Inclusion of Physiological Responses in Insect Pest Risk Analysis: Evaluating Species Potential to Achieve Pest Status

Olga Bykova and Suzanne Blatt

ABSTRACT

Agricultural ecosystems are characterized by high spatial variability in abiotic characteristics that affect insect pest establishment and spread. The role of physiological responses to abiotic factors has been recognized as fundamental to insect range formation. Here we focus on the effects of various abiotic factors with potential to affect the probability of insects achieving pest status and propose ways to improve insect pest risk analyses using empirical as well as theoretical approaches. We discuss the data types used for pest risk analysis and present a process flowchart for preliminary pest risk assessment at both local and regional scales. This approach allows a quick assignment of preliminary risk levels taking into account known thermal thresholds for survival, effect of climatic factors on insect development, population dynamics as well as impact of local and regional landscape characteristics and soil properties on species abundance and dispersal. Using the process flowchart we conduct preliminary risk assessments for the carrot weevil, *Listronotus oregonensis* LeConte (Coleoptera: Curculionidae), and the brown marmorated stink bug, *Halyomorpha halys* Stal (Heteroptera: Pentatomidae), in Nova Scotia to demonstrate the utility of the framework.

RÉSUMÉ

Les écosystèmes agricoles se caractérisent par une grande variabilité spatiale des facteurs abiotiques qui influent sur l'établissement et la propagation des insectes ravageurs. Le rôle des réponses physiologiques aux facteurs abiotiques est reconnu comme essentiel à l'établissement de l'aire de répartition des insectes. Dans le cadre de la présente étude, nous mettons l'accent sur les effets de divers facteurs abiotiques susceptibles d'influer sur la probabilité que les insectes deviennent des ravageurs et proposons des façons d'améliorer les analyses du risque phytosanitaire au moyen d'approches empiriques et théoriques. Nous abordons les types de données utilisés pour l'analyse du risque phytosanitaire et présentons un organigramme de processus pour l'évaluation préliminaire du risque phytosanitaire à l'échelle locale et régionale. Cette approche permet d'attribuer rapidement les niveaux de risque préliminaires, en tenant compte des seuils thermiques connus de survie, des effets des facteurs climatiques sur le développement des insectes, de la dynamique des populations et de l'impact des caractéristiques des paysages et des propriétés du sol à l'échelle locale et régionale sur l'abondance et la dispersion des espèces. À l'aide de l'organigramme de processus, nous effectuons des évaluations préliminaires pour le charançon de la carotte (*Listronotus oregonensis*; Coléoptères : Curculionidés) et la punaise marbrée (*Halyomorpha halys*; Hétéroptères: Pentatomidées) en Nouvelle-Écosse afin de montrer l'utilité du cadre.

INTRODUCTION

In order to anticipate economic losses to the agricultural sector from invasive insect species, it is important to identify the potential pests of the region, and predict their establishment and spread within the landscape. The purpose of species-specific pest risk assessment (PRA) is to estimate the likelihood of successful pest establishment, predict the potential impact and select appropriate preventive measurements or request emergency pesticide registration. However, as species can respond to abiotic factors in very complex ways, it can be difficult to accurately predict pest outbreaks

Olga Bykova and Suzanne Blatt: Agriculture and Agri-food Canada, 32 Main Street, Kentville, Nova Scotia, Canada

Corresponding author (email aktavaolb@yahoo.ca)

without taking into account physiological mechanisms which will influence their distribution and abundance.

Although existing PRA frameworks recognize the role of environmental factors in pest survival and development (CFS 2015; FAO 2017), incorporation of insect physiological responses into pest risk analysis is not an easy task. It requires not only a good understanding of species physiology, but also the identification of mechanistic constraints limiting species distribution. An important breakthrough in this area has occurred following the development of process-based species distribution models (SDMs), like CLIMEX, which link species functional traits to the spatial data (e.g., Kumar et al. 2014; Kriticos et al. 2015). This type of model uses the knowledge on species physiological responses, distribution and abundance data to determine an ecoclimatic index, which indicates the suitability of location for species permanent establishment. CLIMEX is able to significantly improve the predictive capacity of pest risk analysis, yet, brings certain limitations, as it does not take into account biotic interactions (e.g., natural enemies, competitors), dispersal limitations (physical barriers such as sea and mountains), and possible disturbances (Baker et al. 2011; Wakie et al. 2018). It was also suggested that CLIMEX output does not provide useful spatial details. However, this is more likely a result of input data availability and quality rather than the model itself (Elith 2014). Another problem is that CLIMEX software is quite costly and, like any SDM, requires significant time and effort for its construction and validation (Kearney and Porter 2009; Elith 2014). This is where a physiologically-based method for quick preliminary PRA can come into play. This method is largely based on the existing species-specific physiological responses to abiotic factors. It can analyze pest risks (preliminary) relatively rapidly, define a direction for research and make further PRA more focused. Although it cannot replace a comprehensive PRA which requires the collection of specific data (e.g., morphology, physiology, behaviour), this method can provide valuable information for pest management at the early stages of species invasion, particularly on a local scale. Such PRA is accessible to research institutes, academic researchers and regulatory agencies.

