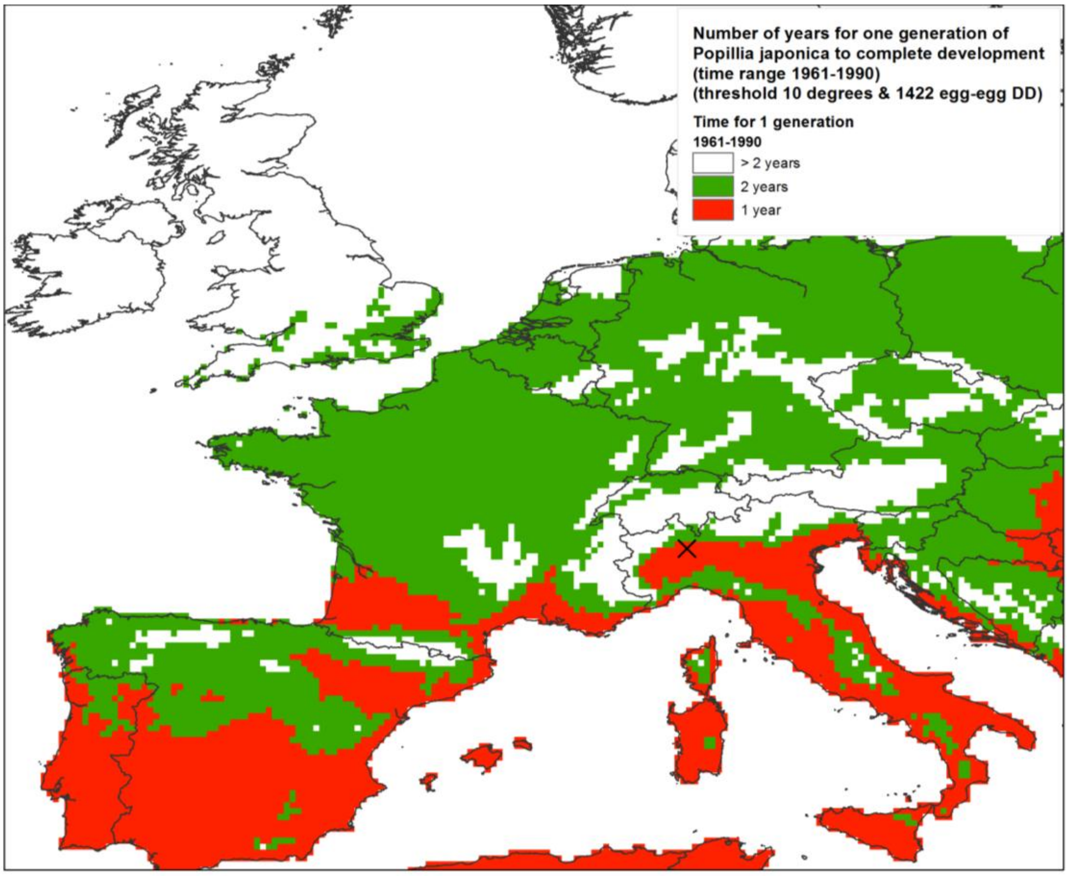

Figure 3. Potential distribution of *Popillia japonica* in Europe based on the number of years needed to complete one generation, using data from New *et al.* (2002) (time period 1961-1990, with a spatial resolution of 0.5° latitude and longitude). The location of the outbreak near Milan is marked by X.

