Complex responses of global insect pests to climate change

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Abstract

Phytophagous insect pests strongly affect the productivity and profitability of agriculture and forestry. Despite the well-known sensitivity of insects to abiotic effects such as temperature, their potential responses to ongoing climate change remain unclear. Here we compile and review documented climate change responses of 31 of the globally most severe insect pests of agriculture and forestry, focussing on species for which long-term, high-quality data are available. Most of the selected species show at least one response affecting their severity as pests, including changes in geographic range, population dynamics, life-history traits, and/or trophic interactions. The agricultural pests show strikingly more diverse and generally weaker responses to climate change than the forestry pests. However, the agricultural pests seem to increase more in detrimental ecological impact than do the forestry pests. Unexpectedly, 59% of the species show responses of reduced potential impacts as pests under ongoing climate change. This reduction in impact is further supported by a thermal sensitivity analysis showing little benefit of climate warming in relation to the optimal developmental temperatures for the majority of these pests under both current climate and future projections. The documented variation in responses indicates that efforts to mitigate undesirable climate change effects must target individual species, taking into account the complex ecological and evolutionary mechanisms underlying their responses.

Keywords: climate adaptation, abiotic stress, integrated pest management, agricultural pest, forestry pest

Significance statement

Here we show that 31 global insect pests in agriculture and forestry have responded to climate change in ways that both increase and decrease their socioeconomic and/or ecological impact. Most pests have responded in more than one major biological trait and furthermore the type and/or direction of responses differ regionally. The agricultural pests show more diverse and generally weaker responses to climate change than the forestry pests. Together these data show the same large variability in responses also documented in non-pest insects, and highlight that efforts to mitigate change effects must target individual species, taking into account the complex both ecological and evolutionary mechanisms underlying their responses.

Climate change and insect pest impact. Insect pests have major detrimental impacts on agricultural and forestry production[1] that are likely to increase with anticipated rise in demands for food[2], bioenergy feedstocks and other agricultural products. For example, animal pests (mainly insects) cause estimated losses of *ca*. 18% of total global annual crop production[3]. Many forest pests, such as the gypsy moth (*Lymantria dispar*) and mountain pine beetle (*Dendroctonus ponderosae*), also have severe ecological impacts: displacing native species, causing widespread defoliation and tree mortality, disrupting ecosystem functions and diminishing biodiversity[4,5]. Further, managing insect pests is financially costly. For example, estimated global costs of managing only one pest species, the diamondback moth (*Plutella xylostella*), are 4-5 billion USD annually[6]. Moreover, many agricultural and forest insect pests are also invasive species that contribute to negative ecological consequences and the costs of managing or mitigating such invasions are estimated to exceed 76.9 billion USD annually globally[7].

The substantial global challenges posed by phytophagous insect pests can be exacerbated by ongoing and projected large-scale climatic changes[8] which could promote increases in pest populations and resulting economic losses[9-11]. Alternatively, pests can be constrained by their environmental niche requirements, physiological tolerances, and phenological or life-history responses to climate, leading to local population declines or extinctions as climates change[12,13]. Clearly, detailed knowledge of insect pests' current and likely responses to ongoing climate change is essential to counter changing risks. Widespread ecological damage through range expansions and increasing frequencies of outbreaks are increasingly reported[13-16], but there is a severe deficiency in comprehensive information on insect pests' responses[17-19].

Climate change and insect pest biology. Efforts to predict climate change impacts on insect pests are typically based on empirical studies of insect responses to geographical and temporal variation in climate[20,21], mechanistic studies of insect responses to varying abiotic conditions (often in controlled laboratory environments)[22], climate modelling studies[23,24], or some combination of these approaches[18]. A common assumption in studies of pests' responses is that climate-limiting factors are constant across their geographic ranges. Thus studies typically ignore intraspecific variation, a well-known source of variability in climate responses[9,21]. Also, pest ranges generally span multiple environments, often including various types of managed landscapes[25], forming complex dynamic matrices of pest-ecosystem interactions[19]. Furthermore, analyses tend to consider a single response (e.g. range expansion), rather than the wide range of pests' potential responses to climate change[19], which can be divided into at least four main categories that are non-mutually exclusive: changes in geographic range, life-history traits, population dynamics, and trophic interactions (Fig 1). Changes in range and particularly population dynamics are likely to be directly linked to economic damage.

To assess current empirically-based knowledge within these four categories of response to climate change, we reviewed primary literature on 31 globally detrimental insect pest species. Species were selected to cover both agricultural and forestry pests, representing various feeding guilds (Supplement 1, Fig S1), being present in various biomes and having large geographic ranges (Fig. 1). Furthermore, we only selected species that have been well studied over a long period. While this approach perhaps leads to biases in terms of geographical range and taxonomy, we feel that it is compensated by having high-quality comprehensive datasets available for the species. This is also critical for allowing an integrated assessment of all the four major response categories outlined above in each species and would not be possible otherwise. As there is a need for more information on biological mechanisms relating to past and present climate change responses in several key biological traits for single organisms[17], we here provide an update on a number of such mechanisms (range expansion, life-history, population dynamics and trophic interactions) for the selected species in hopes that the data can be used for further predictive modelling. This information is presented in the form of species-specific descriptions and data tables in Supplement 2. We also identify critical knowledge gaps, and highlight aspects that require further research to anticipate, mitigate and manage climate-driven changes in pest impacts.

Insect pest responses to contemporary climate change are complex. Of the 31 insect pest species selected for the study, 29 (94%) reportedly show some response attributable to contemporary climate change (Table S1), and 28 (90%) present more than one response (Fig. 2a). Of the 29 showing some response 26 (90%), 18 (62%), 16 (55%) and 4 (14%) respectively show changes in: geographic range, population dynamics, life-history (traits related to phenology and voltinism), and trophic interactions (Fig. 2b). While at least one reported response of almost all of these species is likely to increase pest severity (e.g. range expansion or increases in population density), 59% (17/29) of them also show responses likely to reduce pest severity (e.g. range contraction or decreased physiological performance), and often this reduction occurs simultaneously with other responses likely to increase severity (Fig. 2c). The most common severity-reducing responses are reduction in pest population density (13/29), followed by range contraction (6/29) (Fig. 2c).

Responses of 59% (17/29) of the pest species with reported sensitivity to contemporary climate change have also varied between different parts of their ranges. For example, the range of the Colorado potato beetle (*Leptinotarsa decemlineata*) has expanded northwards in recent decades, and its population density has increased in core European areas (Table S1). The range of the winter moth (*Operophtera brumata*) has also expanded, towards higher latitudes and more continental areas at the northern

European edge of its range, and its trophic interactions have changed in the boreal-tundra ecotone, where outbreaks have spread from the main host *Betula pubescens* to an alternative host (*B. nana*) above the tree-line (Table S1). Several species also show both severity-increasing and severity-reducing responses in different parts of their ranges. Notably, thermal tracking has been observed in some species (4/17), e.g. spruce budworm (*Choristoneura fumiferana*; Table S1), as their geographic range has expanded towards higher latitudes while it has retracted, or their abundance has declined, at lower latitudes. Similarly, northward range expansion of the hemlock woolly adelgid (*Adelges tsugae*) has been observed in the USA, while the economic damage it causes is decreasing in the southern part of its range due to poor heat tolerance of young nymphs during summer (Table S1).

Disparate responses of pests of agriculture and forestry. The main response patterns of pests of agricultural (mainly annual) and forestry (perennial) crops are similar, but there are some striking differences. Contrary to expectations based on differences in feeding or host ecology, and evolutionary constraints, pests of agricultural crops show more severity-reducing responses than pests of forest trees. To assess the potential impact of agricultural and forest pest responses to climate change, we categorized the species according to their historic and current socio-economic and ecological impacts, and effects of contemporary climate change on those impacts. Overall socio-economic and ecological impacts have reportedly increased across the geographic ranges of species that have responded to climate change[11,19]. More importantly, while all the considered forestry pests already have large ecological impact, 85% (17/20) of the agricultural pests currently have relatively low ecological impact beyond the cropping systems they infest. However, climate change might be inducing increases in the relatively low impact of some agricultural pests. For instance, the green stink bug (*Nezara viridula*) and maize stem borer (*Chilo partellus*) displace native bugs and borers, respectively, as their ranges expand (Table S1). Further, the range of the western corn rootworm (*Diabrotica virgifera virgifera*) in Europe has expanded, and it can cause large ecological damage by spreading maize chlorotic mottle virus to several natural hosts (Table S1). A potential explanation is that reductions in phenological constraints associated with climate warming (mediated for instance by increases in host growth season, or shorter and milder winters[26]), can increase interactions between pests in annual agricultural habitats and surrounding ecosystems[27,28], thereby increasing ecological impacts. Indeed even small phenological mismatches might have large knock on effects for ecosystem function and predator prey interactions[13,28].

In addition to the fact that latitudinal differences in pest distributions might modulate climate change effects, several other mechanisms could be involved in the divergence of responses in annual and perennial systems. Unlike forestry pests, agricultural pests are generally associated with fragmented habitats[29] and may therefore have higher local extinction risks due to Allee effects when climate changes[12]. Further, while climate change can disrupt biological control by natural enemies in either annual or perennial systems[30], the biological control agents frequently introduced in annual systems may have lower genetic diversity than native agents, and hence lower adaptive capacity to respond to environmental changes[31]. Direct effects of climate change on the performance and phenology of pests have been detected in both annual and perennial systems. Since pests often persist through part of the season in a resting or dormant stage, especially at high latitudes and/or altitudes[26], climate change can contribute to phenological mismatches between hosts and emergence of key life-stages[13,21,27], as seen in *O. brumata* (Table S1). However, pests in annual and perennial systems might differ in general susceptibility to phenological mismatching, *inter alia* the former might be more sensitive to phenological host limitation; especially relative to bark beetles and root feeders.

Past, present and future temperature stress on the major insect pests. It has been argued that pests may suffer negative consequences of ongoing climate change owing to reduced thermal suitability and increasing frequency of high temperature extremes leading to population reductions[32]. For further exploration of this in our focal species, we assess the proximity of optimum development temperature (T_{opt}) of the 31 pest insects compared to their ambient habitat air temperatures (T_{amb}) (Fig. 3). Relating ambient temperature during the growing season in past, present and future climates to T_{opt} shows large variability in how pests are expected to benefit from climate change owing to regional complexity. In general, warming climates are expected to be beneficial for growth and development, and indeed, in all but two cases T_{amb} closely approached T_{opt} when comparing past, current, near future and future climates (Fig. 3B). This conclusion was also supported by a phylogenetically-informed regression analysis (Table S4). Further, this analysis suggested that pests at higher latitudes have greater disparity between T_{amb} and T_{opt}, indicating greater capacity to benefit from climate warming, unlike more low latitude pests that are already close to T_{opt}. Low latitude species also potentially risk increasing frequency and intensity of heat stress as climate warms[33], a notion receiving support in a recent analysis of the upper thermal tolerance of 15 dipteran pests[32].

However, examination of patterns in more species, as well as on other thermal traits, especially upper thermal limits or feeding (damage) rates, would be required to validate this hypothesis. Agricultural pests accounted for only 4% of the ca. 380 species included in the database of upper thermal limits compiled by Hoffmann et al.[34], highlighting a potential information gap in the current literature. While the pests in the current data represent a wide geographic distribution (Fig. 1A), the studies on T_{opt} used here mostly reflect populations sampled in the northern hemisphere (Fig. 3C). This is a general problem found in other large-scale analyses of climate change responses, such as phenology[28] and insect metabolic or development rate-temperature databases[35] showing a need for further studies covering underrepresented locations. Finally, as air temperatures are reported in the global temperature database, there is risk of underestimation of microclimate variability[33] and thus the extent of potential buffering owing to three-dimensional habitat complexity of operative temperatures[33,36].

Evolutionary responses of insect pests to climate change. Insect pests may evolve rapidly in response to contemporary climate change[15,37-41]. Thus, apparently sound projections of insect pest responses to climate change[11] may be compromised if evolutionary responses are not considered[42]. Indeed, rapid evolutionary effects have influenced - or could influence further - projections for several of the 31 species considered here (Supplement 2). For example, disruption of phenological synchrony between *O. brumata* and oak in temperate Europe due to increasing temperatures[30] has been apparently restored by a hereditary change in egg hatching dates[43]. Also, range expansions of some of the forestry pests induced by climate change have resulted in colonization of areas with novel host tree species that have little innate resistance due to lack of co-evolution with the pests[5]. In contrast, the similarity of crops grown across large areas might promote co-evolution between agricultural pests and their hosts[44]. Links between biological invasions or range expansion events, climate change and evolutionary processes have received recent attention[9,16,20,41], but there is still pressing need for further research in this field. The effects of management practices and evolution have generally been considered too much in isolation, especially in climate-change contexts[17,31].

Conclusions. The 31 widely-distributed pest insects that seriously affect agricultural or forestry systems studied here show multiple and varying responses to climate change. By providing an up-to-date database that reviews biological responses to climate change in the selected pests (Supplement 2) we offer standardized information that can be further explored by other researchers. Although the present analyses cannot be considered absolute, complete, and without taxonomic, geographic and study intensity biases[10], we nevertheless detected several overarching patterns that allow us to draw some general conclusions.

1. The data suggest that determining the net severity change of pests to climate change is complex since most species considered here have shown multiple responses that vary spatially[23]. The present study also provides evidence for mixed directionality of responses as well as potential explanations thereof based on major mechanisms. This set of complex but predictable outcomes and regional heterogeneity of responses is challenging for management but cannot be ignored as it is the emerging consensus in this and other studies[11,18].
2. The current study urges caution in performing large-scale analyses only with single traits, since single pests often show mixed directionality of effects of climate change in different traits. Lacking the interactions among different traits in each pest species may easily lead to incomplete conclusions. To correct this we recommend more in-depth studies of biological mechanisms in a few representative species. For example, a recent meta-analysis shows that models integrating biological mechanisms from multiple traits significantly improve predictions of climate change impacts on global biodiversity[17].
3. Mounting evidence suggests that pests and their hosts are responding not only through ecological, but also evolutionary processes to climate change[16,40,41]. Thus, evolutionary approaches might be under-exploited in pest management strategies[31]. Including evolutionary and ecological information when formulating integrated management strategies may facilitate robust intervention and control (as recently demonstrated in disease vector control programs[45]). Furthermore, it would be useful to pinpoint species with high evolvability in traits relevant to climate change[16], or that

show trade-offs between traits linked to basal climatic stress resistance and plasticity[41,46].

4. Combining data from large-scale experiments (e.g. mesocosm) and computational models may improve estimates of climate change effects[18,41,47]. Experiments should be designed to assess variance components with indicated importance in climate modelling studies, to identify the factors related to climate change that most strongly influence pest population growth and performance, such as for example the increased feeding efficacy of the Japanese beetle (*Popillia japonica*) on carbon dioxide-enriched soybean[48]. Indications that the response to climate change differ among trophic levels, translating into shifts in the relative importance of bottom-up and top-down population processes[49] needs to be studied further as even relatively small changes could result in large effects when multiple interactions are affected simultaneously[50]. Standardized experiments enable high-throughput investigation of pests (for recent example see[51]) and facilitate the development of watchlists or prioritization tools (such as The UK Plant Health Risk Register[52]) of key species that require further study. However, as the current data suggest large regional variability in pest responses to climate change, national or regional databases, while excellent locally, might offer poor insight into invasions into other regions unless coordinated or standardized efforts are attained, especially across political boundaries.
5. As T_{amb} is generally increasing towards T_{opt} for growth and development in these species, there is an expectation of increasing pest severity under future climate scenarios[53]. However, the relative benefit of increasing ambient temperatures is negligible for many of the studied pests (Fig. 3C). Indeed, since low-latitude species

already showed T_{amb} close to T_{opt}, as climates warm T_{amb} for these species may surpass T_{opt}, thus decreasing pest severity, under future climates[32,33].

6. Finally, and importantly, the patterns of regional variability and complexity described here are likely to apply to non-pest insects as well as non-insect species in addition to the 31 insect pest species assessed here. The extent of generality of responses across various taxa will be important to assess in future studies[13,19,41,47].

Methods. Thirty-one of the socioeconomically and ecologically most detrimental insect pests globally were selected that collectively: infest both agricultural and forestry crops, represent diverse feeding guilds, originate from both tropical and temperate environments, have large geographic ranges (preferably covering several continents), and have been well studied and monitored over recent decades (Fig. 1A & 1B). A lack of rigorous long-term monitoring, with consistent sampling effort, is probably the biggest limitation hindering efforts to characterize biological systems' responses to climate change robustly. Because of their large economic impact, insect pests represent a group of organisms with relatively good data compared to other groups; data are collected frequently but not consistently and data quality tend to be positively correlated to density and range expansion of the species. Thus, pests are good models for such efforts because abundant information about their distributions, impacts and interactions is routinely collected. However, since we selected species with large ranges, our results can be biased towards responses of species with broad thermal niches, thus the indicated general effects of climate change are likely conservative. Further, since habitats strongly affect insect ecology, we assume that species in disparate habitats will have different potential responses to climate change, so we chose species prevalent in a wide spectrum of lightly-managed to heavily-managed habitats. Then, using Web of Science searches (Thomson Reuters), we selected three types of studies. First, studies that compared climate trends and empirically determined trends in relevant aspects of the chosen pests, e.g. range, abundance or damage (economic and/or ecological). Second, studies that tracked population-dependent differences in relevant traits (e.g. voltinism) of the pests across time. Third, studies that modelled attributes of the pests, including a substantial historical data component. The responses recorded in these studies were classified into four major types (Fig. 1D), and as either increasing or decreasing pest severity. We used a modified version of a semi-quantitative generic impact score system to assess impact and severity[54]. The data sources include studies published in scientific journals, pest management databases (e.g. EPPO and CABI) and records from national environment/pest management institutions. We also contacted several experts for assessments of data quality. A non-parametric rank order correlation analysis of explanatory and response variables was used to identify significant patterns among pest responses, ecological factors, and habitats (Table S3). Thermal suitability in different climate periods was investigated using phylogenetically corrected generalized linear least square models of thermal performance traits coupled with climate data within sampled areas (Supplement 1).

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Author contributions

All authors jointly designed the study and collected species data. SN performed the rank correlation analysis, PL, JST, MB performed the optimum temperature analysis. All authors contributed to preparation of the supplements. PL, MB, AB, SDE, JST and CB prepared the first draft of the paper, and all authors edited the final version. The authors declare no conflicts of interest.

Supplement 1: Extended materials and methods

Supplement 2: Species descriptions with associated references

Supplement 3: Data used in analysis

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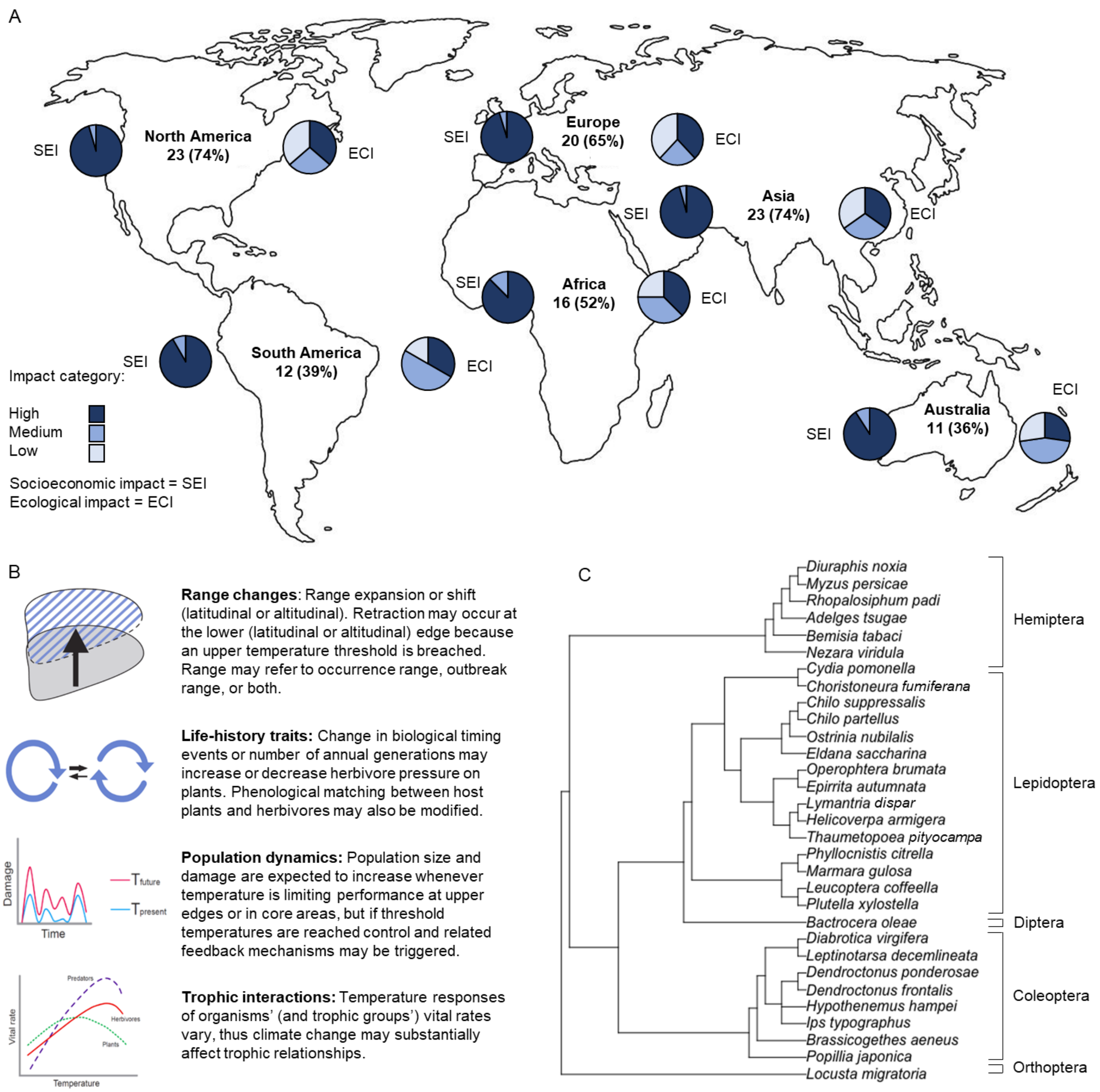
Figure legends

Fig. 1. The distribution of 31 insect pests according to (A) the number of species in the study occurring in each continent (with % of all those included) according to CABI. Note that many species occur on multiple continents. Flanking each continent are pie charts showing the distribution of social ecological impacts and ecological impacts caused by these species. (B) Schematic representation of four major categories of responses to climate change: range changes, life-history traits, population dynamics and trophic interactions (see Supplement 1). (C) A phylogenetic tree (compiled from the Tree-of-life project) of the 31 species considered in this analysis.

Fig. 2. Responses to climate change of 31 insect pests with high socioeconomic and/or ecological impact. (A) Shows the number of species responding in 0 to 4 traits to ongoing climate change. Dark and light blue columns in (B-E) show percentages of species displaying severity-increasing responses (e.g. increased range) and severity-decreasing responses (e.g. decreased economic damage due to smaller population size) to climate change. Single species may show multiple responses and (B-E) only display data for the 29 species that showed some response attributable to climate change (see Supplement 1). Observe that in (B-E) some species showed neither a positive or negative response in some traits, so total percentages in these cases are less than 100%.