The objective of any PRA is to identify high risk species at one or more stages of invasion (Karsten et al. 2018). Insect pest invasion, like any other invasion process, is comprised of three major stages: introduction, establishment and spread (Engel et al. 2011). Once a species is introduced into the region via commerce, personal belongings transport or other methods, it has to pass through the establishment

process and produce self-sustaining populations, which requires an ability to overcome survival and reproduction barriers at the individual and population levels and go through various abiotic and biotic constraints (e.g., extreme temperatures, biological control) (Richardson et al. 2000; Jackson et al. 2009; Blackburn et al. 2011; Engel et al. 2011). Further, during the spread stage, a pest must overcome dispersal and environmental barriers through the acclimation to the new environment and adjustment to any changes in the community (Müller et al. 2010, Blackburn et al. 2011). As a result, not every species introduced into an area develops into a pest species causing economic losses and/or large environmental impacts. It is also possible that some species existing at low levels can achieve pest status due to changes in abiotic conditions which also have to be considered in a risk analysis. The Tens Rule suggests that only ten percent of species introduced into an area become established and only ten percent of those established will spread or turn into pests (Williamson and Fitter 1996). This indicates that local abiotic and biotic factors will basically act as filters in the selection process (Bykova 2012).

When performing a pest risk analysis it is essential to understand that for a species to achieve pest status it usually has a broad physiological tolerance range, high reproductive capacity (high birth rate, short generation time, several generations per season) and an ability to survive and maintain high fecundity under extreme climatic conditions (Walther et al. 2009; Alexander et al. 2011). Insect pests are usually characterized by high intrinsic growth rates, small body sizes and fast maturation rates (Crawley 1986; Lawton and Brown 1986). Their introduction changes ecosystem function once the species achieves pest status. Nonetheless, as environmental and economic effects of pests vary with space and system, it is essential to estimate pest risk level for each particular agricultural region (Kenis et al. 2009). Currently, the Canadian Food Inspection Agency (CFIA) evaluates pest risk using four major factors: 1) Probability of entry, 2) Probability of establishment, 3) Probability of spread after establishment, and, 4) Potential economic and environmental consequences. The assessment process for the second and the third factor includes the analysis of environmental and climatic suitability, species biology, adaptation potential, and sometimes involves GIS and species distribution modelling tools (CFIA, 2011).

How an insect responds to abiotic factors plays a crucial role in pest establishment and successful spread. Unlike species in their natural environment where realized niches are constrained by biotic factors such

as competition, species achieving pest status usually overcome this limitation (Bykova 2012). Therefore, in order to calculate the probability of pest establishment as part of a PRA it is essential to know, or understand, the mechanisms influencing their distribution. Since the beginning of the 20th century, and particularly during the last several decades, ecologists, entomologists and biogeographers have spent considerable time addressing the links between climatic variables, largely temperature, and insect distribution. However, in most cases, the physiological processes underlying these relationships are not fully understood. In this paper we will discuss how abiotic factors affect insect distribution and the importance of incorporating physiological data into PRAs. We will explore the role of landscape characteristics as well as soil properties in insect abundance and will discuss different data types (e.g., soil properties). Finally, using our flowchart we will determine the preliminary level of risk for carrot weevil, *Listronotus oregonensis* LeConte (Coleoptera: Curculionidae), and brown marmorated stink bug, *Halyomorpha halys* Stal (Heteroptera: Pentatomidae), to achieve pest status in Nova Scotia.