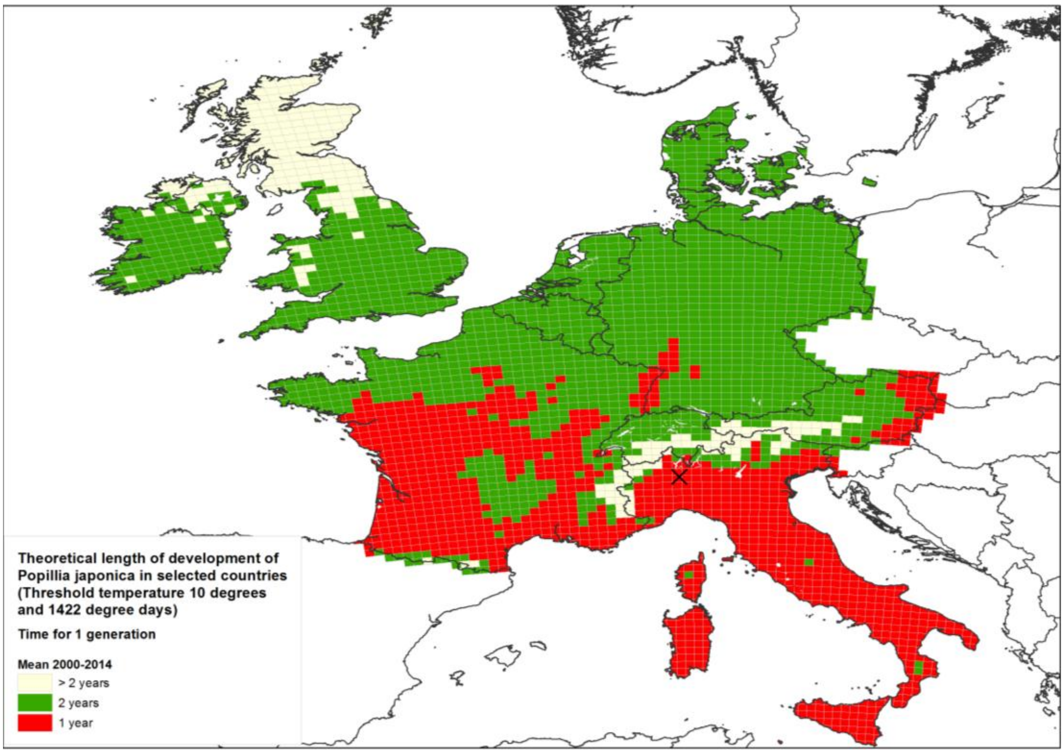

Figure 4. Potential distribution of *Popillia japonica* in Europe based on the number of years needed to complete one generation, using data from MARS-AGRI4CAST (2014) for selected European countries (time period 2000-2014, with a spatial resolution of 25 km squares). The location of the outbreak near Milan is marked by X.

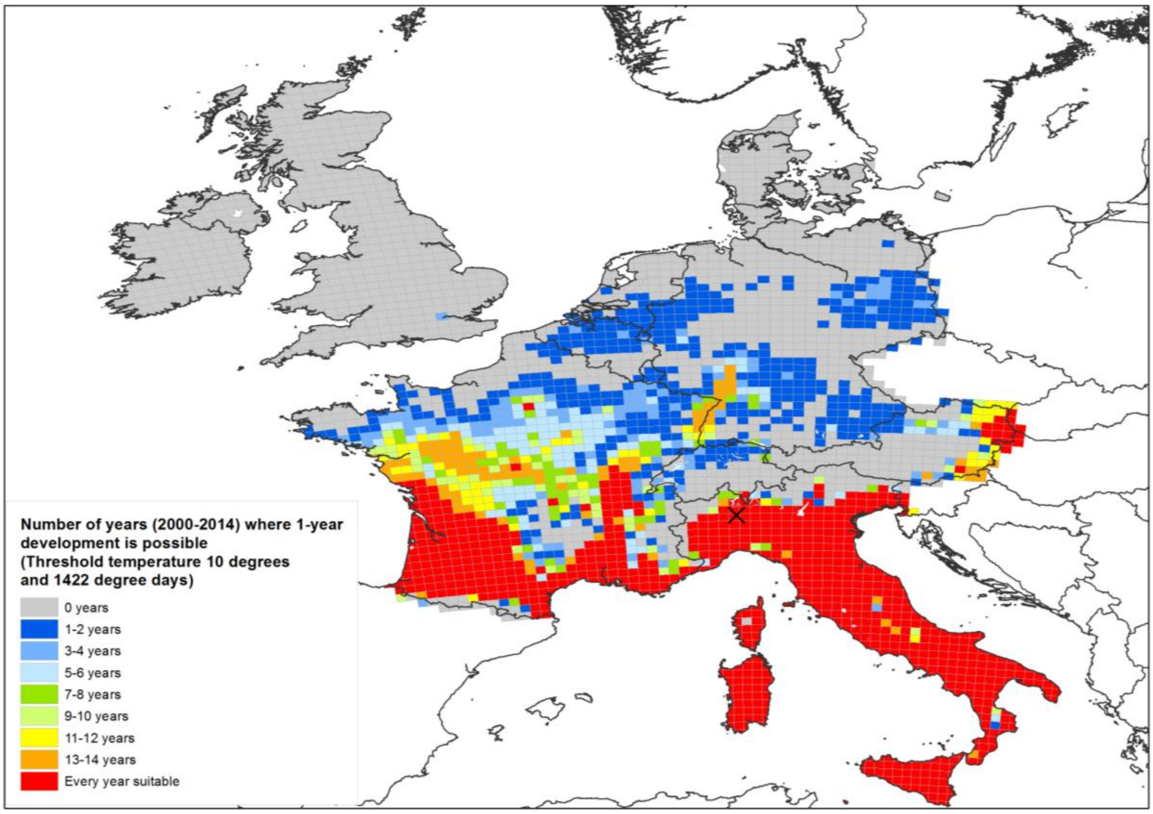

Figure 5. Number of years in a 15-year period where *Popillia japonica* could complete its life cycle in one year, using data from MARS-AGRI4CAST (2014) for selected European countries (2000-2014, with a spatial resolution of 25 km squares). The location of the outbreak near Milan is marked by X.