Fig. 3. Summary figure of thermal sensitivity analysis of 31 insect pests. As input we use published optimum temperatures of the species (T_{opt}, the temperature at which performance is maximised, U_{max}) and mean ambient temperature (T_{amb}) during the growing season. This includes the whole year below 45°S/N, and the summer months above 45°S/N. (A) Schematic thermal performance curve including the two metrics extracted. (B) Here T_{amb} / T_{opt} is plotted against latitude for the four periods investigated (historical: 1960-1969 [blue triangles and dotted line], present: 2006-2015 [fine dashed line], near future: 2056-2065 [coarse dashed line] and future: 2070-2079 [red circles and solid line]). Stars denote significant correlations in a phylogenetically corrected

generalized linear least square model: * = $P<0.05$, ** = $P<0.005$ (Supplement 1). (C) Shows how many degrees T_{amb} differs from T_{opt} in past (left half of circle) and future (right half of the circle) climates. Circles have been placed in the approximate location where individual studies sampled the respective pests. Darker colors reflect ambient temperatures near the optimum temperature and therefore climates likely beneficial for pests.



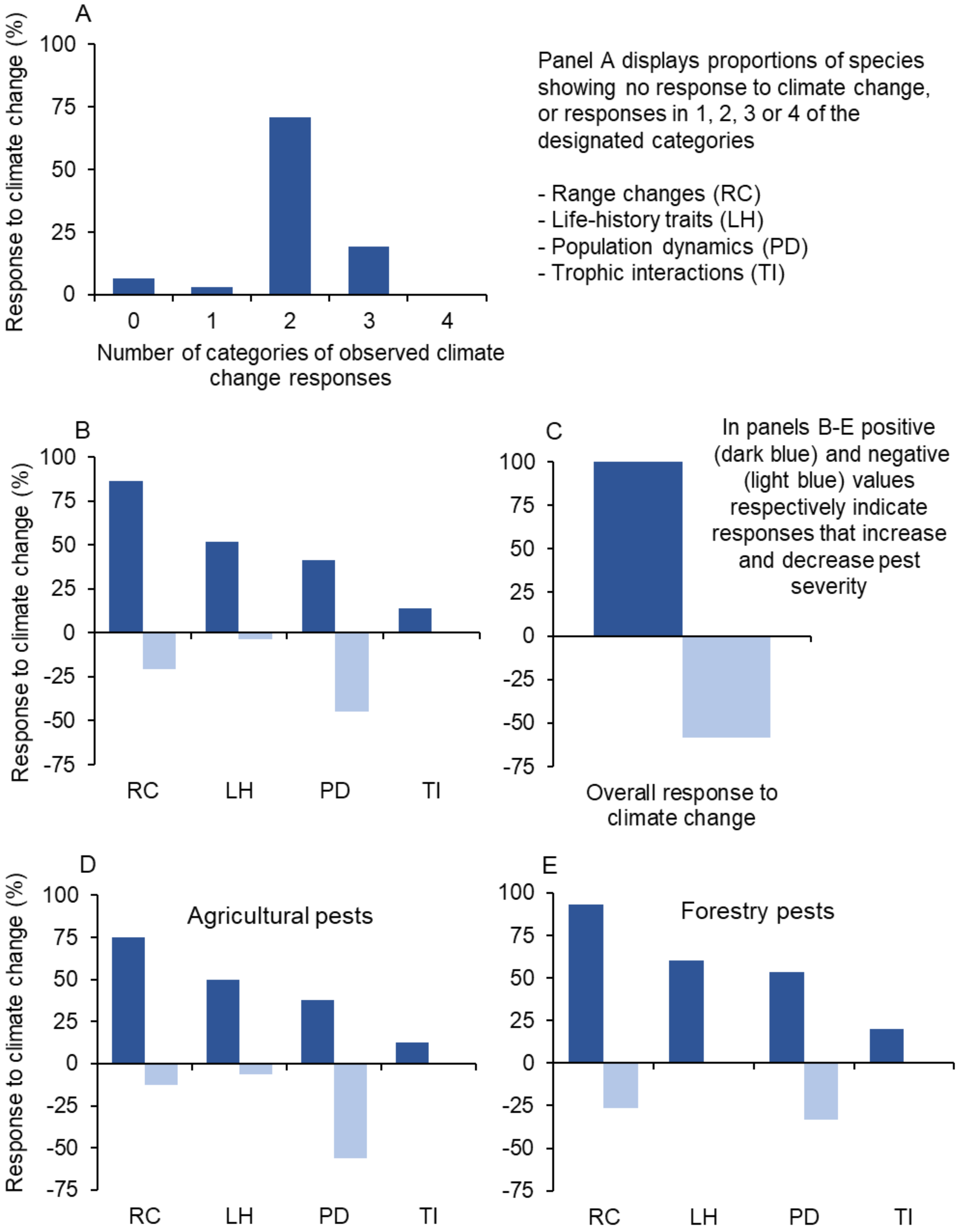
Range changes: Range expansion or shift (latitudinal or altitudinal). Retraction may occur at the lower (latitudinal or altitudinal) edge because an upper temperature threshold is breached. Range may refer to occurrence range, outbreak range, or both.

Life-history traits: Change in biological timing events or number of annual generations may increase or decrease herbivore pressure on plants. Phenological matching between host plants and herbivores may also be modified.

Population dynamics: Population size and damage are expected to increase whenever temperature is limiting performance at upper edges or in core areas, but if threshold temperatures are reached control and related feedback mechanisms may be triggered.

Trophic interactions: Temperature responses of organisms' (and trophic groups') vital rates vary, thus climate change may substantially affect trophic relationships.

Figure 1



Panel A displays proportions of species showing no response to climate change, or responses in 1, 2, 3 or 4 of the designated categories

- Range changes (RC)
- Life-history traits (LH)
- Population dynamics (PD)
- Trophic interactions (TI)

In panels B-E positive (dark blue) and negative (light blue) values respectively indicate responses that increase and decrease pest severity

Figure 2

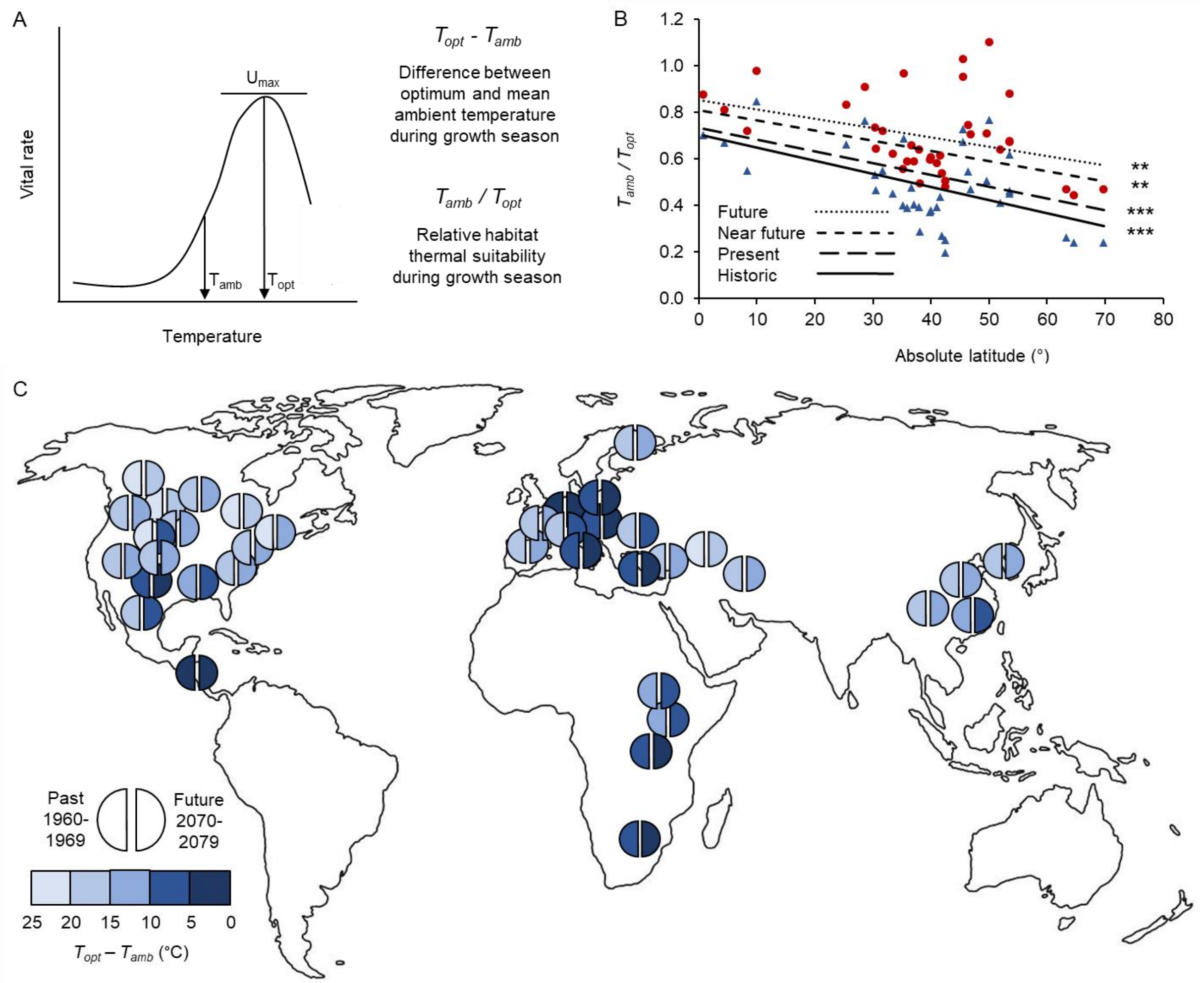

A
Vital rate
Temperature
U_{max}
T_{amb}
T_{opt}
T_{opt} - T_{amb}
Difference between optimum and mean ambient temperature during growth season
T_{amb} / T_{opt}
Relative habitat thermal suitability during growth season
B
T_{amb} / T_{opt}
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
10
20
30
40
50
60
70
80
Absolute latitude (°)
Future
Near future
Present
Historic
**
**
***
***
C
Past 1960-1969
Future 2070-2079
25
20
15
10
5
0
T_{opt} – T_{amb} (°C)

Figure 3

Supplement 1

Complex responses of global insect pests to climate change

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Materials and methods - Definitions and classifications used in the report

Data were acquired from scientific articles, governmental reports or pest record databases (e.g. EPPO, CABI). Relevant articles were primarily obtained from searches of Web of Science (https://apps.webofknowledge.com/). Although not a formal meta-analysis (due to the methods of selecting sources), our assessment is based on published material on the selected species that are methodologically sound and address recent and historic climate change-related responses of these species.

Feeding guilds/Functional groups (Figure S1)

- Defoliators (external feeders)
- Phloem feeders (external feeders)
- Fruit feeders (internal feeders)
- Stem borers (internal feeders)
- Bark beetles (internal feeders)
- Leaf miners (internal feeders)
- Root feeders (internal feeders)

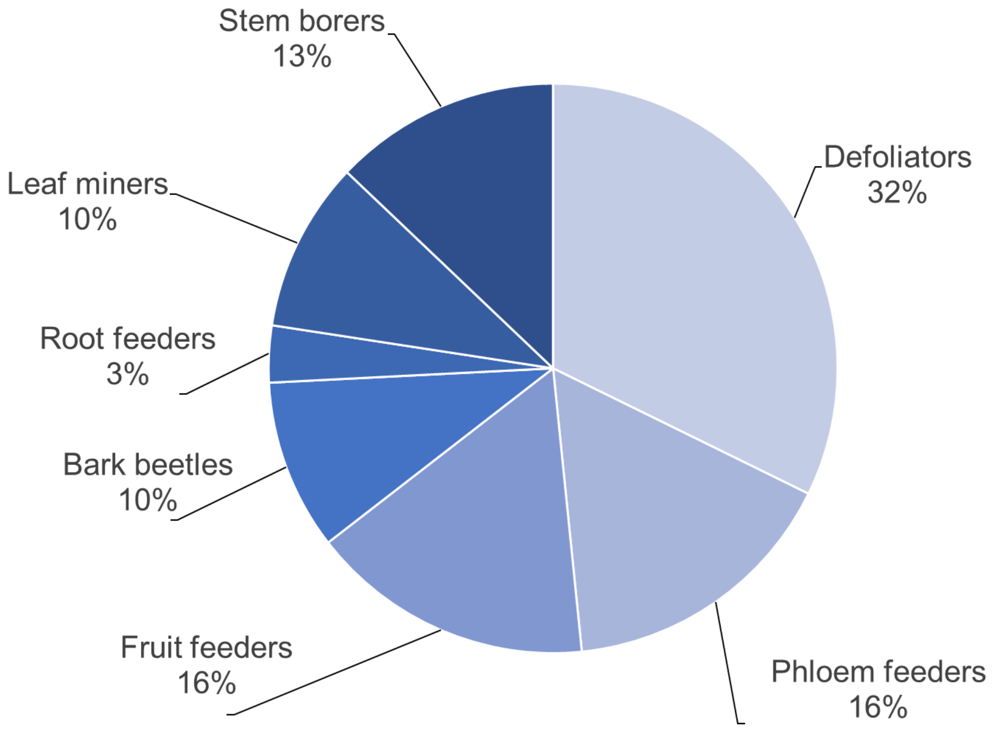

Figure S1 The distribution of the selected 31 insect pests according to feeding guild.

Annual or Perennial host(s):

- Annual
- Annual and Perennial host(s)
- Perennial

Latitude

- Tundra (highest latitude)
- Boreal (high latitude)
- Temperate (low latitude)
- Tropical (lowest latitude)

Categories of responses to climate change

Changes in:

- Range changes: expansion/retraction or shift in either latitudinal or altitudinal range. Warming may increase performance at range edges if temperature has previously limited performance. Retraction may occur if a high temperature threshold is breached. Range may refer to occurrence range, outbreak range or both.
- Life-history traits. A change in generation time or number of generations per year may increase or decrease herbivore pressure on plants. Phenological matching between host plants and herbivores may also be modified (but such responses are classified here as “Trophic interactions”, see below).
- Population dynamics. Damage to host plants, for various possible reasons, e.g. more frequent pest outbreaks, more intense defoliation). Expected to increase whenever temperature is limiting performance at upper edges or in core areas. Threshold levels may be reached, triggering control and related feedback mechanisms.
- Trophic interactions (e.g. host shift or a decrease in efficacy of natural predators following warming). Temperature responses of organisms’ (and trophic groups’) vital rates vary, thus climate change may substantially affect trophic relationships. We include changes in trophic interactions that have arisen due to direct impacts of climate change on the insects’ phenology.

Direction

This refers to the tendency of observed responses to increase, reduce or have neutral effects on pests' severity.

Geographical variation in responses

Responses of pests to climate change may vary in different parts of their ranges in terms of degree, type and direction (i.e. the responses may increase or decrease pests' severity) due to: genetic or plastic population-dependent differences, spatial climatic variability across the range, and varying permutations of these and other factors.

Definitions of Socioeconomic impact

1) Small impact: Negative impact, at most minor (if quantified). Such species are more nuisances than pests.

2) Medium impact: Significant reduction in performance of host (e.g. decreased fecundity, stunted growth), significant economic losses due to direct (e.g. sales) or indirect (e.g. ecosystem services, tourism) effects. Pest controllable without active management, or with reasonably small, often local, effort.

3) Large impact: Very significant reduction in performance of host (e.g. leading to death or destruction of usable product), significant economic losses due to direct or indirect effects. Pest not controllable without active, often nationwide, management, or simply not controllable.

Definitions of Ecological impact

1) Small impact: Primarily restricted to cultivated host. None or few interactions with native species.

2) Medium impact: Primarily restricted to cultivated host. Some negative interactions with native species (e.g. competition for food or resources, spread of pathogens).

3) Large impact: Host is part of natural ecosystem (even though potentially cultivated) or pest can use natural species as hosts and thus spread to the natural

environment. Many negative interactions with native species (e.g. competition for food or resources, spread of pathogens). Some pests may extensively kill hosts that are key species in the ecosystem.

Direction of change in impact category

1) Decrease: Published records show decreasing severity of pest damage, due to reductions in population densities, feeding efficacy, outbreak frequency, range, or other reasons attributable to climate change (i.e. declines in pest species fitness that have occurred in the absence of increased management actions). Reductions in management costs also indicate reductions in impact, but only indirectly so they are not used as criteria here.

2) Stable: No compelling evidence of climate-change related responses has been detected in considered studies. This could be due to several factors, but three main explanations have been proposed. (1) The phenology, abundance or distribution of the focal species may not be strongly influenced by climatic factors. (2) The focal species may be responding at rates (or in ways) that are undetectable using the applied methodology. (3) The phenology, abundance or distribution of the species may be influenced by climatic factors, but responses to current climate change may not yet be detectable due (for instance) to anthropogenic dispersal barriers (habitat fragmentation) or lags in responses[1].

3) Increase: Records show increasing severity of pest damage, in either or both socioeconomic or ecological terms. Increases in damage may occur for any of the reasons outlined above, including (for instance) expansion of range or outbreak range to new cultivated areas, spread to novel hosts, spread of pathogens to novel hosts, and/or increases in number of annual generations.

Critical assessment of species’ responses to climate change (Table S1)

Due to large variation in the amount of data available for the considered species prediction-strength is strongly biased towards the most intensively studied pests. We classify the strength of response-predictions as either strong or weak. Predictions for focal species are regarded as strong if empirically observed biological or ecological changes can be correlated with climatic changes, and reinforced if corroborated by modelling or laboratory studies. In a few cases predictions based on extensive species-specific modelling with extensive historic data components are also deemed strong. In contrast, predictions are regarded as weak if reported responses are based purely on modelling, modelling and laboratory studies, and/or some observations that may be correlated with climactic change, but there are strongly confounding effects of other biological or ecological factors (e.g. invasion dynamics). Predictions for responses of 23 (74%) and eight (23%) of the 31 species considered here were regarded as strong and weak, respectively. Two pests (*Marmara gulosa* and *Phyllocnistis citrella*) were removed from the main analysis (Table S1) since no pertinent information was found.

The assessments for each species can be found in Supplementary File 2, while relevant studies showing or suggesting responses are cited in Table S1. As has been suggested in several recent studies[2-4] holistic integrated analyses are to be preferred over single-trait analyses when assessing climate change responses, and this is what we attempted to achieve with our approach. Thus while the present study is neither a formal meta-analysis nor exhaustive, it synthesizes current knowledge of integrated climatic responses of 31 pests with the aim to illustrate general patterns, problems and challenges, in a precautionary manner.

Rank order correlation (Table S2)

Associations between explanatory and response variables regarding effects of climate change on the 31 selected serious insect pests were explored by Kendall rank order correlation analysis. The results are presented in Table S3, and the following list explains abbreviations and the range of these variables, which are listed in the beginning of this supplementary document and used in the table. NRT = Number of response categories (1 – 3), PA = Perennial or annual host (1 [perennial] – 3 [annual]), IE = Internal or external feeder (1 [external] – 2 [internal]), BRANK = Mean habitat biome ranked from tundra to tropical (1 [tundra] – 4 [tropical]), AF = Agricultural or Forestry pest (1 [agricultural] – 2 [forestry]), SEI = Socioeconomic impact (2 [low] – 3 [high]), SEId = Change in Socioeconomic impact (1 [decrease] – 3 [increase]), ECI = Ecological impact (1 [low] – 3 [high]), ECId = Change in ecological impact (1 [decrease] – 3 [increase]), GD = Difference between geographical areas of range (1 [no] – 2 [yes]).

The results of the correlation analysis were briefly as follows. For some traits, such as NRT, there was very little variation among pests (Fig. 2a), and thus no significant correlations with other variables. There were some expected correlations between explanatory variables such as: a positive correlation between PA and AF, indicating that most pests on forestry hosts are pests on perennial plants; a negative correlation between IE and Brank, indicating that internally feeding pests become less common as latitude increases, and finally; a negative correlation between Brank and AF, indicating that pests in agricultural habitats are generally found at lower latitudes than pests in forestry habitats (Table S2).

There were several strong correlations between explanatory and response variables, and interestingly most of these concerned the ecological impact, rather than socioeconomic impact, of the pests. This is likely due to selection bias, since pests of high socioeconomic impact were chosen, thus there was little baseline variation in that variable. However, there was a positive correlation between IE and SEI, indicating that external feeders among the selected pests generally have higher socioeconomic impact than the internal feeders. ECI was found to be significantly positively correlated with PA, IE, Brank and AF. These findings indicate, briefly, that pests' ecological impact increases with latitude, and externally feeding forest pests have stronger ecological impacts than internally feeding agricultural pests.

The most interesting finding, in the context of this study, was that several of both the explanatory and response variables were significantly correlated with ECId, *inter alia* as Brank was negatively correlated with ECId, indicating that changes in ecological impact increase as latitude increases. There was also a positive correlation between AF and SEId, suggesting that the severity of agricultural pests is increasing more than forestry pests' severity (possibly because most serious forestry pests already have major ecological impact). Furthermore, there was a positive correlation between ECId and SEId, suggesting that pests that are becoming more socioeconomically destructive are also becoming more ecologically damaging. Finally, there was a positive correlation between ECI and ECId, suggesting that pests with the strongest current ecological impacts are more likely to become increasingly damaging than pests with low current ecological impact.

Optimal temperature in the past, the present and the future (Table S3 and S4)

A meta-analysis on optimal temperatures of the 31 insect pest species was conducted to quantify potential climate change stress. We extracted optimal temperatures for development (T_{opt}) for the species from the primary literature, giving priority to studies investigating temperature dependence of the whole life-cycle, as well as using populations from the core of the range. Latitude and longitude coordinates were either copied straight from the article, or extracted from global maps based on the sampling location reported in the original article. The data is shown in Table S3.

Ambient temperatures at each location in our species database (Table 3) were extracted from a Global Circulation Model that forms part of the *Coupled Model Intercomparison Project* phase 5[5,6], which we sourced directly from the Earth System Grid database (http://pcmdi9.llnl.gov/). More specifically we considered predictions of average monthly near surface temperature (ambient temperature hereafter, T_{amb}) from the HadGEM2-CC model[7]. For the present and future conditions, we considered models with a radiative forcing of $8.5 Wm^{-2}$ (Representative Concentration Pathway 8.5), the most extreme climate warming scenario included in the IPCC Fourth Assessment report[8], and that which is most representative of current trajectories[9]. Here, we aimed to capture “present” ambient temperatures (2006-2015), “near-future” ambient temperatures (2056-2065) and “future” ambient temperatures (2070-2079). The “past” temperatures were extracted from the historical experiment of the same model. Across each of these four decades, we calculated an overall average mean temperature from the 12 monthly averages for each year. As species at high latitudes in the northern hemisphere undergo a period of dormancy during winter (and hence are buffered from winter temperatures), for locations above 45° latitude (15 of 38 locations, Table 3), we considered only temperatures during the summer months from May to September inclusive. Data were extracted from raw files, and subsequently cleaned using functions in the “raster” package for R[10]. The full R-code workflow can be found at GitHub: XXX

The overall T_{amb} for each of the four decades were compared against the species T_{opt} at each location in two ways. First by visually comparing the differential between T_{opt} and T_{amb} (Fig. 3) and then with a phylogenetically corrected generalized linear least square model (pgls) investigating the relationship between thermal suitability (expressed as T_{opt} / T_{amb}) and absolute latitude. Data were extracted from the literature (Table S3) and the models run using primarily the “pgls” function in the “caper” package for R[11]. Overall model results are shown in Table S4 and the full R-code workflow can be found at GitHub: XXX

Table S1 The 31 major pest species' responses to ongoing climate change in four major categories (range change, life-history traits, population dynamics and trophic interactions), showing whether they are likely to increase or reduce the pests' severity.