METHODS

Abiotic factors and mechanisms controlling insect pest distribution and abundance

Temperature

Temperature is one of the most important abiotic components influencing insect distribution and abundance (Table 1). It can serve both as a mortality factor, affecting species survival and as a developmental factor, influencing the rate of species development, reproduction, longevity and phenology. Survival thresholds affect species range formation, with minimum and maximum temperatures being the major climatic variables influencing northern and southern range limits of a large number of insects (Table 1). Ungerer et al. (2003), for example, demonstrated that the isocline for average minimum annual temperature (16 °C), which approximated the northern range of the southern pine beetle (Dendroctonus frontalis Zimmermann (Coleoptera: Scolytidae)) distribution, corresponded to the temperature causing 90% mortality in this species. Southern range limits of six weevil species from the sub-Antarctic Marion Island, on the contrary, were explained by the upper thermal thresholds for their survival. The authors reported that all six species were unable to survive temperatures above 33 °C, which was close to the absolute maximum temperatures experienced by these species in their natural

habitat (van der Merwe et al. 1997). Survival thresholds for immature stages can also affect the distribution limits of species, but this information is more important for species that overwinter as immatures, particularly in un-buffered and unprotected microsites (Kinoshita and Yagi 1930).

Precipitation

Precipitation has been observed to affect the distribution of insects that overwinter in soil as pupae or larvae or require moisture for egg development or hatch. Weather events, like heavy rainfall, can disrupt pupal development of overwintering Mediterranean and oriental fruit flies, negatively affecting their populations (Papadopoulos et al. 2001; Wang et al. 2009). Wang et al. (2009) demonstrated that the distribution of the oriental fruit fly, *Bactrocera dorsalis* Hendel (Diptera: Tephritidae), in southern China is strongly limited by precipitation, and more precisely, by soil moisture through its impact on species emergence. However, along with the negative effect of heavy rainfall, this factor may also have a positive impact on the abundance of pests that require moisture to complete development successfully (e.g., Asiatic garden beetle, *Maladera castanea* Arrow (Coleoptera: Scarabaeidae) or the white-fringed beetle, *Naupactus leucoloma* Boheman (Coleoptera: Curculionidae)) (Held and Ray 2009; Visser and Neiderweiser 2012). In order to hatch, eggs of white-fringed beetle require moisture which increases species sensitivity to the amount of rainfall following oviposition (Visser and Niederwieser 2012). In addition, species like the mountain pine beetle (MPB) (*Dendroctonus ponderosae,* Hopkins (Coleoptera: Scolytidae)), that lay their eggs under bark, have high humidity requirements to facilitate hatching (more than 90% relative humidity for MPB), and therefore are more likely to experience outbreaks in areas with high relative humidity (Reid 1969; Safranyik and Carroll 2006). In our preliminary analysis, we include precipitation as a factor affecting insect life cycle completion and as a regulatory factor affecting population size. The addition of this variable in PRA should significantly improve the outcome of analysis for species where survival and development are sensitive to the amount of rainfall.

Wind and storm events

Wind velocity can affect flying insect seasonal migration, their movement from one field to another and, locally, within the same field. It is hard to draw general conclusions about the effect of wind speed on insect population size, as increasing wind speed can facilitate rapid migration, yet, decrease their abundance (Turner 2006). The latter

Table 1. Listing of representative studies demonstrating the relationships between climatic variables and insect geographic range limits. Studies for this listing were randomly sampled.

Species	Limiting climatic variable	Region	Reference
Yellow stem borer, *Scirpophaga incertulas* Walker (Lepidoptera: Pyralidae) / *Tryporyza incertulas* Walker (Lepidoptera: Pyralidae)	Minimum annual temperature, winter rainfall, September rainfall	Japan, China, Pakistan	Kinoshita and Yagi 1930; Shi et al. 2012 a,b; Rehman et al. 2002
Colorado potato beetle, *Leptinotarsa decemlineata* Say (Coleoptera: Chrysomelidae	Monthly mean minimum temperature, maximum summer temperature	Xinjiang province, China	Li et al. 2014
Mountain pine beetle, *Dendroctonus ponderosae* Hopkins (Coleoptera: Scolytidae)	Mean annual minimum temperature	North America	Safranyik 1978
Southern pine beetle, *Dendroctonus frontalis* Zimmermann (Coleoptera: Scolytidae)	Minimum annual temperature, minimum winter temperature	USA	Ungerer et al. 1999; Tran et al. 2007
Six weevil species: *Bothrometopus elongatus* Jeannel, *B. parvulus* Waterhouse, *B. randi* Jeannel, *Ectemnorhinus marioni* Jeannel, and *E. similis* Waterhouse, *Palirhoeus eatoni* Waterhouse (Coleoptera: Curculionidae)	Absolute maximum temperature	Marion Island	van der Merwe et al.1997
Plum curculio, *Conotrachelus nenuphar* Herbst (Coleoptera: Curculionidae)	Mean monthly minimum temperature	USA	Ulrichs and Hopper 2008
Mediterranean fruit fly, *Ceratitis capitata* Wiedemann (Diptera: Tephritidae)	Low maximum winter temperature, annual rainfall; annual average temperature, annual potential evapotranspiration	Global	Vera et al. 2002; Gevney and Worner 2006
Mexican fruit fly, *Anastrepha ludens* Loew (Diptera: Tephritidae)	Maximum summer and minimum winter temperature	USA	Flitters and Messenger 1965
Oriental fruit fly, *Bactrocera dorsalis* Hendel (Diptera: Tephritidae)	Soil moisture, soil temperature	Southern China	Wang et al. 2009
Red imported fire ant, *Solenopsis invicta* Buren (Hymenoptera: Formicidae)	Mean of maximum daily precipitation for month and monthly mean precipitation	USA	Ulrichs and Hopper 2008
Gypsy moth, *Lymantria dispar* Linnaeus (Lepidoptera: Lymantriidae)	Average minimum temperature and minimum day length rang	Global	Gevney and Worner 2006
Processionary moth, *Thaumetopoea pityocampa* Denis & Schiffermüller (Lepidoptera: Thaumetopoeidae)	Average minimum winter temperature	France and Italy	Battisti et al. 2005
Swallowtail butterfly, *Papilio glaucus* Linnaeus (Lepidoptera: Papilionidae)	Minimum winter temperature	USA	Kukal et al. 1991