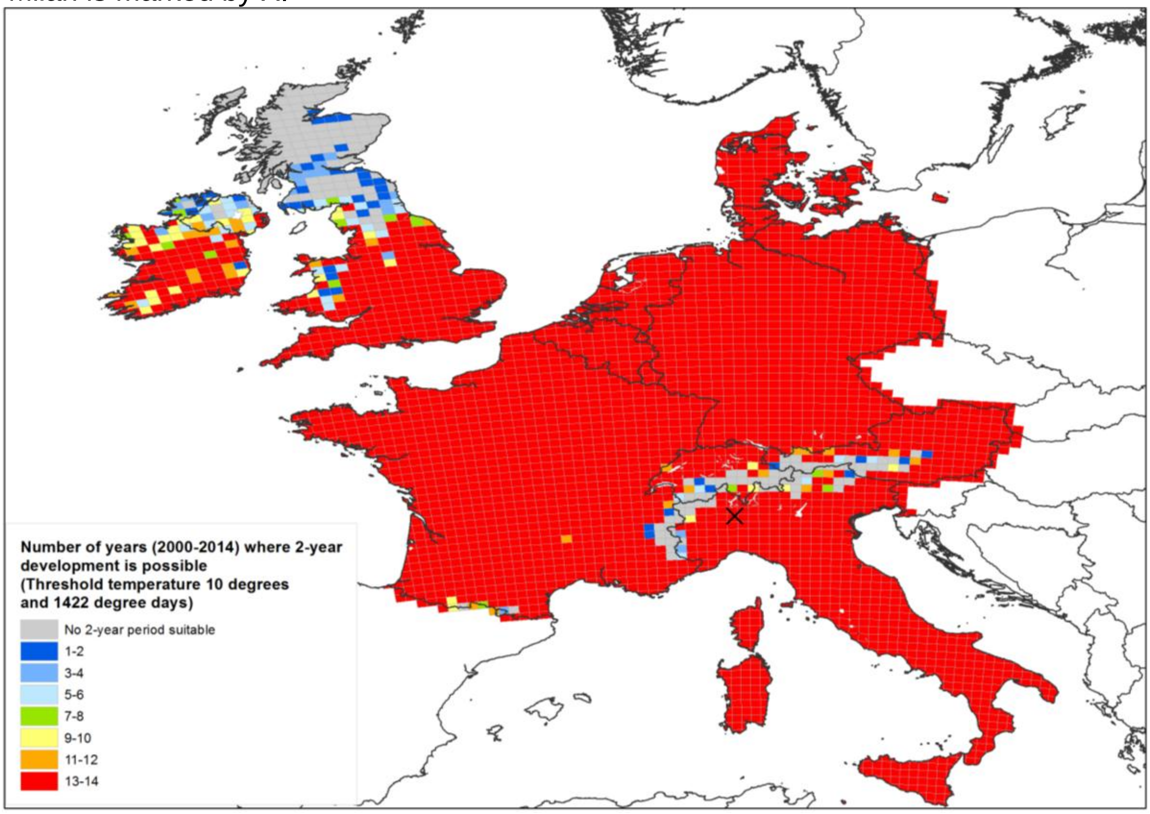

Figure 6. Number of 2-year periods where *Popillia japonica* could complete its life cycle in two consecutive years, using data from MARS-AGRI4CAST (2014) for selected European countries (2000-2014, with a spatial resolution of 25 km squares). The location of the outbreak near Milan is marked by X.