Trait		Range change		Life-history traits		Population dynamics		Trophic interaction	
Change in severity		Increase	Decrease	Increase	Decrease	Increase	Decrease	Increase	Decrease
Name	Order: Family								
Choristoneura fumiferana	Lepidoptera: Tortricidae	12-14	15	-	-	12	-	-	-
Lymantria dispar	Lepidoptera: Erebidae	16-18	15	-	-	15	15	-	-
Operophtera brumata	Lepidoptera: Geometridae	19-21	-	-	-	22	-	23,24	-
Epirrita autumnata	Lepidoptera: Geometridae	19,20	-	-	-	-	25,26	-	-
Thaumetopoea pityocampa	Lepidoptera: Thaumetopoeidae	27-30	-	-	-	-	-	31	-
Leptinotarsa decemlineata	Coleoptera: Chrysomelidae	32-37	-	34,37,38	34	-	-	-	-
Locusta migratoria	Orthoptera: Acrididae	-	39,40	-	-	-	39,40	-	-
Meligethes aeneus	Coleoptera: Nitidulidae	41-43	-	-	-	-	-	-	-
Plutella xylostella	Lepidoptera: Plutellidae	44-46	-	46	-	-	-	-	-
Rhopalosiphum padi	Hemiptera: Aphididae	47-49	-	49,50	-	49	49	-	-
Diuraphis noxia	Hemiptera: Aphididae	51	-	-	-	51	51,52	-	-
Adelges tsugae	Hemiptera: Adelgidae	53-56	-	54	-	55-56	53		-
Bemisia tabaci	Hemiptera: Aleyrodidae	57,58	-	-	-	58	59	-	-
Nezara viridula	Hemiptera: Pentatomidae	60	-	61	-	-	61	-	-
Chilo suppressalis	Lepidoptera: Crambidae	62	-	62,63	-	-	62	-	-
Ostrinia nubilalis	Lepidoptera: Crambidae	-	-	64-66	-	67,68	-	-	-
Helicoverpa armigera	Lepidoptera: Noctuidae	68-70	-	-	-	69,71-73	74	-	-
Dendroctonus ponderosae	Coleoptera: Curculionidae	75,76	-	76	-	75	-	-	-
Dendroctonus frontalis	Coleoptera: Curculionidae	77-81	-	77,79	-	-	-	-	-
Ips typographus	Coleoptera: Curculionidae	82,83	-	82-87	-	84,86,87	-	-	-
Bactrocera oleae	Diptera: Tephritidae	88,89	88	-	-	89,90	89	-	-
Cydia pomonella	Lepidoptera: Tortricidae	91	92,93	91,94,95	-	-	-	-	-
Hypothenemus hampei	Coleoptera: Curculionidae	96,97	-	96-98	-	-	-	-	-
Diabrotica virgifera	Coleoptera: Chrysomelidae	99-101	-	-	-	-	-	-	-
Popillia japonica	Coleoptera: Scarabaeidae	-	-	-	-	102-107	108	106	-
Eldana saccharina	Lepidoptera: Pyralidae	109,110	-	-	-	-	111,112	-	-
Leucoptera coffeella	Lepidoptera: Lyonetiidae	113,114	-	113	-	-	-	-	-
Marmara gulosa	Lepidoptera: Gracillariidae	-	-	-	-	-	-	-	-
Phyllocnistis citrella	Lepidoptera: Gracillariidae	-	-	-	-	-	-	-	-
Chilo partellus	Lepidoptera: Crambidae	115,116	117	117	-	-	-	-	-
Myzus persicae	Hemiptera: Aphididae	-	-	118	-	118	-	119	-

Empty cells indicate lack of data or studies, while numbers refer to individual studies showing (empirical studies) or suggesting (modelling and laboratory studies) a response.

Table S2 Kendall rank order correlations of background traits and responses to ongoing climate change investigated in the 31 serious insect pests.

	NRT[1]	PA[2]	IE[3]	Brank[4]	AF[5]	SEI[6]	SEId[7]	ECI[8]	ECId[9]	GD[10]
N	29	29	29	29	29	29	29	29	29	29
NRT	1									
PA	0.251	1								
IE	-0.248	-0.099	1							
Brank	-0.043	-0.194	-0.310	1						
AF	0.236	**0.699**	0.155	**-0.461**	1					
SEI	-0.109	0.103	**0.377**	-0.143	-0.017	1				
SEId	-0.023	0.097	-0.138	-0.190	0.167	0.084	1			
ECI	0.199	**0.349**	**0.376**	**-0.349**	**0.647**	0.123	0.085	1		
ECId	-0.009	0.132	0.126	**-0.344**	**0.447**	-0.084	**0.597**	**0.463**	1	
GD	0.068	0.116	-0.276	-0.122	0.064	-0.032	**0.318**	0.154	0.316	1

The following list explains abbreviations used (listed in the beginning of this supplement): [1]Number of response types, [2]Perennial or annual host, [3]External or internal feeder, [4]Mean habitat biome ranked from tundra to tropical, [5]Agricultural or Forestry pest, [6]Socioeconomic impact, [7]Change in Socioeconomic impact, [8]Ecological impact, [9]Change in ecological impact, [10]Difference between geographical areas of range. Significant two-tailed correlation coefficient values where $p<0.05$ (>0.312), and $p<0.01$ (>0.430) are indicated in bold, and both bold and underlined, respectively.

Table S3 Input data for optimal temperature analysis.

Scientific name	Topt	Lifestage	Latitude	Longitude	Position in range	Invasion status	Reference	Avg temp 1960-1969	Avg Temp 2006-2016	Avg temp 2050-2059	Avg temp 2070-2079
Choristoneura fumiferana	28.7	Egg to pupa	63,22	-123,48	CR	Native	[120]	7,5	9,4	12,0	13,5
Choristoneura fumiferana	28.6	Egg to pupa	53,50	-113,53	CR	Native	[120]	12,9	14,3	17,5	19,4
Choristoneura fumiferana	29.2	Egg to pupa	64,67	-124,92	CR	Native	[120]	7,1	8,8	11,4	13,0
Choristoneura fumiferana	29.1	Egg to pupa	51,95	-114,25	CR	Native	[120]	12,0	13,5	16,8	18,6
Choristoneura fumiferana	30.9	Egg to pupa	53,52	-113,26	CR	Native	[120]	14,3	15,7	19,1	20,9
Choristoneura fumiferana	33.0	Egg to pupa	49,65	-110,03	CR	Native	[120]	16,7	17,9	21,7	23,5
Lymantria dispar	28,0	Egg to pupa	39,83	-74,87	CR	Native	[121]	10,4	12,3	15,1	16,7
Operophtera brumata	22,0	Larva	69,64	19,01	CR	Native	[122]	16,9	19,0	21,7	24,3
Epirrita autumnata	25,0	Larva	50,09	7,32	CR	Native	[123]	6,1	7,8	10,5	11,7
Thaumetopoea pityocampa	25,0	Larva	69,64	19,01	CR	Native	[124]	18,2	19,6	23,9	25,8
Leptinotarsa decemlineata	28,0	Egg to pupa	69,73	27,01	UN, HA	Invasive	[125]	7,0	9,1	12,3	14,1
Locusta migratoria	30,0	Nymph	45,50	11,15	CR	Native	[126]	13,6	14,1	17,4	18,7
Meligethes aeneus	24,0	Egg to pupa	42,41	-71,38	CR	Native	[127]	14,9	16,9	19,1	21,1
Plutella xylostella	28,8	Whole life cycle	33,46	120,01	CR	Native	[128]	11,2	13,0	15,3	16,9
Rhopalosiphum padi	28,5	Whole life cycle	53,53	10,01	CR	Native	[129,130]	12,5	13,5	16,6	17,5
Diuraphis noxia	20,0	Whole life cycle	35,84	50,96	CR	Invasive	[131,132]	13,7	15,7	17,6	19,3

Adelges tsugae	X	X	X	X	X	X	X	X		X	X
Bemisia tabaci	31,0	Whole life cycle	35,16	128,14	CR	Native	[133,134]	12,4	13,3	16,3	17,3
Nezara viridula	27,0	Nymph	37,99	-84,66	CR	Native	[135]	10,6	12,5	15,5	17,3
Chilo suppressalis	31,0	Egg to pupa	30,53	114,33	CR	Native	[136]	14,5	15,3	18,4	20,0
Ostrinia nubilalis	34,0	Larva	46,40	0,05	CR	Native	[137]	18,6	20,5	22,8	25,4
Helicoverpa armigera	27,5	Whole life cycle	40,97	23,59	CR	Native	[138]	10,8	12,2	15,3	16,0
Dendroctonus ponderosae	24,0	Whole life cycle	41,83	-111,60	CR	Native	[139]	6,5	8,4	11,1	13,0
Dendroctonus frontalis	31,1	Whole life cycle	31,59	-94,80	CR	Native	[140]	17,1	18,6	21,0	22,5
Ips typographus	30,4	Whole life cycle	46,86	9,66	CR	Native	[141,142]	14,2	15,6	19,2	21,4
Bactrocera oleae	27,0	Egg to pupa	45,50	11,15	CR	Invasive	[143,144]	18,2	19,6	23,9	25,8
Cydia pomonella	30,7	Larva	38,10	46,48	CR	Native	[145]	8,9	10,9	13,6	15,2
Hypothenemus hampei	26,7	Whole life cycle	-0,76	34,72	CR	Native	[96]	18,7	19,8	22,1	23,4
Diabrotica virgifera	28,0	Egg	42,44	-81,89	CR	Invasive	[146]	5,5	7,9	11,4	13,5
Popillia japonica	27,5	Larva	39,96	-75,19	UN, HA	Invasive	[147]	10,4	12,3	15,1	16,7
Eldana saccharina	29,0	Egg to adult	-25,46	31,58	CR	Invasive	[148]	19,3	20,2	22,3	24,1
Leucoptera coffeella	30,0	Larva	9,95	-84,01	CR	Native	[149]	25,4	26,2	28,0	29,3
Marmara gulosa	29,0	Egg to pupa	36,60	-119,51	CR	Invasive	[150]	13,8	15,4	18,0	19,1
Phyllocnistis citrella	30,0	Adult	36,99	35,34	CR	Invasive	[151]	12,2	13,4	16,2	17,7
Chilo partellus	32,0	Larva	4,43	39,31	UN, HA	Invasive	[117]	21,4	22,6	24,8	26,0

Chilo partellus	32,0	Larva	8,40	39,35	UN, HA	Invasive	[152]	16,5	17,6	20,1	21,6
Chilo partellus	32,0	Larva	28,64	77,16	UN, HA	Invasive	[153]	21,0	21,6	23,4	25,0
Myzus persicae	26,5	Egg to pupa	30,30	120,12	CR	Native	[154]	14,1	14,8	18,0	19,4

CR = Core range, UN, HA = Unknown position in range, but occurring in high abundance. For some pests there are several thermal performance studies available. Here we chose the most comprehensive (in terms of methodology, temperature range, and life-stages analysed), and for two species (Choristoneura fumiferana and Chilo partellus) we included several populations that had been investigated.

Table S4 Coefficients of variation in phylogenetically controlled generalized least square models (pgls) testing the relationship between temperature suitability and latitude in four different time-periods (past: 1960-1969, present: 2005-2015, near future: 2056-2065 and future: 2070-2079).

Effect	Estimate	Std. Error	t value	Significance
Past				
Intercept	0.741	0.078	9.464	< 0.001
Latitude	-0.008	0.002	-3.879	< 0.001
Present				
Intercept	0.768	0.073	10.475	< 0.001
Latitude	-0.007	0.001	-3.788	0.001
Near future				
Intercept	0.831	0.079	10.514	< 0.001
Latitude	-0.006	0.002	-2.980	0.007
Future				
Intercept	0.878	0.081	10.872	< 0.001
Latitude	-0.006	0.002	-2.790	0.011

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Supplement 2

Complex responses of global insect pests to climate change

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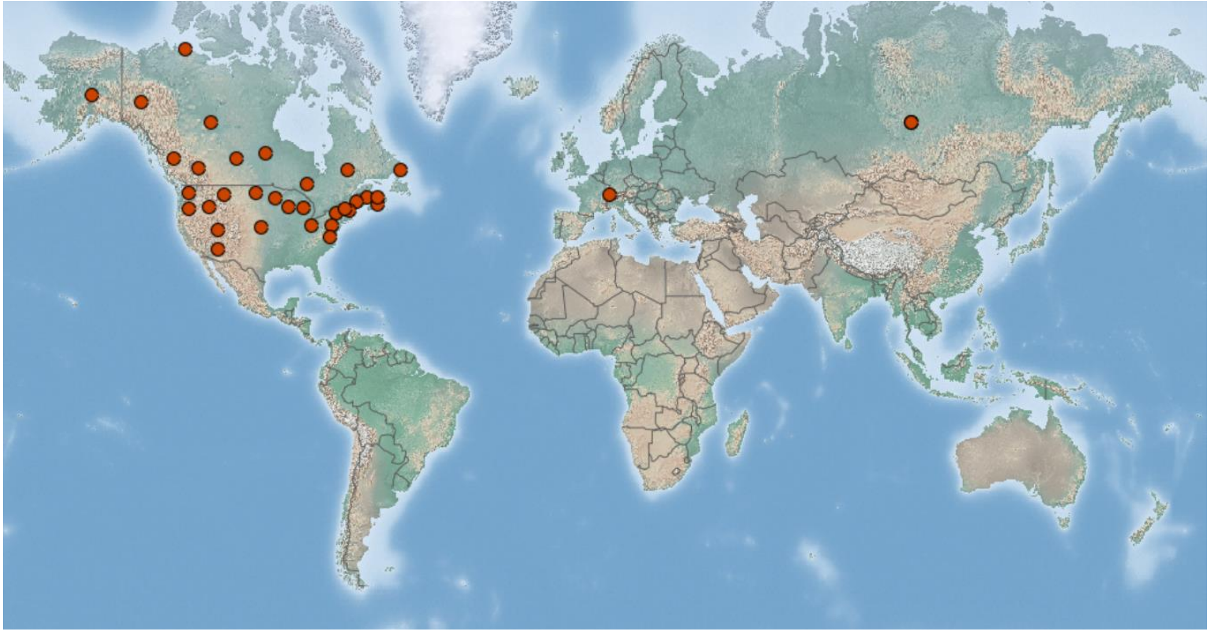
Surveyed pests and their responses to climate change

1. Eastern spruce budworm (*Choristoneura fumiferana*) Lepidoptera: Tortricidae (Clemens 1865)

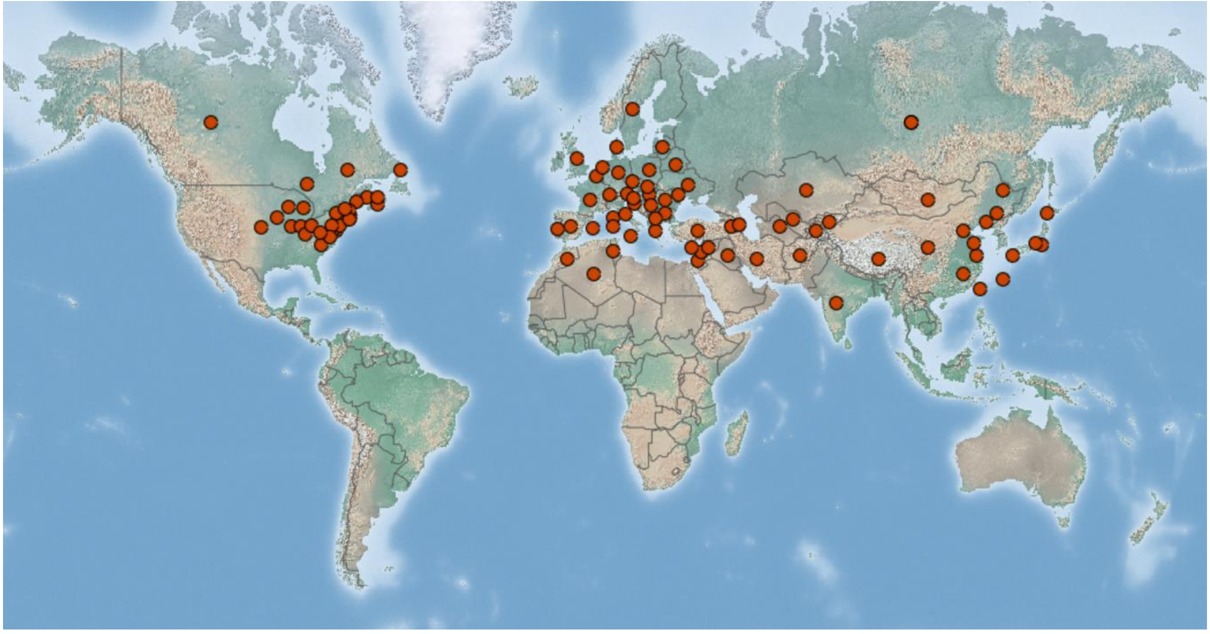
The eastern spruce budworm *Choristoneura fumiferana* is a native defoliator of North American conifer forests. The main host of the eastern spruce budworm is balsam fir, *Abies balsamea,* though it may also utilize white, red and to some extent black spruce, *Picea glauca*, *P. rubens* and *P. mariana.* The eastern spruce budworm causes considerably more damage than any other defoliating insect in North America's boreal forests (Volney and Fleming 2000). The northern range of the eastern spruce budworm is predicted to shift towards north and higher elevations under projected climate change. The expansions are predicted to be spatially non-uniform depending on the distribution of the main host species, but temperate regions are expected to be most affected (Réniere et al. 2012). Climate change and forest composition are predicted to influence the outbreak characteristics of the eastern spruce budworm in Canada (Gray et al. 2000, Gray 2013). Outbreak duration has been shown to be most strongly influenced by spring accumulation of degree days and outbreak severity most influenced by the extreme maximum temperatures of spring (Gray 2013). Forest characteristics (tree species composition, basal area) influence the outbreaks duration and severity. In Pennsylvania increased temperature with increasing precipitation is predicted to increase defoliation area whereas increased temperature alone or combined with low precipitation decreased the defoliation area (Williams and Liebhold 1995).



Distribution map from: CABI, 2018. *Choristoneura fumiferana*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission.

2. Gypsy moth (*Lymantria dispar*) Lepidoptera: Erebidae (Linnaeus 1758)

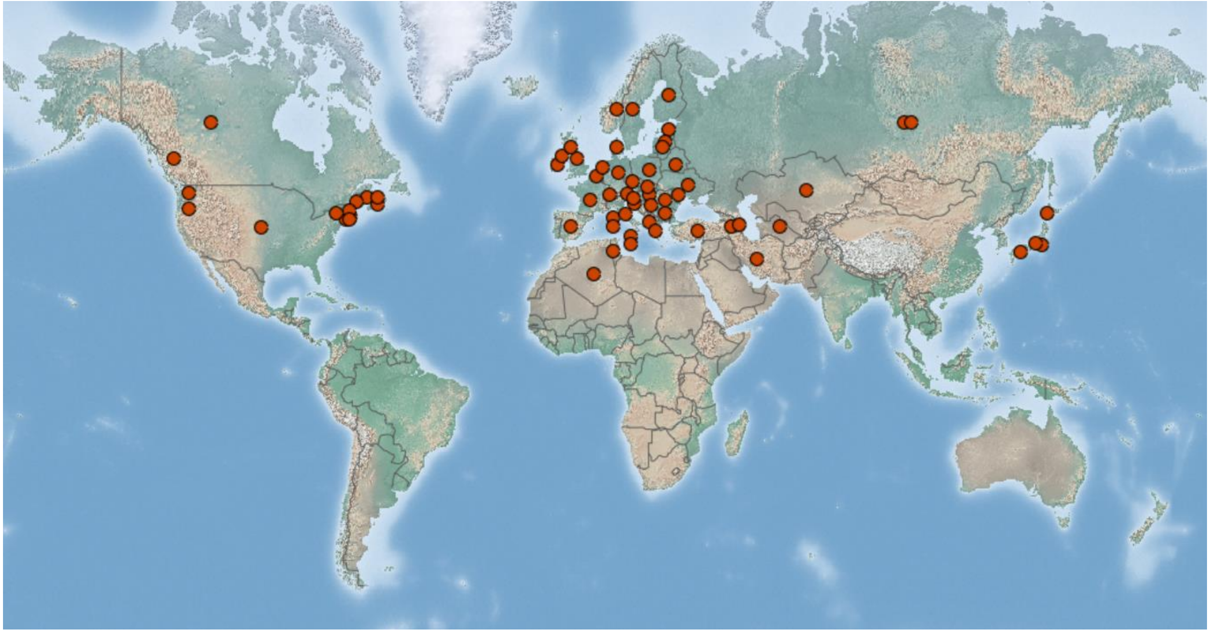
The major insect pest of temperate central European and eastern North American forests is the gypsy moth, *Lymantria dispar*. The gypsy moth is native to southern Europe, northern Africa, central and southern Asia and Japan. The European strain has been introduced to the United States (in 1869) and Canada and is now present in most of northeastern N. America but its range is expanding to the south and west. In its caterpillar stage, the gypsy moth can feed on more than 500 different species of trees and shrubs. In N. America the preferred hosts include oak, cherry white birch, maple, alder, willow, elm and trembling aspen. Defoliations may change oak dominated forest to maple dominated forests thus causing considerable forest ecosystem changes (Fajyan and Wood 1996). In eastern N. America current climate change forecasts are expected to increase the area of climatic suitability for the gypsy moth (Regniere et al. 2009). Williams and Liebhold (1995) modeled that in Pennsylvania increased temperature alone or with increasing precipitation are expected to increase defoliation areas whereas increasing temperature with decreasing precipitation is expected to decrease defoliation area. Control of gypsy moth populations by the fungal pathogen *Entomaphaga maimaiga* has decreased damage in N. America during the last decades (Oswalt & Smith 2014). In Europe climate change is expected to increase range shift towards north (e.g. Vanhanen et al. 2007, Fält-Nardmann et al. 2018a, b, c). Also Asian gypsy moth populations are modeled to have potential to expand towards north and west under changing climate (Peterson et al. 2007). Finally, the Nun moth, *Lymantria monacha*, has been shown to spread northwards in Europe probably due to increased winter survival because of reduced thermal constraints (Fält-Nardmann et al. 2018a, b).