Table 1: continued

Great mormon butterfly, *Papilio memnon* Linnaeus (Lepidoptera: Papilionidae)	Annual minimum temperature	Japan	Yoshio and Ishii 2001
Honeybee, *Apis mellifera carnica* Pollman, *Apis mellifera macedonica* Ruttner (Hymenoptera: Apidae)	Average temperature	Romania	Coroian et al. 2014
Thorn bug, *Umbonia crassicornis* Amyot & Serville (Hemiptera: Membracidae	Minimum winter temperature	Florida, USA	Dowell and Wood 2014
Glassy-winged sharpshooter, *Homalodisca vitripennis* Germar (Hemiptera: Cicadellidae)	Daily average temperature	USA	Gutierrez et al. 2011
Leafminers, *Liriomyza sativae,* Blanchard, *Liriomyza huidobrensis* Blanchard (Diptera: Agromyzidae)	Average temperature	Central Java, Indonesia	Tantowijoyo and Hoffmann 2010
Western corn rootworm, *Diabrotica virgifera virgifera* LeConte *(Coleoptera: Chrysomelidae)*	Accumulated temperature	North America and UK	Baker et al. 2003

occurs mainly through the negative effect of wind on insect reproduction and food sources, suggesting that areas prone to higher wind speed might have lower risks for infestations by flying insects (Møller 2012). Wind Energy Resource maps provide seasonal average wind resources for different territories which could be a very useful tool in pest risk management. Moreover, as severe storm and cyclones can negatively affect insect pest fitness, the probability of their occurrence could also be taken into account in PRA. Currently, PRAs recognize wind and storm events only as natural means of pest spread (FAO 2004); yet, we propose to consider these factors also as important climatic factors that affect pest population density and to include them in the estimation of pest risk levels.

Landscape characteristics and topography

Unlike temperature and precipitation that affect insect distribution at large scales, landscape characteristics and topography usually influence species fitness at smaller and rather local scales. Landscape features can create microclimates, regional pockets which can be suitable or non-suitable for insect survival. The analysis of European corn borer (*Ostrinia nubilalis* Hübner (Lepidoptera: Pyralidae)), Colorado potato beetle, (*Leptinotarsa decemlineata* Say (Coleoptera: Chrysomelidae) and plum curculio (*Conotrachelus nenuphar* Herbst (Coleoptera: Curculionidae)) distributions demonstrated that these species were strongly limited by the percentage of shrub land present in the area (Ulrichs and Hopper 2008). The presence of adjacent fields of alfalfa and corn contributes to higher densities of stick bugs in peanut and sorghum fields (Tillman 2011; Venugopal et al 2014). It was also shown that isolated fields usually favour higher insect richness; whereas fields with high disturbance rates are regularly associated with low insect abundance values (Fahrig and Jonsen 1998). Accordingly, woody borders, windbreaks and hedges are generally assumed to act in opposition to insect pest management practices, providing complementary habitats and shelters (e.g., overwintering or mating sites and alternate hosts) that increase insect population size. However, it has also been suggested that woody borders may increase predation and prevent insect movement from one field (breeding site) to another by trapping them within the field and protecting other fields from new infestations (Dunning et al. 1992; Bhar and Fahrig 1998). These factors are extremely important, yet, to our knowledge, have not been included even conceptually in previous PRAs. Conversely, large physical barriers like mountain ranges or large water bodies can limit insect pest distribution at the continent level. However, an increasing level of globalization and human-facilitated transport systems calls into question the existence of permanent geographical barriers (Pratt and Center 2012). Overall, we are confident that insect PRA would gain greater accuracy when taking into account landscape elements and topography during the

evaluation of species capacity to maintain high population density and abundance. Several ecological models already account for changes in landscape characteristics when estimating the probability of transition from the status of minor to major pest (e.g., Sporleder et al. 2013). Nonetheless, this approach is not widely accepted and these factors are usually not included in pest risk analysis.