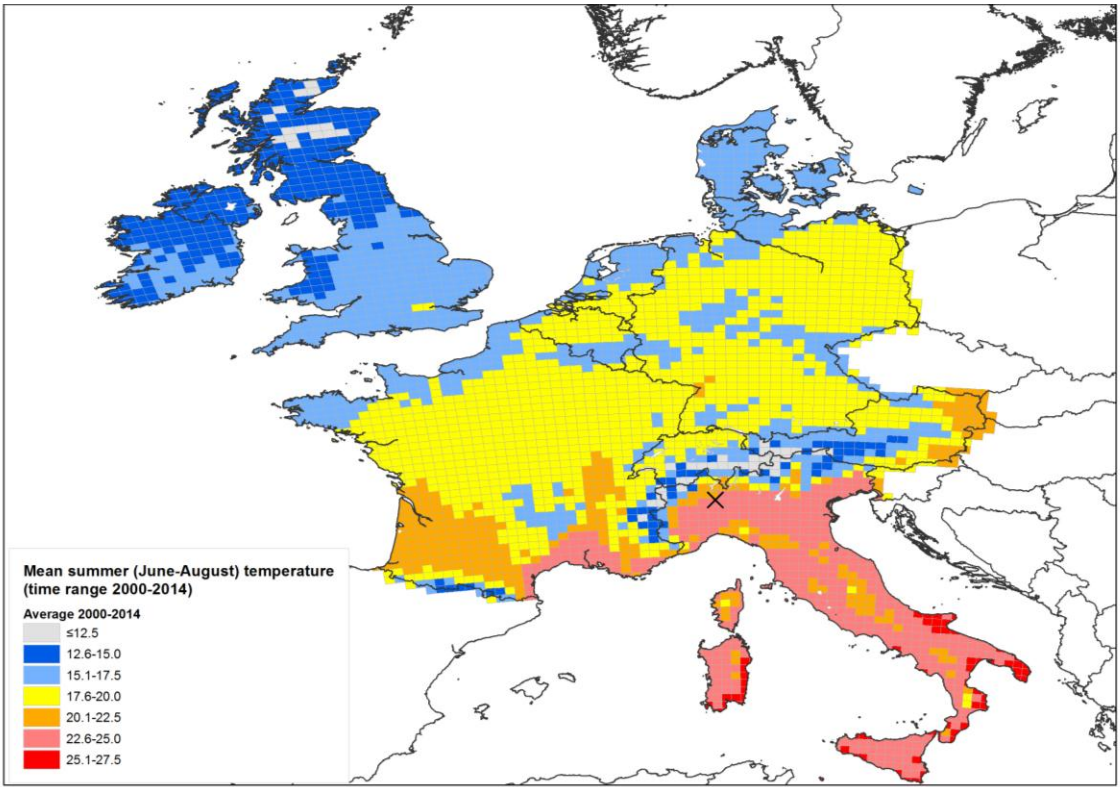

Figure 7. Areas in yellow to red are represent areas where the mean temperature in June-August is ≥17.5°C and suitable for the early stages of *Popillia japonica*, using data from MARS-AGRI4CAST (2014) for selected European countries (time period 2000-2014, with a spatial resolution of 25 km squares). The location of the outbreak near Milan is marked by X.