Distribution map from: CABI, 2018. *Lymantria dispar*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission. Reviewed by: Patrick Tobin, School of Environmental and Forest Sciences, University of Washington, Seattle, USA

3. Winter moth (*Operophtera brumata*) Lepidoptera: Geometridae (Linnaeus 1758)

The winter moth (*Operopthera brumata*) is distributed in temperate, boreal and sub-arctic forests throughout Europe, western Russia, south-east Russia and parts of Asia (Tenow 1972). In North America it has been accidentally introduced to both eastern and western Canada. From the latest introduction in Nova Scotia it has spread into the north-eastern coastal states of the US (Elkinton et al. 2014). The species is univoltine with overwintering eggs and spring-feeding larvae, which feed on a variety of mostly deciduous trees. In northern regions it displays a pronounced cyclic dynamics with decadal outbreaks of varying amplitude. In temperate Europe the winter moth is an important pest in orchards and natural oak forest, while in northern Fennoscandia, outbreaks by winter moth and autumnal moth (see elsewhere) have defoliated 1 mill ha of birch forest during the 2000’s (Jepsen et al. 2009a) and caused ecosystem levels changes in the birch forest system (Jepsen et al. 2013, Kaukonen et al. 2013). At its northern range the winter moth has spread northwards and inland during the last few decades (Jepsen et al. 2008) probably due both to a release from climatic constraints on eggs survival in winter (Ammunet et al. 2012), and a better phenological synchrony with the main host tree, mountain birch (Jepsen et al. 2009b). In temperate Europe, a disrupted phenological synchrony between winter moth and oak caused by warming temperatures (Visser and Holleman 2001) appears to have been restored by a hereditary change in egg hatching dates in response to the altered selection pressure . In the Netherlands observations of winter moth damage have increased over the last 50 years (Moraal & Jagers op Akkerhuis, 2011).



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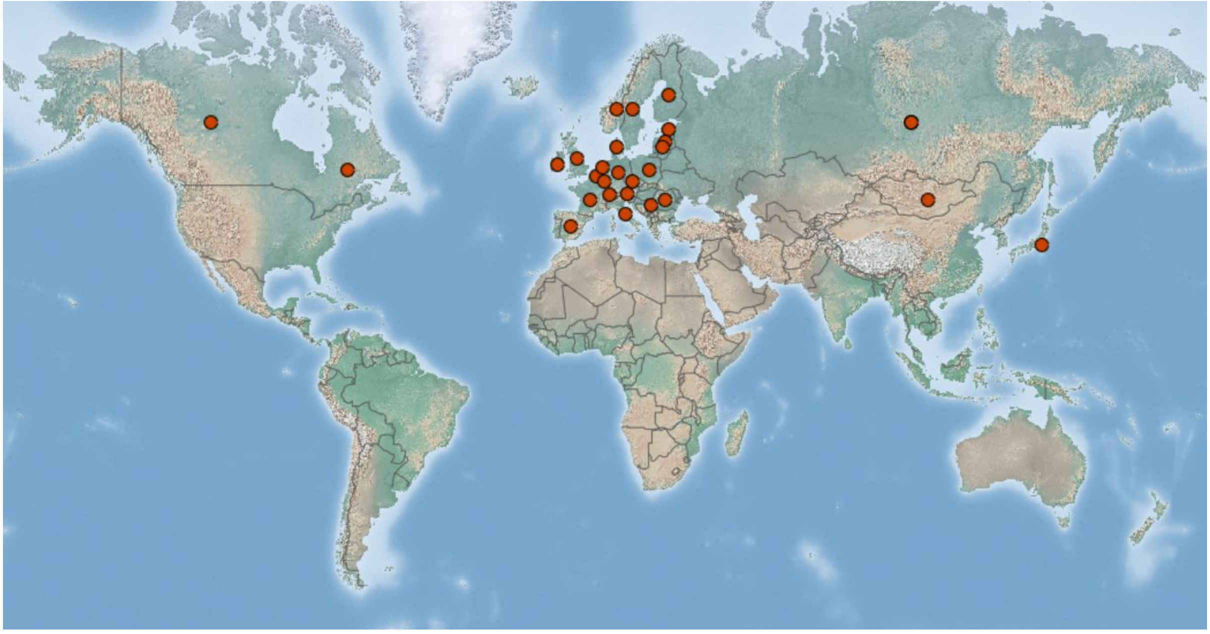
4. Autumnal moth (*Epirrita autumnata*) Lepidoptera: Geometridae (Borkhausen 1794)

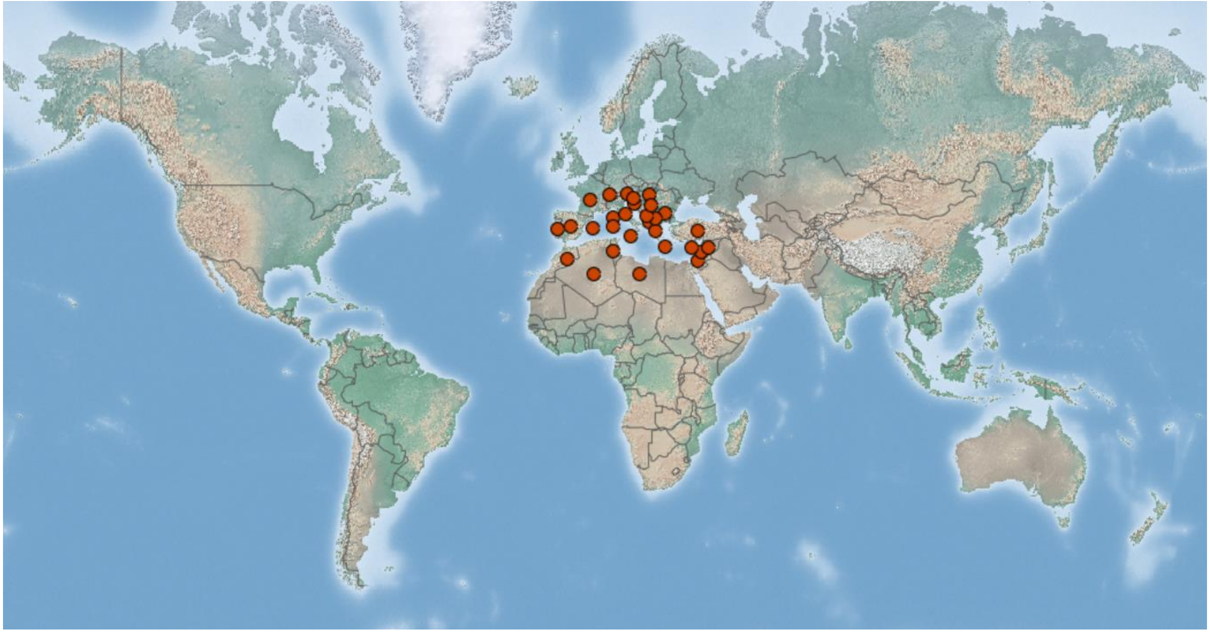
The autumnal moth (*Epirrita autumnata*) is distributed mainly in boreal, alpine and sub-arctic forests throughout the northern hemisphere (Tenow 1972). The species is univoltine with overwintering eggs and spring-feeding larvae, which feed on a variety of mostly deciduous trees. As the winter moth, it displays pronounced cyclic dynamics with decadal outbreaks of varying amplitude in Fennoscandia, causing large-scale and severe damage to alpine and sub-arctic mountain birch forests (Jepsen et al. 2013, Karlsen et al. 2013). At its northern range the species has recently spread into colder and more continental areas (Jepsen et al. 2008), probably due to a release from climatic constraints on egg survival in winter (Ammunet et al. 2012). The autumnal moth is a widespread species but outbreaks occur mainly near the northern margin of its distribution (Tenow 1972, Neuvonen et al. 1999). Therefore, it seems plausible that at least one reason behind this pattern is higher numbers or efficiency of natural enemies in more southern areas, and there is evidence that the efficiency of the parasitoids of the autumnal moth is higher in warmer temperatures (Virtanen & Neuvonen 1999). Finally, in a seven-year field experiment, Svensson et al. (2018) showed links between habitat warming and trophic shifts in herbivore-plant interactions leading to more severe pest outbreaks.



Distribution map from: CABI, 2018. *Epirrita autumnata*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission.

5. Pine processionary moth (*Thaumetopoea pityocampa*) Lepidoptera: Thaumetopoeidae (Denis & Shiffermüller 1775)

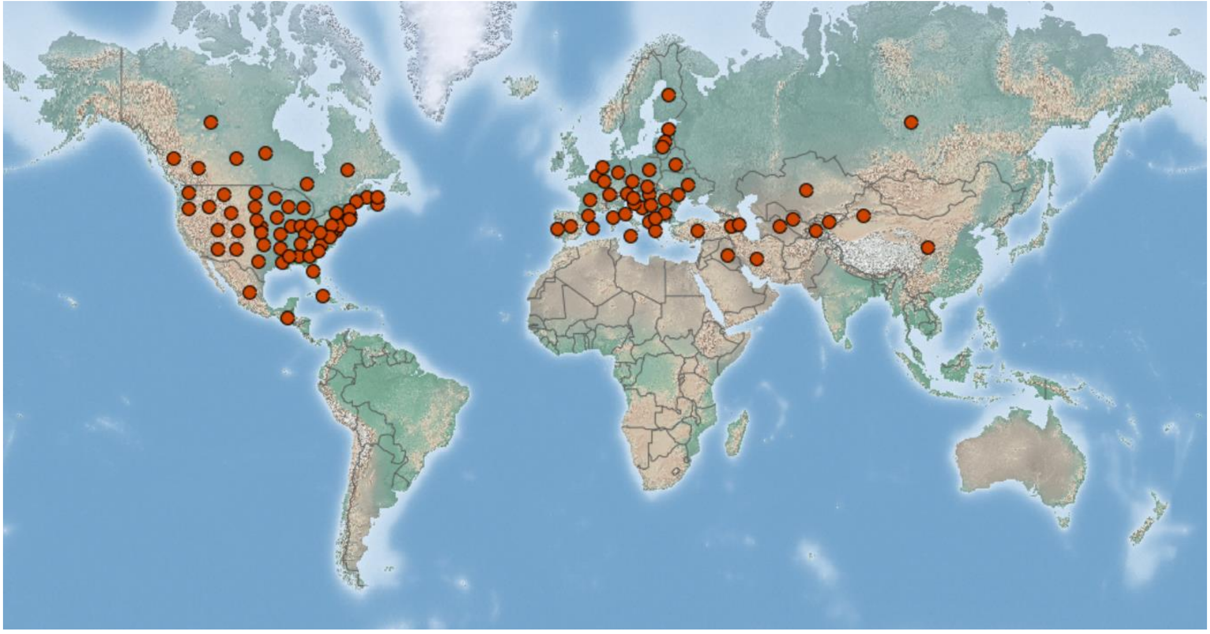
The pine processionary moth (*Thaumetopoea pityocampa*) native to the western Mediterranean basin (Kerdelhué et al. 2009). It is currently extending its distribution northwards and into higher elevations and breeds as far north as the Paris basin (Roques 2014). The species has a univoltine life cycle, with larvae that feed gregariously during winter on coniferous tree species. The main hosts are *Pinus* spp., in particular *P. nigra*, but the species can also attack other conifers such as *Cedrus* ssp. Adoption of new native and non-native hosts (*P. mugo*, *Pseudotsuga menziesii*) has been observed, although female host choice appears conservative (Stastny et al. 2006). The range expansion in pine processionary moth has been shown to be facilitated by an increase of winter temperatures, resulting in better thermal conditions for both female dispersal (Battisti et al. 2006, 2017), and for larval feeding activity in winter, the latter resulting in higher probabilities of winter survival (Battisti et al. 2005; Buffo et al. 2007; Robinet et al. 2007, Toigo et al. 2017). However, accidental human-mediated dispersal is likely to have contributed to the establishment of recent pioneer colonies north of Paris and in eastern France (Robinet et al. 2012).



Distribution map from: CABI, 2018. *Thaumetopoea pityocampa*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission.

6. Colorado potato beetle (*Leptinotarsa decemlineata*) Coleoptera: Chrysomelidae (Say 1824)

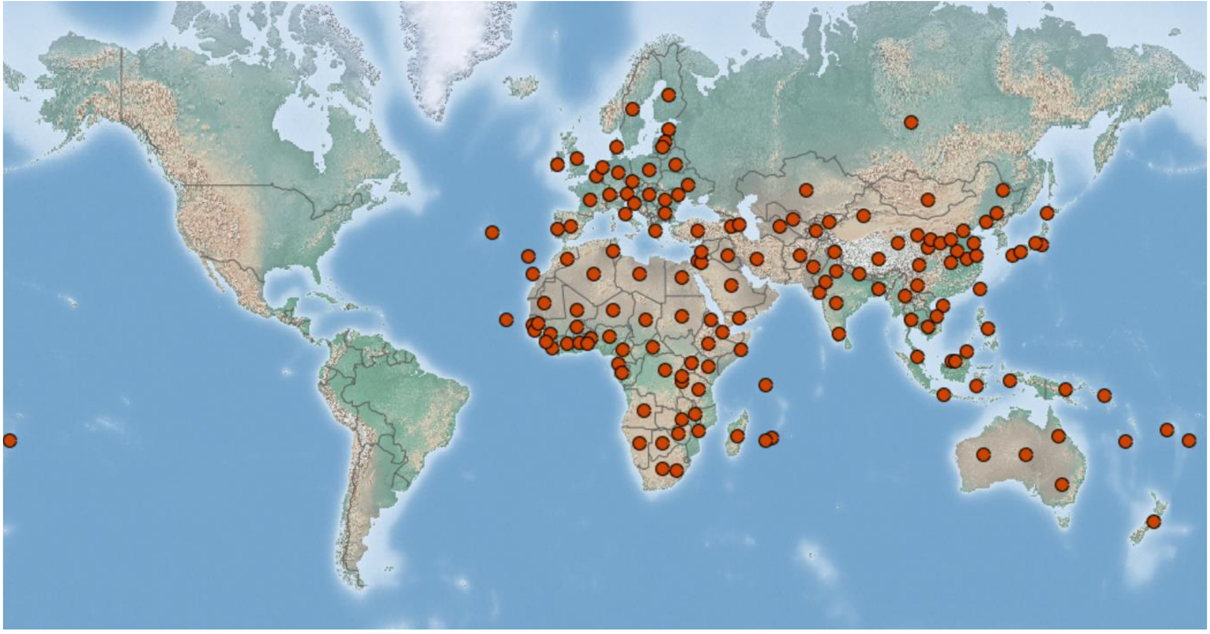
The major insect pest of cultivated potato is the Colorado potato beetle, *Leptinotarsa decemlineata*. This species has spread from native habitats in northern Mexico to cover a range of over 16M km^2 in North America, Europe and Asia (Alyokhin 2009). The species differs in voltinism and generation time across latitude (Hsiao 1985) and increasing mean temperatures associated with climate change have been observed to increase the range of *L. decemlineata* in temperate regions, due to ecological release of thermal constraints as well as a lengthening growth season (Boman et al. 2008, Valosaari et al. 2008, Lyytinen et al. 2009, Piiroinen et al. 2011, Lehmann et al. 2014, 2015). The species has been shown to be able to adaptively synchronize its life-cycle with novel environments (Danilevskii 1965). However, due to the low scale of potato cultivation at higher latitudes than the current range limit, net socioeconomic effects of range expansion might be negligible. Instead a larger socioeconomic impact might be seen at lower latitudes, where the species likely instead will increase in voltinism (Jönsson et al. 2013, Pulatov et al. 2016, Wang et al. 2017). Potential desertification at low latitudes (e.g. the Mediterranean region) is unlikely to constrain *L. decemlineata* since adults can aestivate over periods of harshness during summer (Tauber et al. 1986). In conclusion, as long as the host plant is cultivated, climate change is likely to have net positive effects on *L. decemlineata*, leading to an increase in socioeconomic impact of this important pest species.



Distribution map from: CABI, 2018. *Leptinotarsa decemlineata*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission.

7. Oriental migratory locust (*Locusta migratoria manilensis*) Orthoptera: Acrididae (Meyen 1835)

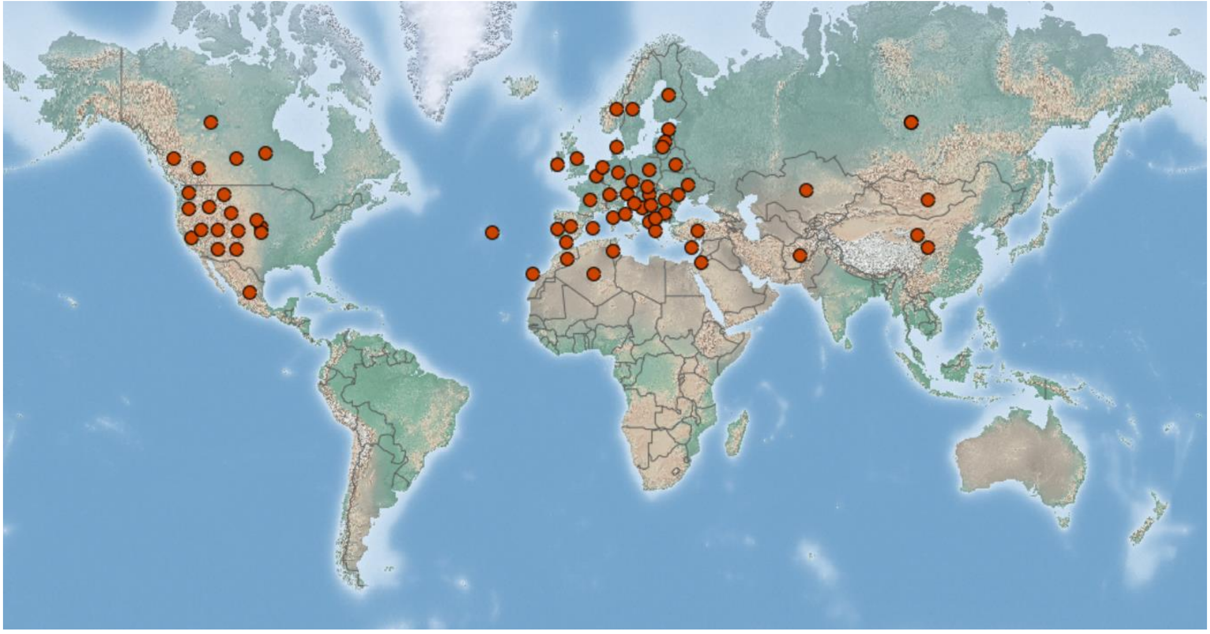
The migratory locust is an important polyphagous defoliator of crops occurring in a wide area across Africa, Asia, Australia, New Zeeland and occasionally in Europe (e.g. Brázdil et al 2014). Due to its large geographical range the species has been divided into a number of subspecies (see Chapuis et al. 2008). In Asia the primary subspecies is *Locusta migratoria manilensis*, sometimes referred to as *L. migratoria migratorioides*, a pest with a very long history in the region (Uvarov 1936). Indeed, the first records are over 3500 years old (Tian 2011). The species is generally quite harmless and exists in low-density populations along the coastal and sub-coastal regions. However, changes in local climatic conditions can rapidly cause locusts to shift into a high-density, gregarious, migratory phase, with profound negative impact on local ecosystems (Uvarov 1936). What triggers outbreaks is still a matter of debate, with on the one hand, warm temperatures and dry conditions (Ma 1958) and on the other hand, droughts/floods (Stige et al. 2007; Liu et al. 2008; Zhang et al. 2009, see also Brázdil et al. 2014 for an European example) suggested to act as outbreak triggers. Due to the long history of record-keeping in the region, Tian and colleagues (2011) correlated historical records of locust outbreaks in China with historical meteorological records and found that across a 1900-year period, outbreaks are positively associated with dry conditions and low temperatures. Since climate change scenarios in the region suggest increasing temperatures and a decreasing frequency of droughts and floods (Zhang et al. 2009) these findings suggest that net effects of climate change on the Oriental migratory locust are negative, with the pest decreasing in severity due to reduced outbreak frequency.



Distribution map from: CABI, 2018. *Locusta migratoria*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission.

8. Pollen beetle (*Meligethes aeneus*) Coleoptera: Nitidulidae (Fabricius 1775)

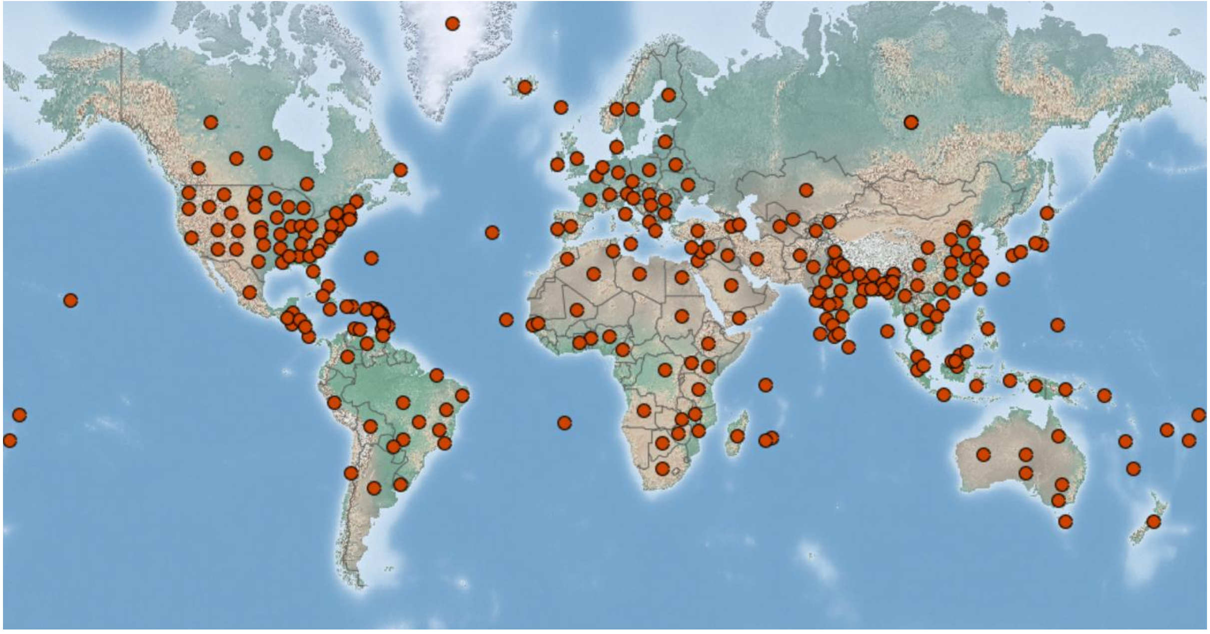
The rape beetle, *Meligethes aeneus* is a common beetle occurring in most of the Holarctic region (Alford 2003). It feeds on a range of naturally occurring plants, especially *Brassica* and *Sinapis* species where it is not considered particularly harmful (Alford 2003). However, since it also feeds on commercially grown rape crops, it might become a serious pest with a large regional economic impact. Populations of *M. aeneus* are generally univoltine, and adults overwinter in woodlands (Tiilikainen and Hokkanen 2008). Rape is one of the most important crop plants in Europe with a total production volume of 19 x 10^6 tonnes grown during 2010-2011 in the EU (Coyette et al. 2012). An increasing utilization of rape has led to the development of winter hardy high latitude variants which can be found in northern Europe (Mäkelä et al. 2011). Increasing the growing areas of rape crops has also resulted in positive effects on *M. aeneus*, which has increased in abundance in concert with its host plant (Tiilikainen and Hokkanen 2008). In case populations are not controlled, yield losses in commercial rape crops can be up to seventy percent (Nilsson 1987). Populations of *M. aeneus* are widely controlled both through biological (Veromann et al. 2006), and more commonly, chemical means (Smatas et al. 2012). Chemical management is complicated by high levels of pesticide resistance (Tiilikainen and Hokkainen 2008; Smatas et al. 2012) which is exacerbated by host shifts of *M. aeneus* individuals from commercially grown rape crops to wild relatives (Hokkanen 2000). The shift of host plants can increase spatial heterogeneity and contribute to the maintenance of large potential genetic variation in the populations. The effect of climate change is difficult to estimate in *M. aeneus* since this univoltine species already has a more northern distribution than its crop host plants. Therefore climate change effects will likely act indirectly as warming affects the range of its host plant if rape is going to be cultured at higher latitudes and in larger areas. According to Bebber et al. (2013) *M. aeneus* has not shifted or enlarged its range during the last 60 years; however its severity has increased, primarily through an enlargement of host plant planting areas and increasing pesticide resistance (Tiilikainen and Hokkainen 2008; Smatas et al. 2012). According to Hakala et al. (2011) climate change might make cultivation of different rape variants possible even above the Arctic Circle (65°N). If this is the case, *M. aeneus* most likely will transition along with its host, and further increase in severity as pest. A similar scenario has been outlined for the bean beetle *Cerotoma trifurcata*, where it is the response of the primary host, *Glycine max*, to climate change, that will determine the changes of the pest as well (Berzitis et al. 2014).



Distribution map from: CABI, 2018. *Meligethes aeneus*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission.

9. The diamondback moth (*Plutella xylostella*) Lepidoptera: Plutellidae (Linnaeus 1758)

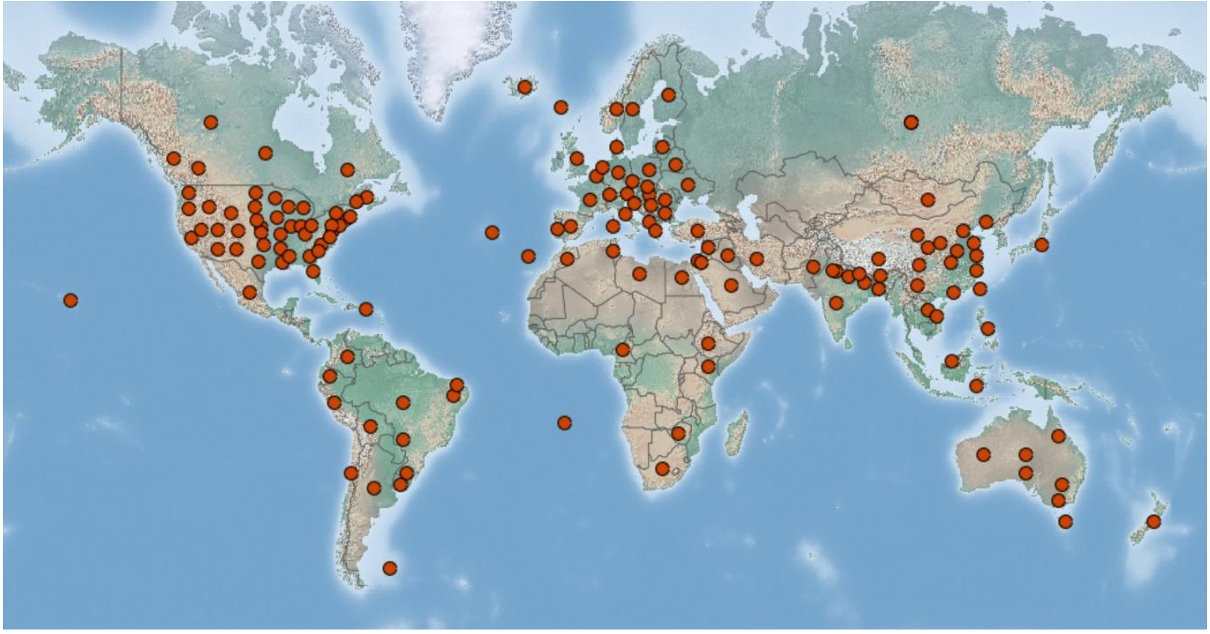
The diamondback moth (*Plutella xylostella*) has an European origin, but has now spread all over the world where its Brassicaceae hosts are cultivated or it can feed on native Brassicaceae plants (Talekar & Shelton 1993). This microlepidopteran starts its lifecycle as a leaf miner in the first two instars, after which it is a free-moving defoliator. The larvae cause severe damage on flowers, leaves, buds and seed pods (siliquae) when numerous and management costs are estimated to be between 4 and 5 billion USD per year (Zalucki et al. 2012). The diamondback moth is the first crop pest known to have developed resistance against DDT. It is also the first insect known to develop resistance against biological control by Bt toxin (*Bacillius thuringiensis*) (Shelton et al. 1993, Talekar & Shelton 1993). The thermal developmental range is very wide (4-37°C) and in the tropics and subtropics the diamondback moth occurs throughout the year (Zalucki et al. 2011; Li et al. 2012, Marchioro & Foerster 2012; Nguyen et al. 2014, Li et al. 2016). The number of generations is dependent on temperature and varies from 4 in the northern latitudes to 12 in the south. The high number of generations has probably influenced the development of resistance. Migration and southern air currents allow the species to be found all the way up to Svalbard (Coulson et al. 2002) and yearly migration (exceeding 3000 km) allows for growing season invasions in areas too cold during the winter while the moth overwinters in more southern areas (Dosdall et al. 2001; Chapman et al. 2002; Gu, 2009; Wei et al. 2013). Drought has a positive effect on the diamondback moth survival (Talekar, Lee & Huang 1988; http://eap.mcgill.ca/CPCM_3.htm). While a modeling study suggested an increase in voltinism over time in several replicated locations at the northern range limit of the species with increasing temperature (Collier et al. 2008), a similar study at tropical latitudes suggested more variable, both severity increasing and decreasing effects (Ngowi et al. 2017).



Distribution map from: CABI, 2018. *Plutella xylostella*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission. Reviewed by: Rana M. Sarfraz, Department of Zoology, Biodiversity Research Centre, The University of British Columbia, 4200-6270 University Blvd., Vancouver, British Columbia, Canada V6T 1Z4

10. Bird cherry oat aphid (*Rhopalosiphum padi*) Hemiptera: Aphididae (Linnaeus 1758)

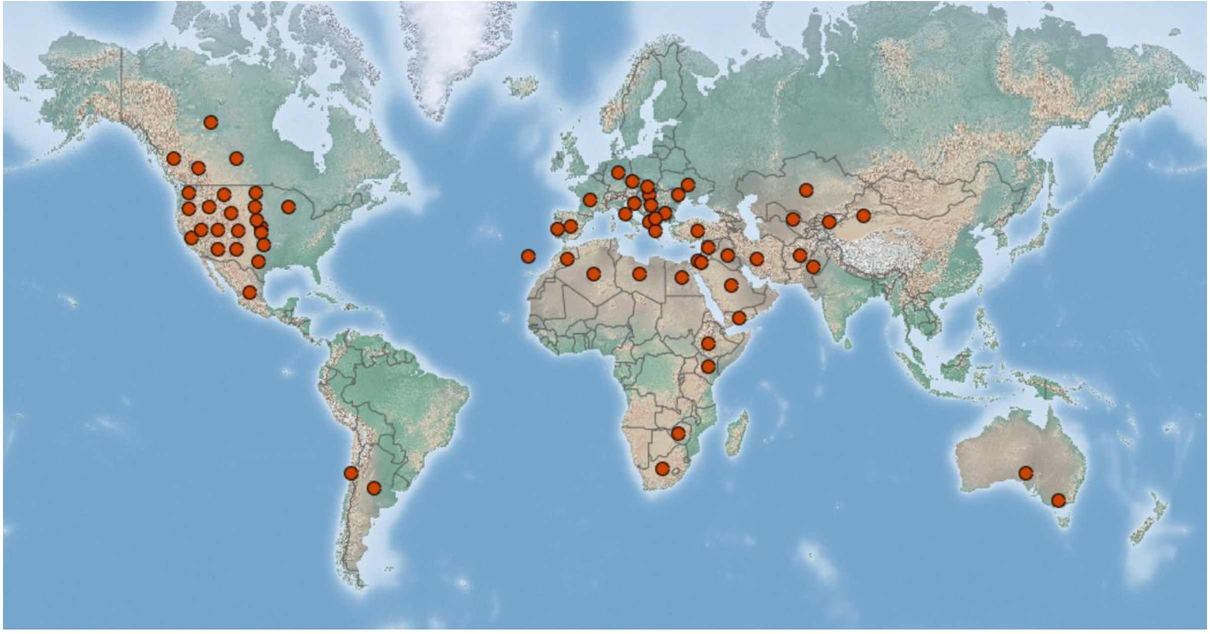
The bird cherry oat aphid *Rhopalosiphum padi* is a principal pest and vector of *Barley yellow dwarf virus* in wheat and other cereals in UK, NA, Europe, but also attacks other plant species. The species is thought to have originated in North America (Halbert & Voegtlin 1998), but now has a cosmopolitan distribution. It is one of the 14 most important aphid species worldwide because of its impacts on globally significant staple grasses. As a result it has been extensively studied on various aspects of its biology. Across this range it is primarily heteroecious holocyclic with the predominant primary host *Prunus padus* or other *Prunus* species, but where winters are mild and primary hosts rare, it is anholocyclic, moving from wild grasses to cultivated cereals (Williams and Dixon 2007). Its pest status is amplified in some regions where it is a vector of viruses affecting noncereals, potato, where its transient movements and transient feeding makes is a vector for Potato virus Y (Katis and Gibson 1985). Outside of cropping systems, the ecological impact of the bird cherry oat aphid is likely minimal. Nonetheless as a vector of cereal yellow dwarf viruses, it contributes to complex interactions among competing grasses, including invasive and native ones (Malmstrom et al. 2006). In many areas, these viruses can readily be found in perennial grasses (Ingwell et al. 2012) with implications for the functioning of these systems. Potentially, the bird cherry oat aphid could respond to climate change directly, due to the constraints of its optimal thermal range and indirectly due to changes in the quality of its host plants under climate related stress, or changes in its natural enemy complex. Finally, climatic conditions could influence the bird cherry oat aphid as a vector of viruses. As is true for most aphid species (Awmack and Leather, 2007), increases in temperature accelerates development and the potential number of generations that can be achieved within a single growing season. A number of laboratory studies have delineated the temperature envelope for the bird cherry oat aphid (reviewed in Finlay and Luck 2011). There appears to be an optimum near 26°C, above which development is retarded and below which it declines to around 10°C. Developmental thresholds range between 4° and 6°C. Thus, as climates in particular regions warm, as is generally projected, the aphid could exhibit extended seasons of viability and more rapid growth where lower temperatures are currently limiting, and reductions where higher temperatures are limiting. Since there is considerable variation among clones of bird cherry oat aphid that have been investigated in the laboratory (e.g. Valenzuela et al. 2008), the potential responses to climate trends are difficult to project. Despite several laboratory studies of bird cherry oat aphid responses to climatic drivers, and the significance of this aphid as a pest worldwide, there are few studies and no evidence that its populations respond to documented trends in temperature or other drivers (Newman et al. 2003; Hoover and Newman 2004, but see Andrade et al. 2016). In the Pacific Northwest of the USA, a network of 28 suction traps acquired extensive data on flights and inferred abundance of bird cherry oat aphid abundances over a 17-year trapping period. Interannual abundance exhibited evidence for biotic feedback, but was unrelated to trends or variability in temperature and precipitation throughout the sampled period (Davis et al. 2014). In Sweden, trends in temperature and precipitation explained a small amount (1-9%) of the variation in abundance of bird cherry oat aphids from four trap locations over a 20-year period and do not support any robust projections of responses of the aphid to climate trends (Bommarco et al. 2007). Long-term data sets do not exist for the bird cherry oat aphid in other regions or have not been analyzed. Although climate related stress on the first and higher trophic levels could affect populations of the bird cherry oat aphid, current data do not allow robust projections about the effects of climate change on the bird cherry oat aphid (Newman et al. 2003; Hoover and Newman 2004; Finlay and Luck 2011, but see Andrade et al. 2016 and Wade et al. 2017).



Distribution map from: CABI, 2018. *Choristoneura fumiferana*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission.

11. Russian wheat aphid (*Diuraphis noxia*) Hemiptera: Aphididae (Kurdjumov 1913)

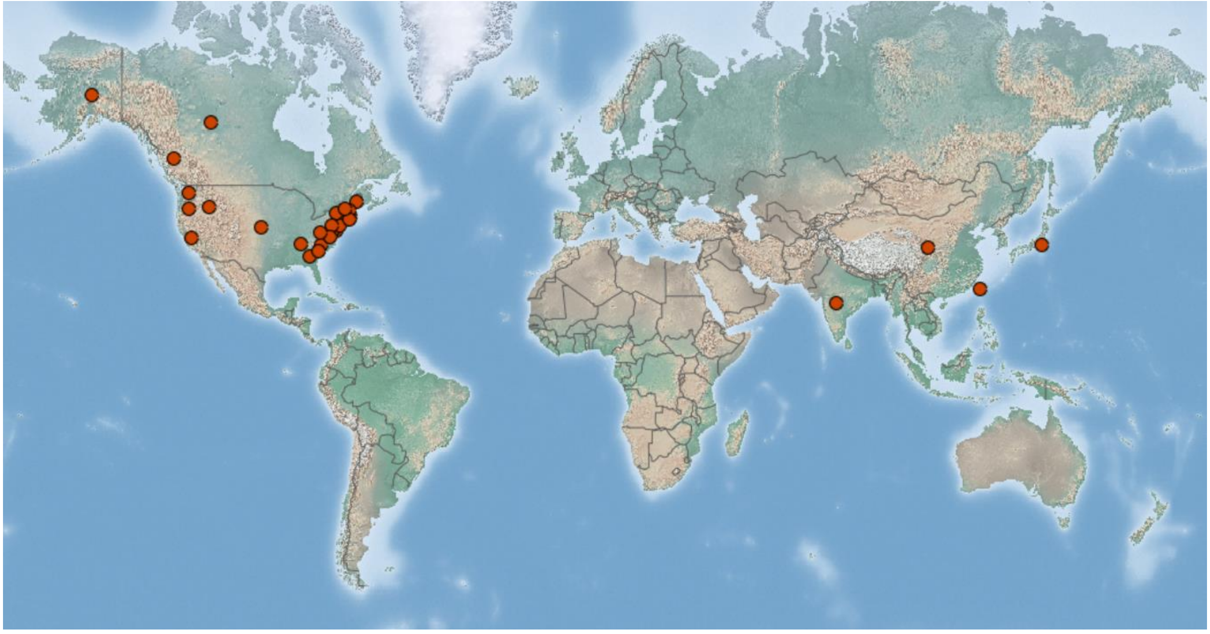
This aphid is a pest of wheat in North America, Africa, and Eurasia, Central Asia, Middle East, North Africa, Kenya, South Africa, Chile, Argentina, North America (first record 1986, Shufran et al. 2007) and South America (first records for Chile 1988, Argentina 1992; Clua *et al.* 2004). The species is well studied because of its global distribution and potential for causing significant direct injury to wheat and other cereal crops. The species impact on natural systems is probably minimal. Potentially, *Diuraphis noxia* could respond to climate change directly, due to the constraints of its optimal thermal range and indirectly due to changes in the quality of its host plants under climate related stress, or changes in its natural enemy complex. The species is relatively well studied because of its global distribution and potential for causing direct injury to wheat and other cereal crops. This has included assessments of its development and mortality under varying thermal regimes (Michels and Behle 1988), which appeared to show reproductive an optimum at a relatively cool 20°C (see also Scott and Yeoh, 1999). Thus, like other aphid species responses to warming trends will likely be complex and dependent upon baselines. There are few long-term data sets that could be used to develop projections of *D. noxia* responses to climatic drivers. In the Pacific Northwest of the USA, a network of 28 suction traps acquired extensive data on flights of *D. noxia* abundances over a 17-year trapping period. Interannual abundance exhibited evidence for biotic feedback, but in addition populations of the aphid were negatively correlated with increasing temperatures during the sampled period in the absence of density-dependent effect (i.e., considering residuals after accounting for feedbacks) (Davis et al. 2014). Coupled with the relatively cool documented temperature optimum for this species (Michels and Behle 1988), this suggests warming trends would be associated with reduced abundance and therefore pest pressure from *D. noxia,* although this inference has not been fully substantiated. However, in Australia, a CLIMEX modeling approach suggested high suitability of dry inland wheat growing regions would be highly favorable for *D. noxia* infestation (Hughes and Maywald, 1990). Therefore, responses are likely to vary locally.



Distribution map from: CABI, 2018. *Diuraphis noxia*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission. Reviewed by: Mohammad Reza Nematollahi, Assistant Professor of Entomology, Department of Plant Protection, Isfahan Research Center for Agriculture and Natural Resources, Isfahan, Iran.

12. Hemlock woolly adelgid (*Adelges tsugae*) Hemiptera: Adelgidae (Annand 1928)

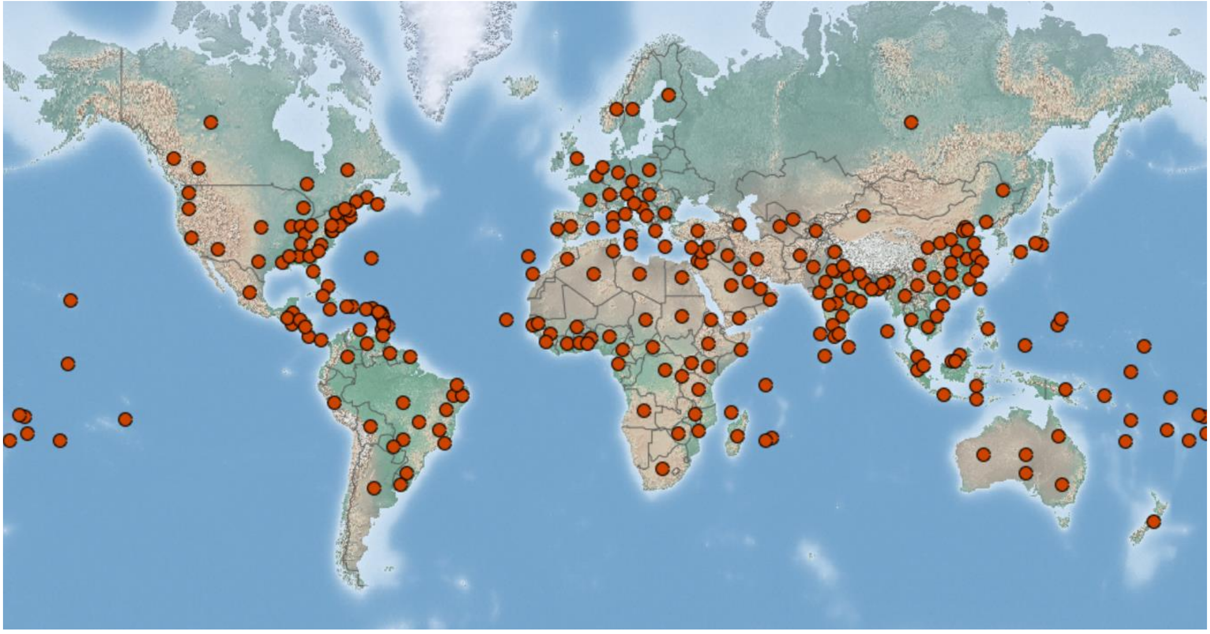
The hemlock woolly adelgid (*Adelges tsugae*) is endemic to Eastern Asia and became a pest on the eastern hemlock (*Tsuga canadensis*) in N. America, causing extensive tree mortality in natural forests. It has extended its distribution range into north-eastern USA from the site of introduction in Virginia (Evans and Gregoire, 2007; Paradis et al., 2008). The limiting factor is winter temperature, which can be lethal for the overwintering stages (Paradis et al., 2008). With the increase in mean minimum winter temperature accompanying climate change, the aphid has progressively expanded to the north and simultaneously built up high densities in the already colonized areas, contributing greatly to hemlock dieback (Fitzpatrick et al., 2012, Leppanen & Simberloff 2017, McAvoy et al. 2017). In this view, the temperature-dependent spreading occurs from the south to the north, leaving behind dead trees on which the insect cannot persist. However, there are indications that at the southern edge of the range the young nymphs suffer increased mortality because of summer heat, allowing the trees to survive (University of Georgia, personal communication).



Distribution map from: CABI, 2018. *Adelges tsugae* (original text by National Biological Information Infrastructure (NBII) & IUCN/SSC Invasive Species Specialist Group (ISSG)). In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission.

13. Sweet potato whitefly or Silverleaf whitefly (*Bemisia tabaci*) Hemiptera: Aleyrodidae (Gennadius 1889)

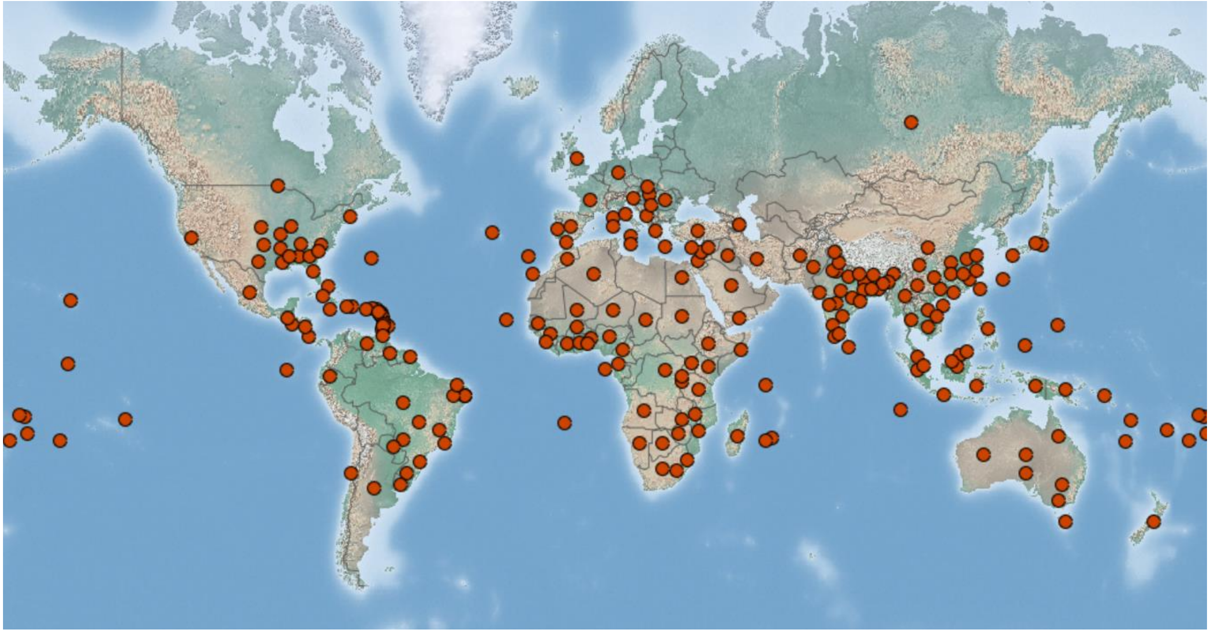
Although *Bemisia tabaci* is now recognized as a probable species complex (De Barro et al. 2011), collectively the group includes significant pests, including two species (now referred to as MEAM1 and Med) that are serious pests in the tropics and subtropics worldwide. Other members of the complex are regional pests. The pests cause direct injury and act as vectors of viruses affecting several important tropical crops, including cassava. The ecological impact of these species is little studied. As vectors of several plant viruses, they could affect natural communities and otherwise contribute to the stability of foodwebs. The general expectation for the Sweet potato whitefly is an expansion of range northward with warming, which would exacerbate its importance as a pest worldwide. This would presumably be most important in more temperate zones where its range could be currently constrained by cooler temperatures. In Europe, where Bemisia is currently confined to southern coastal environments, expansion of the pest northwards is thought to be prevented by lower temperatures. A process-based modeling exercise, with inputs from the extensive literature on the life history of the species and hypothetical uniform temperature changes of 1°C and 2°C project range expansions of *B. tabaci* into northern Spain, central France, Italy, Greece and along the Adriatic coast of the Balkans, but not into northern parts of Europe (Gilioli et al. 2014). Similar patterns are possible in other temperate regions (e.g. Zidon et al. 2016). Ongoing studies are examining responses to temperature and CO_2 increases have detected constraints at higher temperatures (between 28°C and 33°C) (Curnutte et al. 2014), which may indicate reductions in pressure from the Sweet potato whitefly in certain regions as temperatures increase. These inferences pertain to the Sweet potato whitefly species that have been most widely studied. It is possible that other species within the complex and almost certain that other *Bemisia* species will respond differently to changing climate.