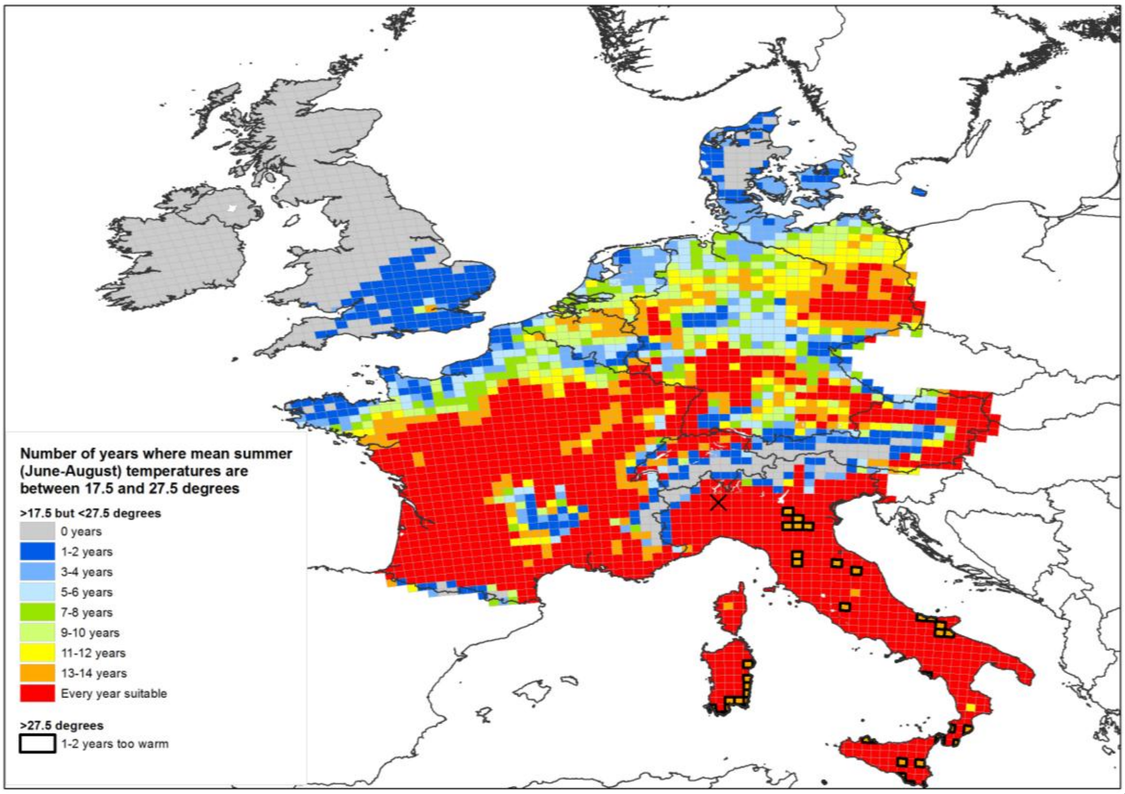

Figure 8. Number of years where the mean temperature during June - August is ≥17.5°C and ≤27.5°C, and thus suitable for the development of *P. japonica*, using data from MARS-AGRI4CAST (2014) for selected European countries (time period 2000-2014, with a spatial resolution of 25 km squares). The location of the outbreak near Milan is marked by X.

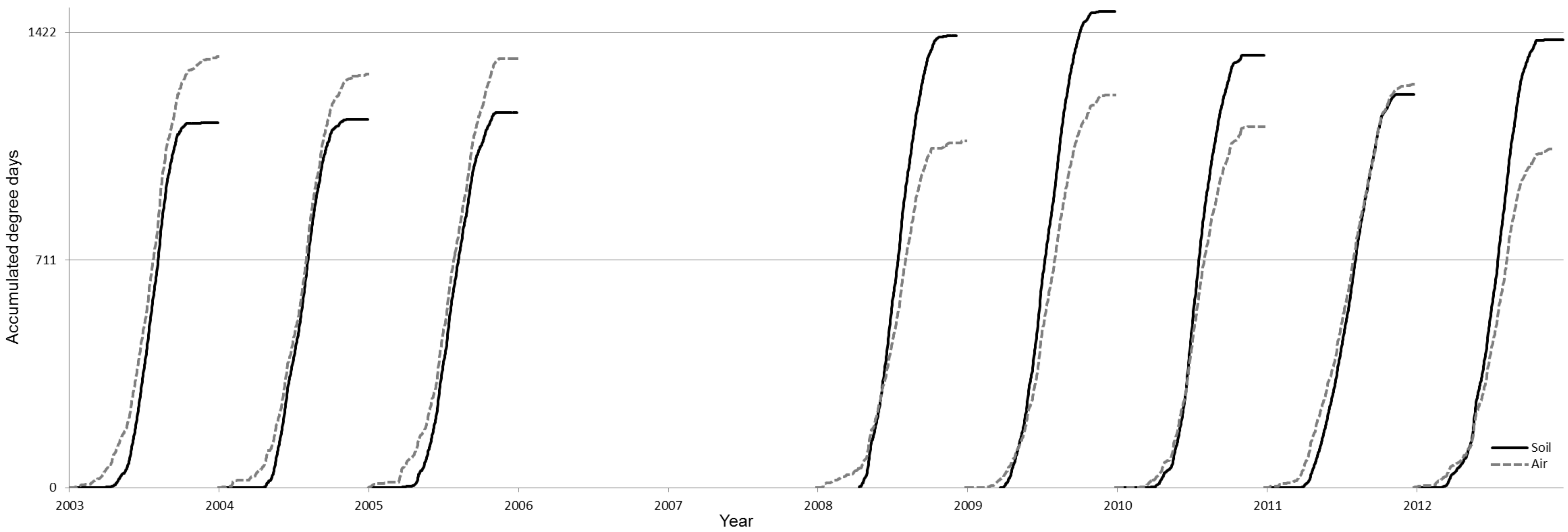

Figure 9. Comparing accumulated degree days (threshold temperature 10°C) at Kew Gardens, based on soil temperatures (10 cm depth) and air temperatures, between 2003 and 2012, using data from Met Office (2012). Grid lines are for a single generation of *Popillia japonica* (1422 degree days), or half a generation (711 degree days), i.e. the latter allowing for development over two years. Data for 2006 and 2007 are omitted due to the large number of missing values.

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