Distribution map from: CABI, 2018. *Bemisia tabaci*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission. Reviewed by: Andrew Cuthbertson, Food and Environment Research Agency, Sand Hutton, York, UK

14. Southern green stink bug (*Nezara viridula*) Hemiptera: Pentatomidae (Linnaeus 1758)

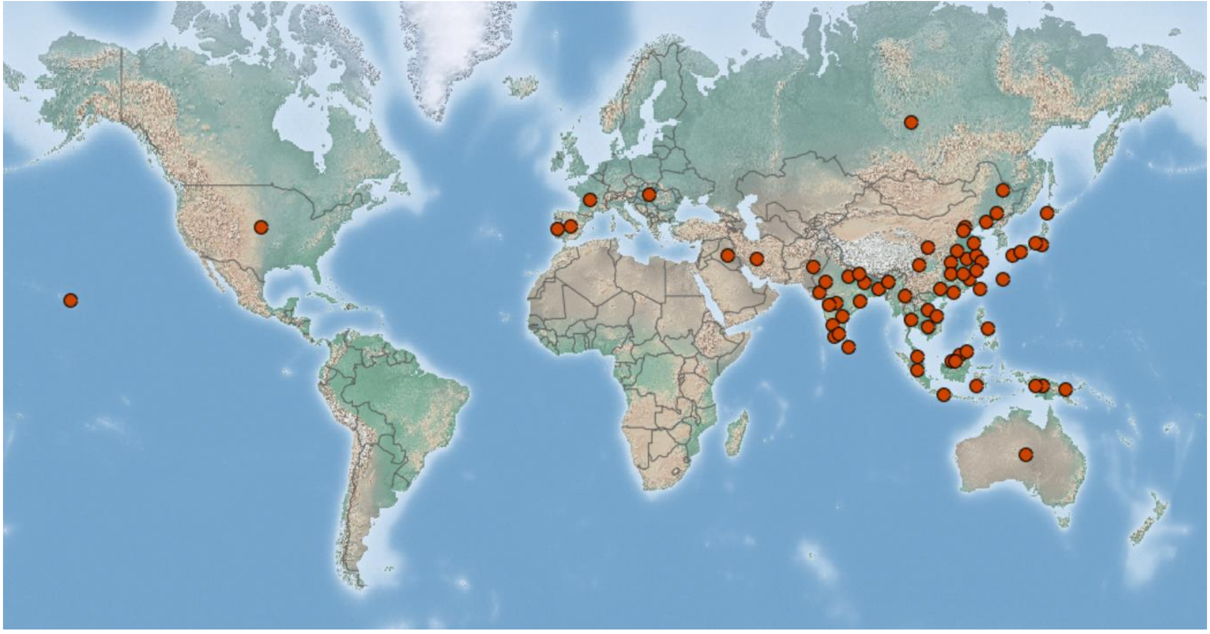
The southern green stink bug (*Nezara viridula*) is a cosmopolitan pest of fruits and seeds, especially on herbaceous crops, with multiple generations per year and overwintering as an adult in a number of shelters, including buildings where it can become a nuisance. In Japan *N. viridula* is progressively occupying areas located outside the historic northern edge of the range, because of more favourable winter temperature for the adults (Musolin and Saulich 2012). Interestingly, the expansion has resulted in a displacement of a native bug of the same genus (*N. antennata*) (Tougou et al. 2009). Laboratory studies reveal a sensitivity to thermal conditions during development, with higher temperatures leading to an increase in development rates and higher voltinism, though these responses were coupled with increased adult mortality (Musolin et al. 2010). It is therefore difficult to predict how warming temperature will affect the phenology, voltinism and survival of *N. viridula* in the field (Panizzi & Lucini 2016).



Distribution map from: CABI, 2018. *Nezara viridula*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission.

15. The Asiatic rice borer (*Chilo suppressalis*) Lepidoptera: Crambidae (Walker 1863)

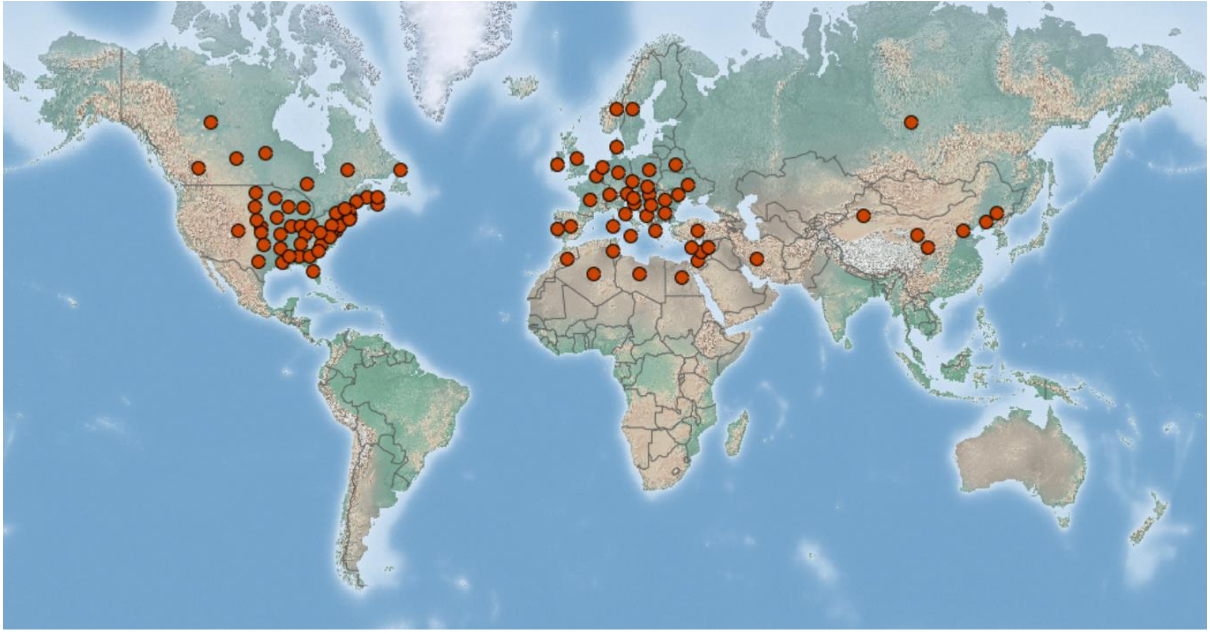
The Asiatic rice borer, *Chilo suppressalis*, is a widely distributed and serious pest of rice. It occurs in large parts of the world but the main area is East Asia. Accidental introductions into Australia, North America, Hawaii and Europe have been observed but there are yet no records from Africa (Bleszynski 1970, Waterhouse 1993). Under favourable conditions the borer can have up to six generations per year but two is most common. The cold hardiness of the larvae seems to be independent of the diapause state of the insect (Lu et al. 2013), indicating that climate-induced changes in the life cycle will not lead to decreased risks for damage. The heat tolerance of the species is generally high and is better among larvae than adults, which translates into effects especially on fertility and less on survival (Lu et al. 2014). Analysis of 50-year annual light trap data from Japan indicates an increase in trap catches in years following winters with increasing temperatures (Yamamura et al. 2006). However, it is unlikely that climate warming will bring *C. suppressalis* back to its former pest status that peaked in the 1950's and early 1960's in Japan (Kiritani 2006). Observed increase in damage in later years in a closely related rice borer, *Tryporyza incertulas*, corroborates the findings of Yamamura et al. (2006) and has been attributed to warmer winters but also changes in cropping systems and cultivation practices together with decreased parasitism are considered to be of importance (Sun et al. 2003).



Distribution map from: CABI, 2018. *Chilo suppressalis*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission.

16. The European corn borer (*Ostrinia nubilalis*) Lepidoptera: Crambidae (Hübner 1796)

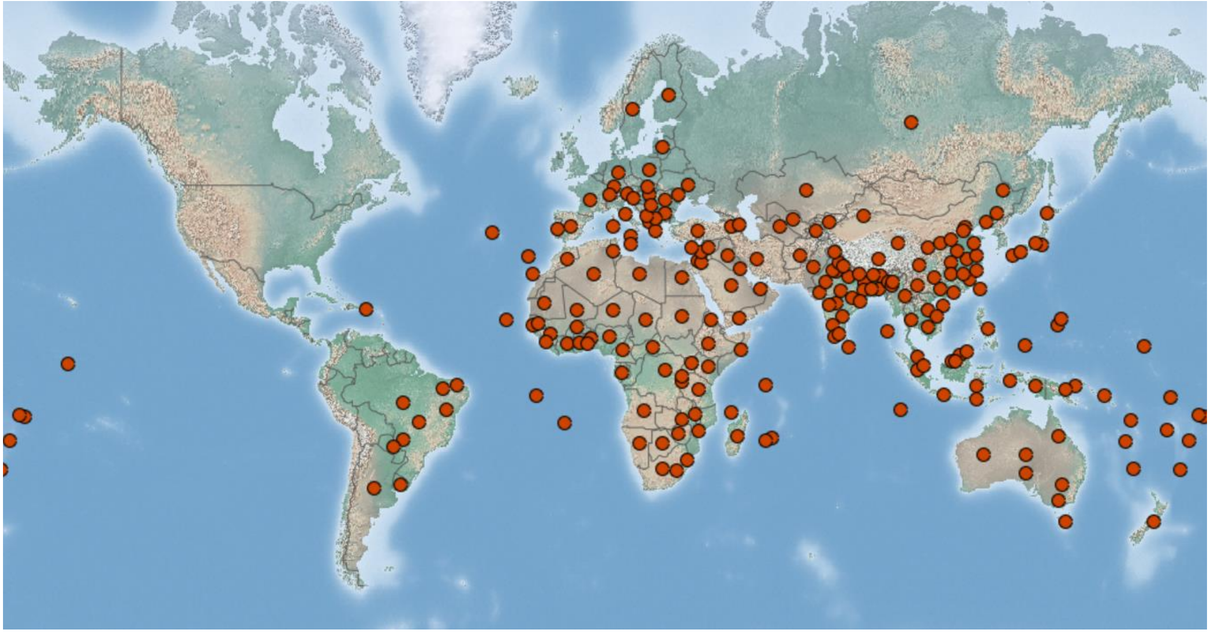
The European corn borer, *Ostrinia nubilalis*, is one of the most important pests on corn but cause damage also in potato and cotton. Its main distribution is in Europe, North America and some parts of northern Africa. In northern regions it has one generation per year but may have more than two in warm areas (Showers 1981, 1993). The ecological impact of *O. nubilalis* may be indirect and 'positive'; an increased use of Bt-resistant GM-corn reduces the need for insecticides but the positive effect may be reversed and worsened if the pest develops resistance to Bt and non-target organisms are hit (Medvinsky et al. 2004; Speiser at al. 2013). The development and voltinism of *O. nubilalis* seems to be particularly sensitive to climatic conditions (Onstad and Brewer 1996), making it suitable to use in climatic modeling efforts (Svobodova et al. 2014). However, the outcome of modeling efforts may vary considerably (Maiorano 2012). The directly observed evidence of a climatic response include observations from Czech Republic of a sudden increase in infestation during the unusually warm period 1991-2000 (Trnka et al. 2007). In addition, analysis of light trap data from Hungary indicates an increase in number and damage, probably partly as a consequence of the appearance and spread of a bivoltine strain, connected to warming (Radin 1990; Keszthelyi 2010). A trend for decreasing damage during a cold period during the 1960's in Minnesota was broken in the warm year 1970 when the highest population densities since the peaks in early 1950's were observed (Chiang and Hudson 1972). Further, in a series of experiments, Xiao et al. (2017) were able to link poor spring performance to warm winter climates, indicating that future warming could have negative effects on this pest, this however remains unsubstantiated in the field.



Distribution map from: CABI, 2018. *Ostrinia nubilalis*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission.

17. The Cotton bollworm (*Helicoverpa armigera*) Lepidoptera: Noctuidae (Hübner 1808)

The Cotton bollworm, *Helicoverpa armigera*, is a polyphagous pest causing damage on 200 plant species. It is a cosmopolitan pest mainly occurring in central and southern Europe, temperate parts of Asia, Africa Oceania, and Australia and has recently invaded South America (Kriticos et al. 2015). Beyond its present range, as a migrant, in Europe, it may reach northern regions where it cannot overwinter at present climatic conditions outdoors but still causes severe damage, particularly in glasshouses (Smith 1999). The damage in some core areas, such as India, has shown a general decline (Dhaliwal et al. 2010) but increases in damage has also been observed, as in for instance Japan (Kiritani 2006). The density and damage of the species have been observed to increase in later years in China (after analyzing the period 1975 – 2011) due to increased temperature, declining rainfall and agricultural intensification (Lu et al. 2013), resulting in weakened negative density dependence, in turn, leading to the population equilibrium increasing to a higher level (Ouyang et al. 2014, 2016). In Hungary *H. armigera* was first observed in 1993 and had by 2001 spread over 94 % of the country; the spread – and the level of damage – seems to be connected to moderately dry and warm weather conditions (Keszthelyi 2013). In Australia, a series of studies suggest that rainfall, rather than temperature is the major driver of population dynamics during summer, with early winter rainfall exerting positive and spring rainfalls negative effects on *H. armigera* and *H. punctigera* summer population sizes (Maelzer et al. 1996; Maelzer and Zalucki, 2000, Zalucki and Furlong, 2005).



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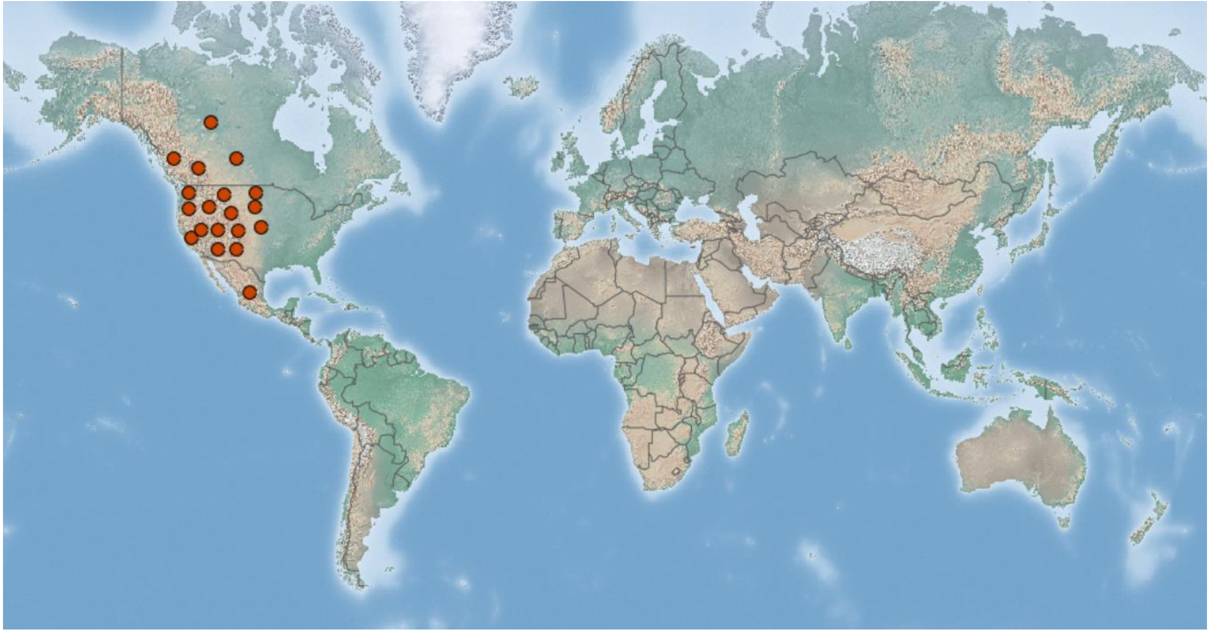
18. Mountain pine beetle (*Dendroctonus ponderosae*) Coleoptera: Curculionidae (Hopkins 1902)

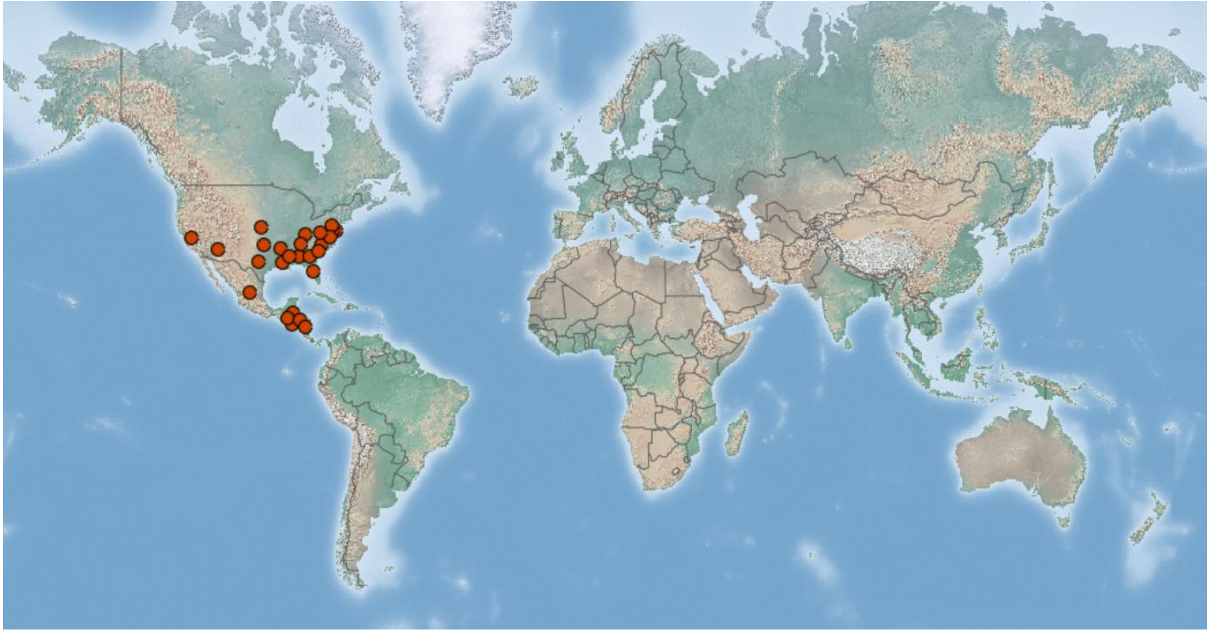
The Mountain pine beetle, *Dendroctonus ponderosae*, is the most destructive insect pest of lodgepole pine (*Pinus contorta*) and other pine forests in the mountains of western North America. During the last decades vast Mountain pine beetle outbreaks have destroyed millions of hectares of pine forests in USA and Canada. The species has generally one generation per year at low elevations and the generation time is one or two years at high elevations (Bentz et al., 2014). Changing climate affects Mountain pine beetles at least in three main ways: 1) summer temperatures affect the timing of life history events which is important for the phenological synchrony of adult emergence – a necessary condition for mass attacks; 2) cold winter temperatures cause high mortality of overwintering beetles in some areas but not in all (Weed et al. 2015); 3) there are also indirect effects of weather on Mountain pine beetle dynamics via different mechanisms, especially via drought-altered changes in the defensive capacity of host trees. There appears to be genetic variability among Mountain pine beetle populations in their sensitivity to weather factors. Degree days required for the development of one generation are clearly less in populations living in cooler than warmer locations (Bentz et al., 2011). At higher summer temperatures populations at the warmer edge of the distribution mostly remain univoltine, but in the north the generation time shortens from two years to one, which increases the growth rate of these populations. At the cooler edge of its distribution, increasing winter temperatures (decreased winter mortality) also have facilitated range expansion northwards and to higher elevations than recorded previously. Due to this climatically driven range expansion, Mountain pine beetle encounters naïve (and less well defended) host populations and species (Cudmore et al., 2010; Raffa et al., 2013). There is also concern about the potential for the Mountain pine beetle to expand its range over the jack pine forests of central and eastern North America. Modeling work, however, suggests that the probability of this remains low to moderate during this century (Benz et al., 2010, 2016).



Distribution map from: CABI, 2018. *Dendroctonus ponderosae*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission.

19. Southern pine beetle (*Dendroctonus frontalis*) Coleoptera: Curculionidae (Zimmermann 1868)

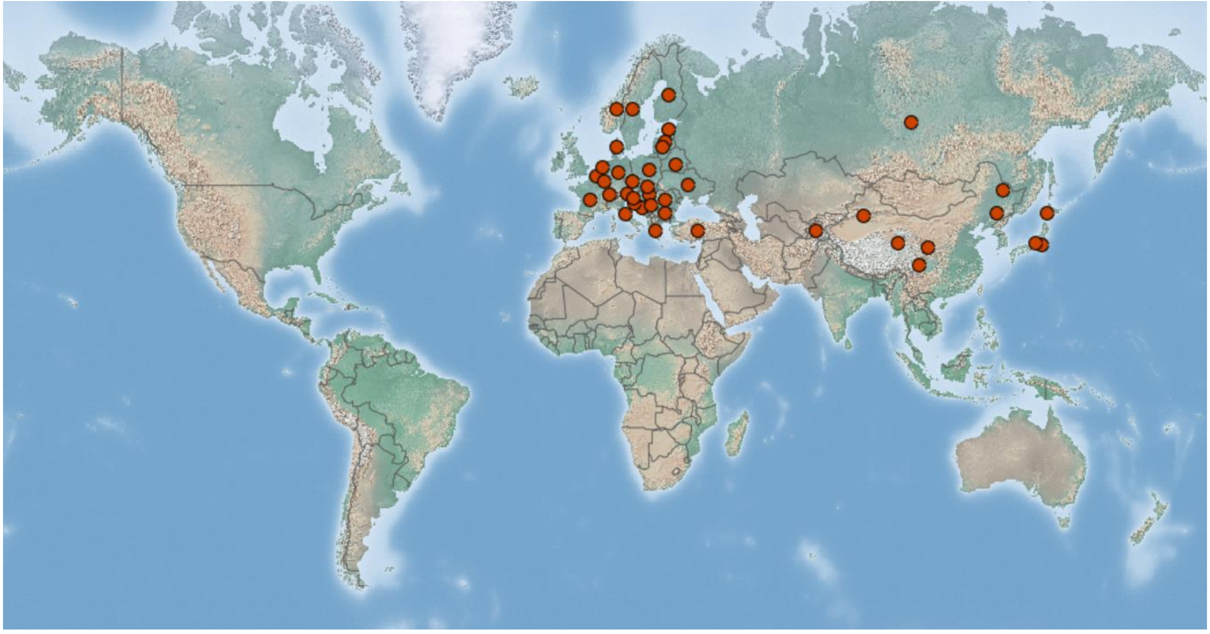
The southern pine beetle, *Dendroctonus frontalis* Zimmermann, is the economically most important pest insect of pines (primarily loblolly, *Pinus taeda,* and shortleaf, *P. echinata*, pines) from Central America to southern USA. Most of the time the Southern pine beetle lives on trees weakened or damaged by e.g. lightning strikes, storms or diseases, but during occasional outbreaks (normally lasting 2-3 years) these beetles can kill thousands of healthy pines. The annual economic losses due to the Southern pine beetle can exceed $200 million in US. Depending on temperature the Southern pine beetle can have from one to nine generations per year. The relationships between climatic variables and Southern pine beetle outbreaks are complex and these may interact with other environmental effects and management activities (McNulty et al., 1997; Gumpertz et al., 1999; Ungerer et al., 1999; Williams & Liebhold 2002; Gan, 2004; Tran et al. 2007; Friedenberg et al, 2008; Duehl et al., 2011, Marini et al. 2017). The most important factor limiting the northern distribution limit of Southern pine beetle outbreaks is minimum winter temperatures, as air temperatures of -16^{o}C cause almost total mortality of the Southern pine beetle. Recently, Southern pine beetle outbreaks have been observed in New Jersey and even further north, of the historical outbreak range (Weed et al. 2013, Dodds et al. 2018). As climate warms further, the outbreak range is predicted to increase to large areas in northeast USA and southern Canada (Lesk et al. 2017).



Distribution map from: CABI, 2018. *Dendroctonus frontalis*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission.

20. Eurasian spruce bark beetle (*Ips typographus*) Coleoptera: Curculionidae (Linnaeus 1758)

The Eurasian spruce bark beetle (*Ips typographus*) is a major insect pest of spruce forests in Europe and some regions in Asia, mass-attacking and killing spruces over extensive areas during outbreaks (Grégoire and Evans 2004, Økland et al. 2012). More frequent extreme damages and drier and warmer summer climate may trigger both population growth and susceptibility of spruce stands to attack (Økland & Bjørnstad 2006, Marini et al. 2012, Netherer et al. 2015). In northern areas, global warming may increase the productivity of host trees and indirectly the beetle populations due to more access to breeding substrates and enhanced conditions for flight and attacks. A warmer climate is expected to give a northern expansion of the area experiencing two generations per year (Lange et al. 2006, Jönsson et al. 2012), and more cases of bivoltinism have been observed in Finland and southern Scandinavia during the last years (Pouttu & Annila 2010). There have been few bark beetle outbreaks in the extensive areas of spruce forest in Finland and the northern part of Scandinavia, but increasing bark beetle populations and infestations have been reported in these areas during warm years in the last decades (Økland et al. 2009). Increased frequency of drought periods due to global warming may extend the areas of bark beetle infestations in Southern and Central Europe, since lower than average precipitation seems to generally favour bark beetle infestations at the southern margin of the spruce distribution in Europe (Marini et al. 2012, Netherer et al. 2015). While the optimal areas for spruce are in northern Europe and the mountain ranges of Central Europe, even-aged plantations outside the natural range of Norway spruce are highly susceptible to disturbance events such as wind throw and bark beetle attacks.



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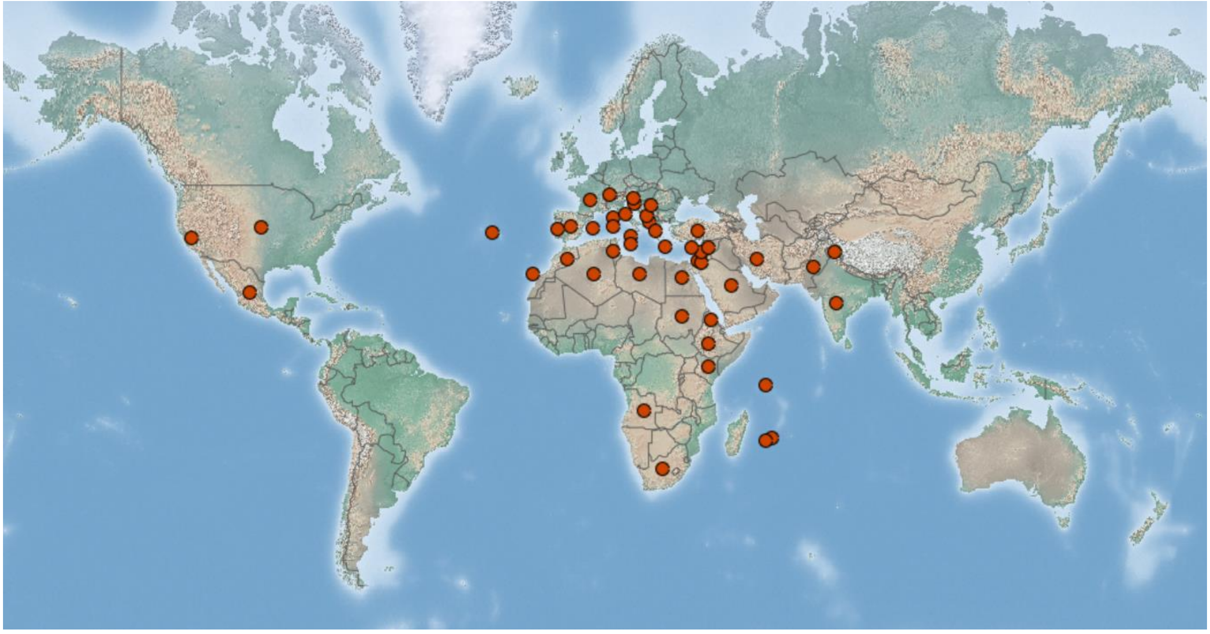
21. Olive fruit fly (*Bactrocera oleae*) Diptera: Tephritidae (Rossi 1790)

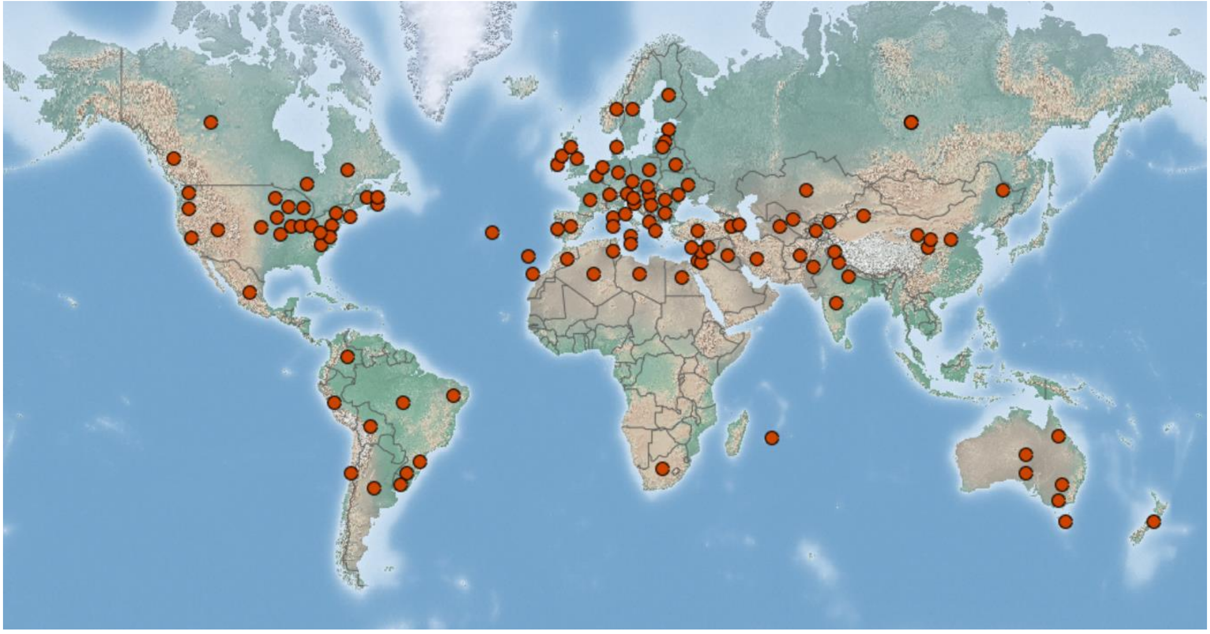
Bactrocera oleae is a specialized fruit feeder associated with the olive tree (*Olea europaea*) in most of its cultivation range. It is active all year long, depending on temperature and availability of fruits, with multiple generations. Gutierrez et al. (2009) suggest that the range of the olive fly will retract in the south and expand in the northern part of the range, both in North America and Europe, due to the effect of high temperature during summer and milder winter on the adult flies, respectively. Ponti et al. (2014) predict that in the Mediterranean region the damage of the pest will change dramatically in the near future as a consequence of climate change, with large socio-economic impacts on farmers. This effect was documented by Marchi et al. (2016) using a 13 year dataset from central Italy, suggesting that mild winter temperature is the main driver of high infestation rates.



Distribution map from: CABI, 2018. *Bactrocera oleae*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission.

22. Codling moth (*Cydia pomonella*) Lepidoptera: Tortricidae (Linnaeus 1758)

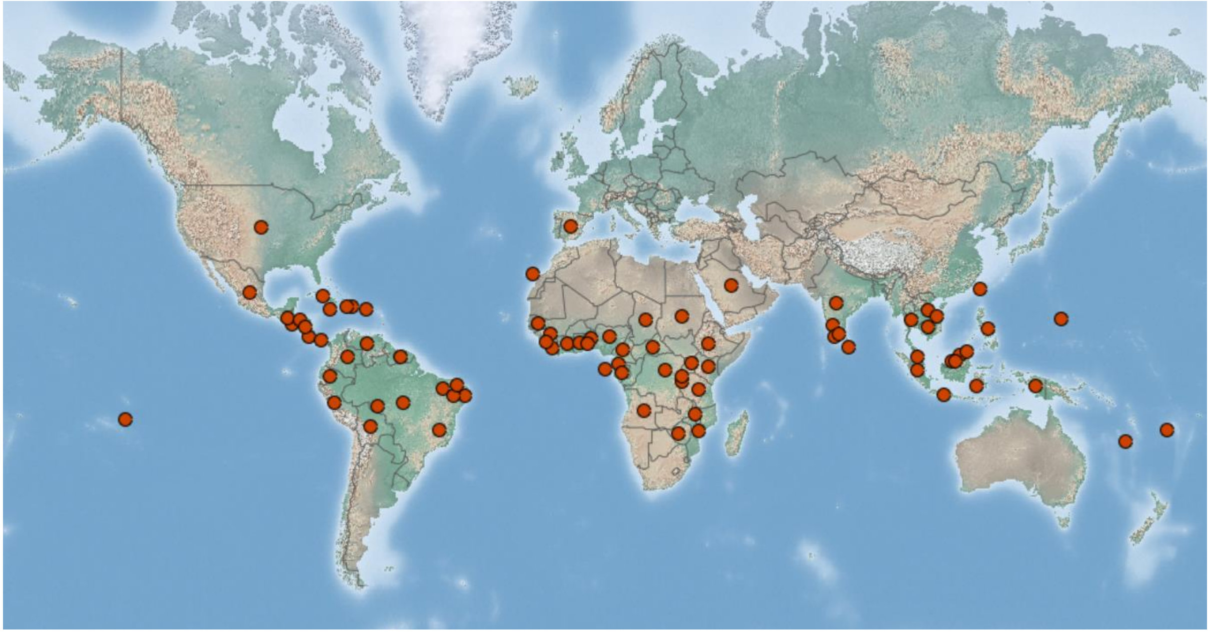
The Codling moth (*Cydia pomonella*) is a major polyphagous pest of fruit trees including apple, pear and walnut, and impacts the economies of many countries across the globe (Dorn et al., 1999). The species is native to Europe, but it can now be found in nearly all temperate fruit-growing regions across the world (generally above 30°N and below 30°S; (Willett et al., 2009). The Codling moth undergoes a facultative diapause in the larval stage, and across its range voltinism varies, generally decreasing at higher latitudes. In walnut orchards across California rising temperatures over the past 50 years have been associated with increases in the number of generations completed each season (Luedeling et al., 2011). These patterns are also reflected in modeling studies that consider Codling moth populations in Switzerland (Stoeckli et al., 2012), Norway (Rafoss and Saethre, 2003), Poland (Juszczak et al., 2013) and Marocco (El Iraqui and Hmimina 2016). By driving these models with data of future climate change scenarios, the authors consistently predict further increases in voltinism, as well as an expansion in distribution into higher latitudes (Rafoss and Saethre, 2003). The boundary of this species range at low latitudes, however, is currently constrained by winter temperatures that fail to induce larval diapause (Sheldeshova, 1967; Willett et al., 2009). Therefore, a contraction in this species' range boundary at low latitudes due to increasingly warmer winters may also occur, leading to an overall shift in this species' distribution. As such, changes in crop damage caused by the Codling moth under future climate change scenarios are likely to vary among different fruit growing regions.



Distribution map from: CABI, 2018. *Cydia pomonella*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission.

23. Coffee Berry Borer (*Hypothenemus hampei*) Coleoptera: Curculionidae (Ferrari 1867)

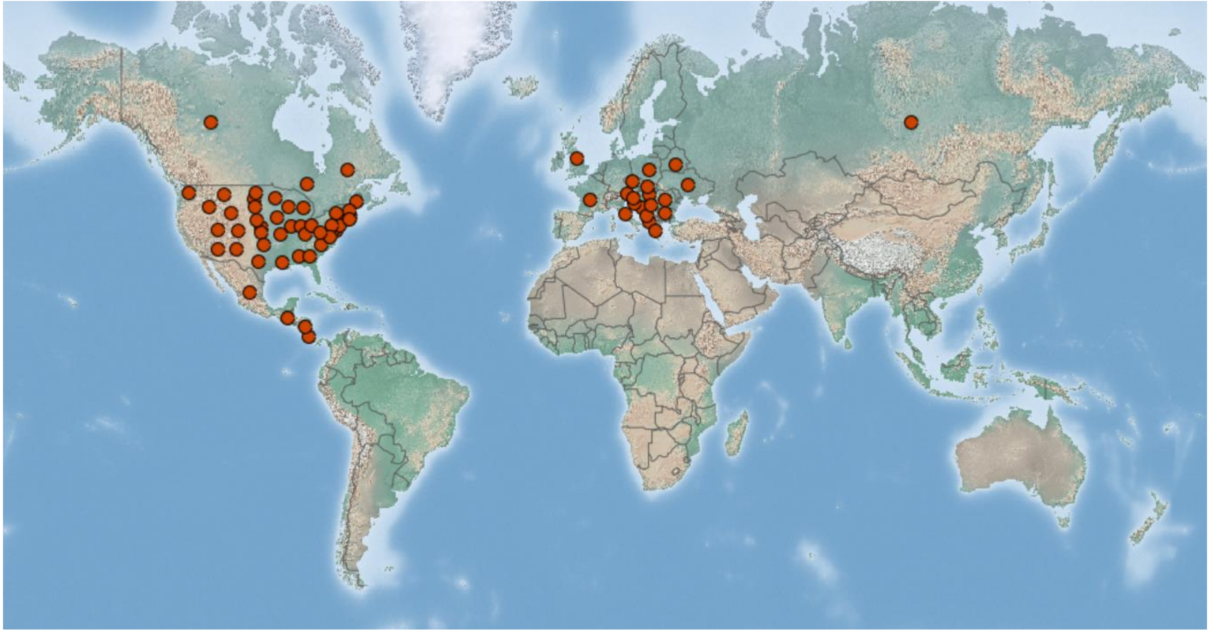
The Coffee berry borer (*Hypothenemus hampei*) is an important global pest of *Coffea* species including *C. arabica* and, to a lesser extent, *C. canephora*, causing global economic losses of up to $US 500 million per annum (Vega et al. 2003; Vega & Hofstetter 2015). The species is thought to originate in Eastern and Central Africa (Le Pelley 1968); however it has spread through human-mediated dispersal to all coffee growing regions across Africa, Asia and the Americas (Jaramillo et al. 2006). All life-history stages of *H. hampei* inhabit and feed on coffee berries and so, across its distribution, the number of generations completed per year varies from one to nine depending on the duration of the local fruiting season (Damon 2000). Survival and performance of this species are directly affected by temperature (Jaramillo et al. 2009), and recent warming conditions have been associated with an expansion of its range into higher elevations, where it was previously thought to be too cold for the beetle to inhabit (Jaramillo et al. 2009). For example, in comparison to 1984 when there were no infestations of the Coffee berry borer at Jimma in Ethiopia, current conditions allow for the completion of one to two generations per year (Mendesil et al. 2003; Jaramillo et al. 2009). Increases in voltinism of this species in Kenya and Colombia have also been linked to rises in temperature over recent decades (Jaramillo et al. 2009). As such, future increases in temperature are predicted to have an overall positive effect on this species (Jaramillo et al. 2011). The income from coffee production sustains an estimated 20 million families (Vega et al. 2003), and so the increasing voltinism and expanding distribution of this pest under future climates will likely have substantial socio-economic impacts on a global scale.



Distribution map from: CABI, 2018. *Hypothenemus hampei*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission. Reviewed by: Peter Baker, CAB Europe - UK, Bakeham Lane, Egham, Surrey TW20 9TY, UK

24. Western corn rootworm (*Diabrotica virgifera virgifera*) Coleoptera: Chrysomelidae (LeConte 1868)

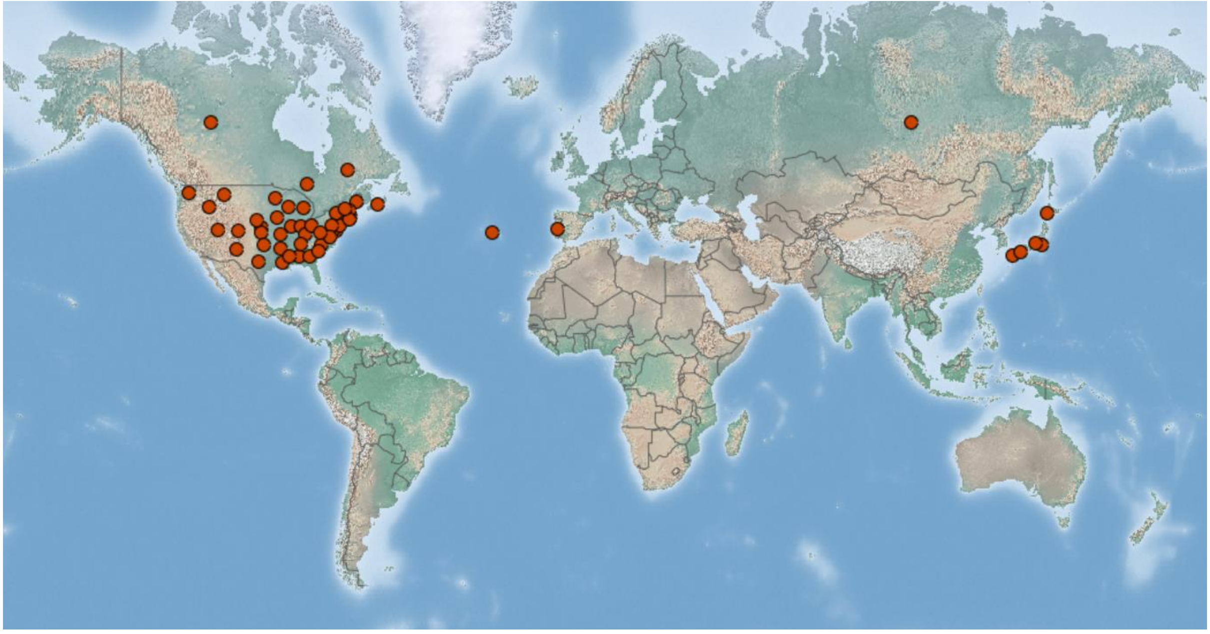
The western corn rootworm *Diabrotica virgifera virgifera* is a chrysomelid beetle native to Central America and an oligophagous pest of maize and other cereals. While it has been one of the most important insect pest species in the US for many decades (coined “one billion dollar bug” in the 1980ies - Gassmann 2012), starting early in the 1990s the Western corn rootworm was accidentally introduced to Europe by a series of invasion events (Miller et al. 2005, Ciosi et al. 2008) where it now causes extensive damage to European maize crops. A northward range expansion is indicated by the repeated introductions at increasing latitudes in Europe (Miller et al. 2005, Ciosi et al. 2008, Bermond et al. 2012). Establishment in many parts of Central Europe seems to be likely (e.g. Baufeld et al. 1996) and further northward range expansion due to advancement of the upper physiological limit has been modelled (Aragón and Lobo 2012, see also Haridas et al. 2016). As a vector of the *Maize chlorotic mottle virus*, known to infect a range of naturally occurring grasses of the family *Poaceae* (Scheets 2004), the Western corn rootworm has the potential to cause significant ecological damage.



Distribution map from: CABI, 2018. *Diabrotica virgifera virgifera*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission.

25. Japanese beetle (*Popillia japonica*) Coleoptera: Scarabaeidae (Newman 1841)

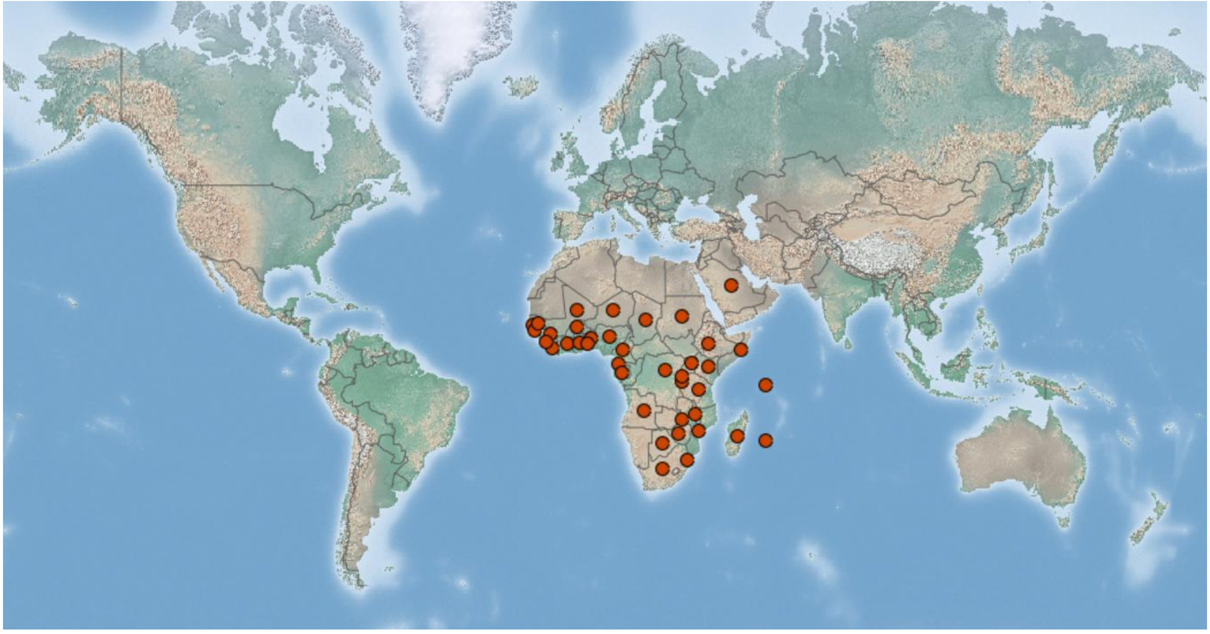
The Japanese beetle *Popillia japonica* is a scarabaeid beetle native to the main islands of the Japanese archipelago where this species is not considered a pest due to a lack of suitable habitats, effective control by its natural enemies and regular shortages of its main resources (Fleming 1972, 1976). After its introduction into the United States in the early 20th century, however, it became a very successful pest species of high socioeconomic impact in large parts of the eastern US while its potential distribution includes many other humid, temperate regions globally (Allsopp 1996). *Popillia japonica* is a generalist considered one of the most polyphagous of plant-feeding insects and it is known to feed on more than 300 species of wild and cultivated plants (Fleming 1972, Potter and Held 2002, Lemoine et al. 2013). Amongst these many potential beetle-plant interactions the effects of *P. japonica* on soy bean appear to be covered best by recent, climate-change related research (e.g. Hamilton et al. 2005, DeLucia et al. 2012, Niziolek et al. 2013, but see Lemoine et al. 2013). The root feeding grubs are important turf pests in parks, gardens or golf courses (Fleming 1972, Potter and Held 2002). Generally, economic damage caused by *P. japonica* is mainly attributed to defoliating adults but fruit and flower feeding also has considerable impact (Held and Potter 2004). While there is little information about climate change effects on the damage potential of *P. japonica* root feeding grubs, there are considerably more studies analyzing climate change effects on the feeding damage caused by adult beetles. For instance several studies demonstrate a high potential for enhanced foliar damage in soy bean related to elevated CO_2-levels and/or higher temperatures (Hamilton et al. 2005, Zavala et al. 2008, O'Neill et al. 2008, Dermody et al. 2008, Niziolek et al. 2013). On the contrary DeLucia et al (2012) report that earlier emergence of *P. japonica* caused by progressively warmer winters and spring should reduce the potential for defoliation-induced yield losses in the interaction with this particular host species. Finally, there is one recent study that has looked at the impact of rising temperatures on diet composition in *P. japonica* by testing nine different plant species: Lemoine et al (2013, 2017) found that (1) consumption generally increases with rising temperature while (2) diet breadth is reduced. These findings suggest that the consequences related to climate change are highly crop-species specific and predictions at the global socio-economic scale are complex and hard to make.



Distribution map from: CABI, 2018. *Popillia japonica*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission. Reviewed by: Michael Klein, Ohio Agricultural Research and Development Center, Adjunct Associate Professor, 1680 Madison Avenue, Wooster, OH 44691, USA

26. African sugarcane stalk borer (*Eldana saccharina*) Lepidoptera: Pyralidae (Walker 1865)

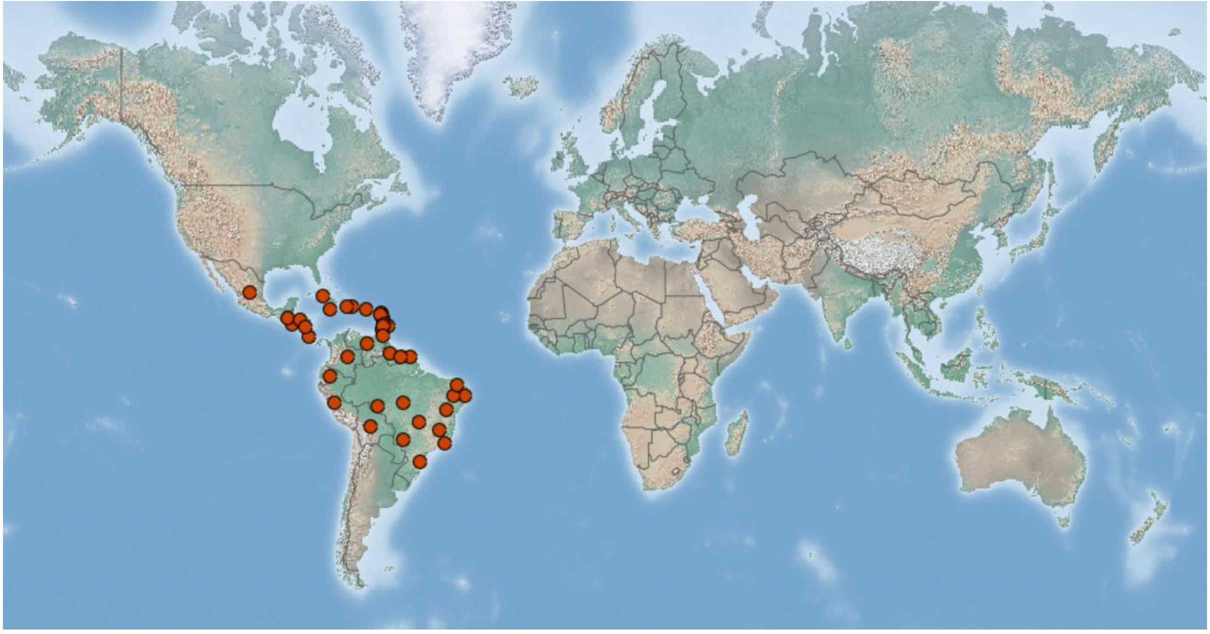
The African sugarcane stalk borer (*Eldana saccharina)* is a multivoltine Lepidopteran pest that infests a wide range or crops including sugar cane, maize and sorghum (Assefa et al., 2006). The larval stage of this pest infests its host by boring into its stalks, resulting in major tissue damage and economic losses. This species originated in western Africa, but is now found broadly across sub-Saharan Africa (from 15°N to 30°S). Since its initial invasion into South Africa in the 1930's the species has more recently spread from coastal to inland regions which were previously thought to be too cold to inhabit (Dick, 1945; Way, 1994). Studies suggest that this range expansion has been facilitated by a switch in host plant from sugar cane to maize (Assefa et al., 2008; Assefa et al., 2006), and an adaptation in the lower critical temperature threshold (Kleynhans et al., 2014a; Kleynhans et al., 2014b). The species also exhibits phenotypic plasticity in response to variation in rearing conditions: warmer temperatures induce faster development and growth (Atkinson, 1980; Way, 1995), but adults emerge with a smaller body size, increased rates of water loss and reduced longevity and fecundity (Kleynhans et al., 2014b). These laboratory findings suggest that as temperatures in the field continue to warm, we may expect an increase in voltinism across the range of the African sugarcane stalk borer. However, given that higher temperatures also lead to smaller adults and reduced performance of size-related traits (Kleynhans et al., 2014c), any likely changes in crop damage caused by this pest remain difficult to predict. Making such predictions is further complicated by the high rates of adaptation observed in this species (Assefa et al., 2006; Kleynhans et al., 2014b). Further work that compares recent changes in local temperature and rainfall with the expansion of this species into central South Africa may, nonetheless, provide valuable insights into the role that climate plays in limiting the distribution, phenology and damage caused by this invasive pest.



Distribution map from: CABI, 2018. *Eldana saccharina*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission.

27. Coffee leaf miner (*Leucoptera coffeella*) Lepidoptera: Lyonetiidae (Guérin-Méneville 1842)

The larvae of the Coffee leaf miner (*Leucoptera coffeella*) damage the assimilative parenchyma of *Coffea* species (Pereira et al. 2007) during 9-40 days confined within the leaf, and then form pupae on the outside of the leaf. The damage may extend to 37% of the cultivated coffee plantations leading to reduced flower formation, fructification and consequently up to a yearly loss of 40-80% in yield. The damage was considered to occur only during the dry season up to 1970, but recently the leaf miner has caused damage in both dry and wet seasons in areas of Sao Paolo in Brazil (Ghini et al. 2008). Studies indicate that temperature and precipitation are significant factors in the pest population dynamics. Currently approximately 8-12 overlapping generations may occur during the year. However, more generations of the coffee leaf miner per year would be possible to achieve in the predicted climate change scenarios (Ghini et al. 2008). As the performance of the coffee leaf miner is limited at high elevation in Mexico (Lomelí-Flores et al. 2010), mainly because of reduced temperature, it seems likely that climate change will facilitate range expansion into areas which at the moment are unaffected or only affected to a small degree.

890 

891 Distribution map from: CABI, 2018. *Leucoptera coffeella*. In: Invasive Species
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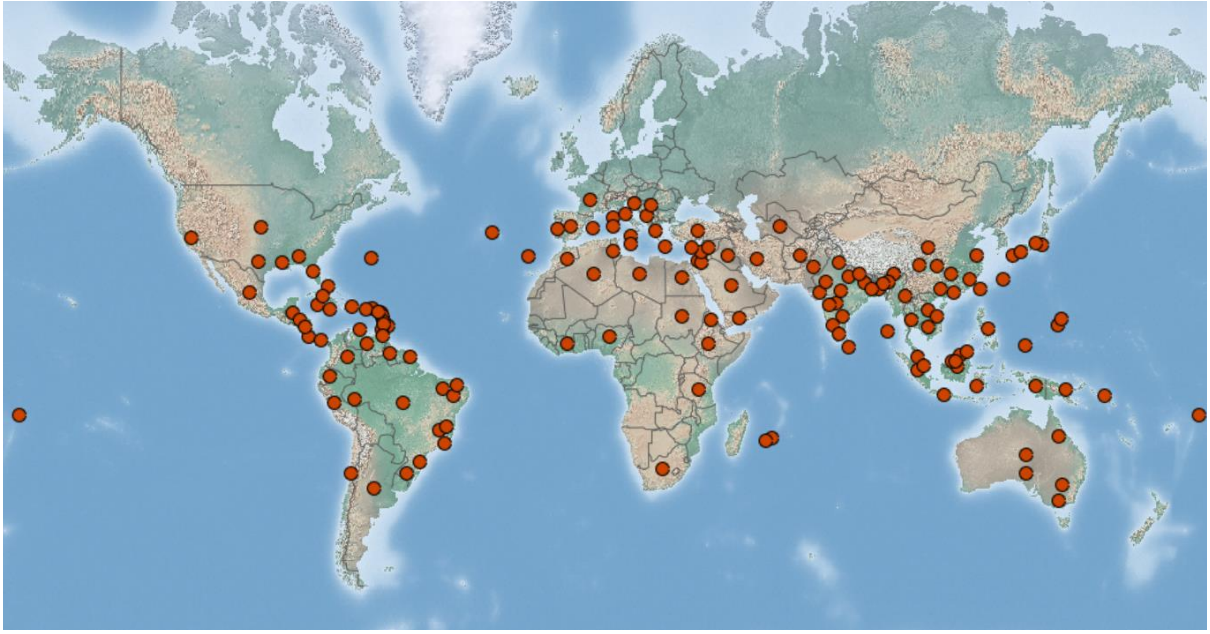
28. Citrus peel miner (*Marmara gulosa*) Lepidoptera: Gracillariidae (Guillén & Davis 2001)

The peel mining moth, *Marmara gulosa*, feeds on and damages the peel of the fruit of more than 31 families of plants. These include grapefruit, lemon, oranges and citrus, but also other orchard fruit such as apple and avocado and ornamental trees such as oleander and willow (Guillén et al. 2003). The wide host range allows the moth to switch hosts according to availability during the growing season (Grafton-Cardwell et al. 2008). The damage on the commercial citrus fruits is economically important only in California, Arizona, Mexico and Cuba, although the species occurs throughout the United States (Guillén et al. 2003). Two to three mines per fruit renders the fruit commercially unacceptable. On occasion, the damage may cause up to 80-90% fruit loss (Guillén et al. 2003). The temperature range for development is between 12-33°C and the average degree days required for the development of one generation is 309-375, depending on the host species (O'Neal et al. 2011). The peel miner is fairly efficiently controlled by a biocontrol agent (*Cirrospilus coachellae*). However, this parasitoid wasp does not tolerate as cold temperatures as the peel miner (Grafton-Cardwell et al. 2008).

No distribution map available at CABI, but the species is restricted to California, Arizona, Texas, Florida and Cuba according to Jones et al. 2001.

29. Citrus leaf miner (*Phyllocnistis citrella*) Lepidoptera: Gracillariidae (Stainton 1856)

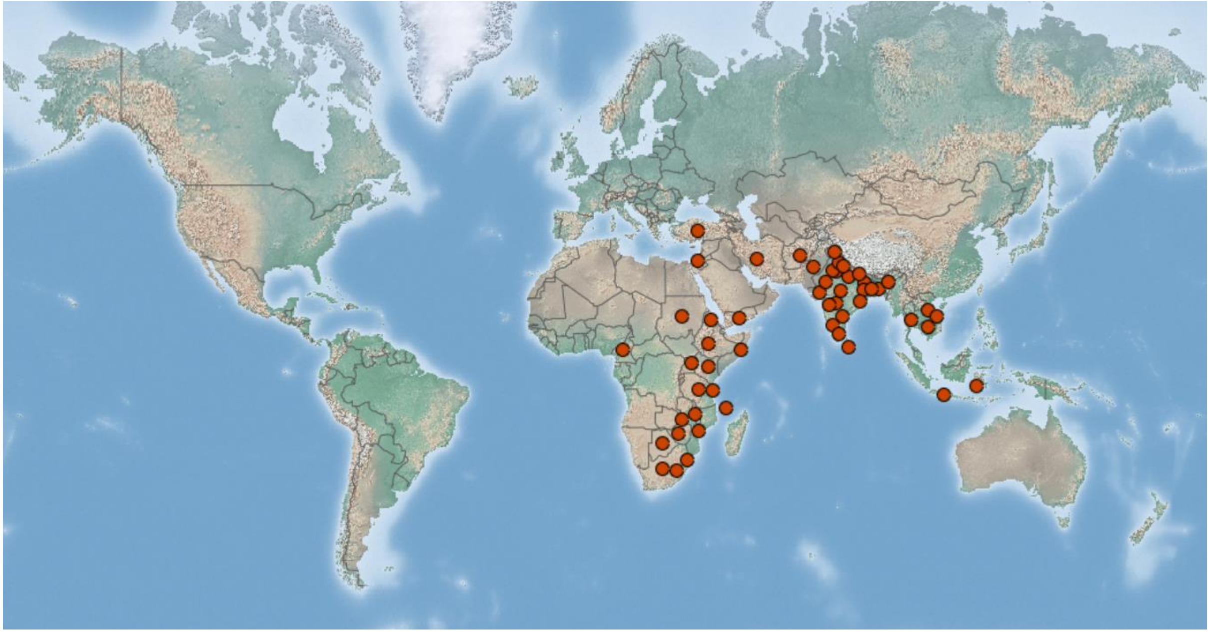
The citrus leaf miner is native to Asia, but currently occupies a global distribution range from Japan to Australia to India and Africa to South and North America (Grafton-Cardwell et al. 2008). The larvae mine the leaves of citrus trees, such as mandarins, lemons, limes and grapefruit. Damage on the leaves is most notable in the nurseries, but does not kill the trees. More severe damage is caused by a bacterial disease, the citrus bacterial canker (*Xanthomonas axonopodis* pv. *citri*), facilitated by the feeding damage done by the leaf miner. The citrus bacterial canker, while primarily a pathogen of cultivated plants, is known to infect a range of natural plants in the family Rutaceae. The annual losses due to the disease and consequent costs of eradication during 20 years after discovering, have been estimated at 28 million USD in the USA (Gottwald 2000). Efficient management of the disease involves eradication of the host within a radius from the infestation point. The leaf miner completes 5-6 generations in Asia (Grafton-Cardwell et al. 2008) with a generation time between 11.4 to 32.8 days (at 32°C and 18°C respectively), and shows no significant reduction in survival within a temperature range from 18 to 32°C (Chagas & Parra 2000). Furthermore, the Citrus leaf miner does not enter diapause in the colder months of the year, but instead slows down development (Lim and Hoy 2006). Therefore, it may be hypothesized that a warming climate allows for faster development and a consequent increase in the number of generations. It can be noted that ongoing climate warming is suggested to be an important factor in facilitating northward range expansion in the closely related species *Phyllonorycter leucographella* (Gröbler & Lewis 2008).



Distribution map from: CABI, 2018. *Phyllocnistis citrella*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission.

30. Spotted stem borer (*Chilo partellus*) Lepidoptera: Crambidae (Swinhoe 1885)

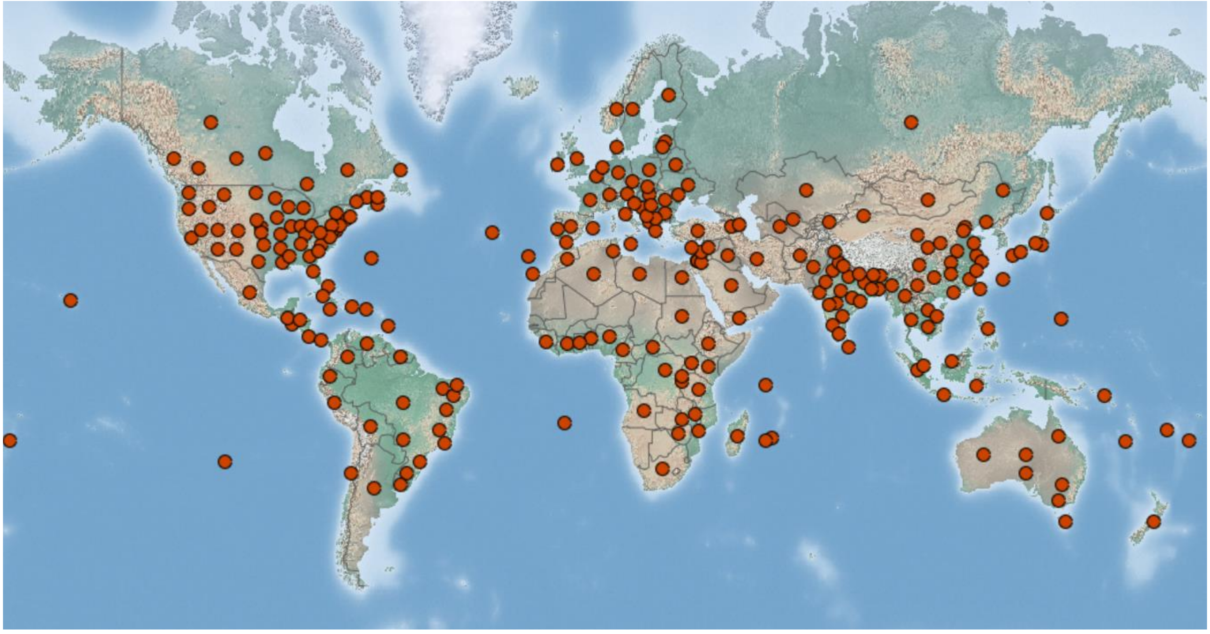
The spotted stem borer (*Chilo partellus*) is one of a complex of stem borer species that severely constrain maize production in Africa (de Groote 2002, Kfir et al. 2002). It is unique amongst these species in that it is invasive across the continent, having originated in India. Thus, there has been considerable interest in this invasion process and the role of climatic factors in determining its current and potential range (Kfir et al. 2002, Overholt et al. 2000), which, as of 2002 included Ethiopia, Sudan, Somalia, Kenya, Tanzania, Uganda, Mozambique, South Africa, Swaziland, Lesotho, Zimbabwe, Zambia, Malawi, and Botswana. This species alone can account for 50% yield losses in sorghum and it is a major target of pest management efforts, including the development of ‘push-pull’ technologies, which have proven successful in many contexts (Pickett et al. 2014). The ecological impact of this species is little studied. There is evidence that this invasive species has displaced native borers in native grasses in Kenya (Kfir 1997, Overholt 2008) raising the possibility that it could disrupt native grassland communities elsewhere in its invaded range (Mutamiswa et al. 2017). Overall, the climatic niche of this species appears to be well validated and supported by current distributions. Climatic models employed in 2000 predicted its eventual establishment in Namibia, Angola and parts of Nigeria, Cameroon, Togo, Benin, Ghana and Ivory Coast (Overholt et al. 2000), which has come to pass in some of these areas. Climate models predict that warming temperatures will facilitate its invasion and establishment at higher elevations where it does not occur presently (see also Tamir et al. 2012), but that it also could disappear from low lying regions where higher temperatures will constrain it ecologically (Khadioli et al. 2014). In some areas, warming will facilitate an increase in the number of generations of the pest per year (Khadioli et al. 2014). Although the pest has expanded its range to some uplands where it previously did not occur (Ong’amo et al. 2006), it is not clear whether this has been facilitated by the warming trend in the continent, or is the result of continued invasion with possible local adaptation by spotted stem borer populations.



Distribution map from: CABI, 2018. *Chilo partellus*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission.

31. Green peach aphid (*Myzus persicae*) Hemiptera: Aphididae (Sulzer 1776)

The Green peach aphid, *Myzus persicae*, is a global pest of Asian origin which occurs on over 40 different plant families (including many economically important plants). It has a complex geographically varying life-history strategy which varies between Heteroecious holocyclic in temperate climates and anholocylclic in most tropical climates (Blackman 1974). Holocyclic populations reproduce sexually and overwinter on *Prunus* species, while summer generations reproduce asexually on a wide variety of hosts. The overwintering eggs are extremely cold tolerant (Strathdee et al. 1995). Anholocyclic populations exist where winters are mild and mostly reproduce asexually on a variety of hosts; however also sexual reproduction exists to some degree in most populations (Blackman 1974). The most detrimental feature of *M. persicae* is its role as a virus vector, as it can transmit over 100 plant virus diseases which affect plants from over 30 families. Mild climates are directly linked to increased population densities, increasing numbers of generations and outbreak frequencies which lead to increased overall damage (Bale and Hayward 2010) and have been documented during the past 60 years in northern Europe (Harrington et al. 2007). While not studied to the same degree, absence of an equal effect on the predators of the aphids suggests decreased predation pressure under warmer climates (Bale and Hayward 2010).



Distribution map from: CABI, 2018. *Myzus persicae*. In: Invasive Species Compendium. Wallingford, UK: CAB International. www.cabi.org/isc. Printed with permission.

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