Soil properties

The most important soil characteristic to be considered with respect to insect survival is soil type, as this affects the texture and drainage of the area. Soil moisture content is influenced not only by the amount of precipitation, but also soil water holding capacity which will influence the developmental processes of some insect pests. Soils with high clay content are known to have reduced soil drainage and therefore, along with heavy rainfall, can decrease the survival of soil overwintering insects. Moreover, soil texture may influence larval survival, as newly hatched larvae must move through the soil towards a food source (e.g., root). Dry sandy soils can damage larvae during the burrowing process, affecting emergence success and reducing insect population size. Low emergence rates in Mediterranean fruit fly (*Ceratitis capitata* Wiedemann (Diptera: Tephritidae)), for example, were observed in silty clay loam; whereas low pupation rates were found in sandy loam soil (Ali Ahmed et al. 2007). Additionally, soil texture has potential to influence insect movement within a field, particularly for insects that disperse by walking. Certain soil types and hence textures can serve as barriers and prevent colonization of nearby areas. Insects like carrot weevil, pine weevil (*Hylobius abietis* Linnaeus (Coleoptera: Curculionidae)) could be particularly affected by this factor. It was demonstrated that pine weevil, for example, moves faster on mineral than on organic soil, which decreases insect density (Björklund et al. 2003). Moreover, we have recently showed that soil type also influences carrot weevil burrowing activity and movement and demonstrated that carrot weevil is more inclined to burrow into mineral and organic soils than pure sand, and displays avoidance of the latter (Bykova and Blatt 2018). Such effects, to our knowledge, have not been largely evaluated, yet it is likely that the role of soil texture in PRAs has been underestimated. Unfortunately, the data on soil properties are not readily available worldwide, therefore we suggest including this factor only in PRAs.

Preliminary pest risk assessment
The purpose of PRA is to identify the pathways a pest could

use that result in introduction or spread into a region and estimate the likelihood of its establishment and impact. Ideally, a pest risk framework has to incorporate various abiotic factors, species phenology and include modelling tools. Nonetheless, as species distribution modelling can be very complex and time consuming, we suggest first performing a preliminary pest risk analysis, especially when a quick risk assessment on a local scale is needed, using a simple process flowchart consisting of 6 major process steps (Boxes) to generate 7 risk levels (Figure 1). The following approach allows a quick assignment of preliminary risk levels taking into account known thermal thresholds for survival, effect of climatic factors on insect development, population dynamics as well as impact of local and regional landscape characteristics and soil properties on species abundance. We assign 7 risk levels: no risk, insignificant risk (assuming a possibility of species establishment in a controlled environment, such as a greenhouse), low risk, moderate risk, moderately high risk, high risk and extremely high risk. Species that fall within the last four categories are the immediate candidates for further PRA.

The hierarchy of factors used in this flowchart is based on the sequence of invasion stages and barriers (survival, reproduction, dispersal and environmental), identified in a unified framework for biological invasions (Blackburn et al. 2011), that have to be overcome in order to move from one stage to the next. First, a species has to go through the introduction phase and find a suitable host (Box 1). Second, it has to get established in the region and therefore survive and be able to reproduce (Boxes 2 and 3) (Blackburn et al. 2011). Here we are interested in temperature as a major factor regulating species survival during adult as well as immature stages. The temperature-dependence of each phenological stage needs consideration as well as species developmental responses to precipitation, wind, storm events and soil properties (only for species associated with soil and local assessments, such as farmland, with readily accessible data on soil properties). In order to pass on to the next stage, a species has to be able to reproduce, but also show a positive long-term population growth rate, which can be achieved only after several survival-reproduction cycles ensured by favorable climatic conditions (Blackburn et al. 2011) (Box 4). Next stage of invasion process, spread (Boxes 5 and 6), is characterized by dispersal and environmental barriers. At this point, we are interested in the landscape characteristics and biological control availability. In Box 5, we are looking at the effects of adjacent habitats, such as woody borders, windbreaks, hedges and cultivated crop habitats that support high pest

Figure 1. Process flowchart for preliminary pest risk assessment.
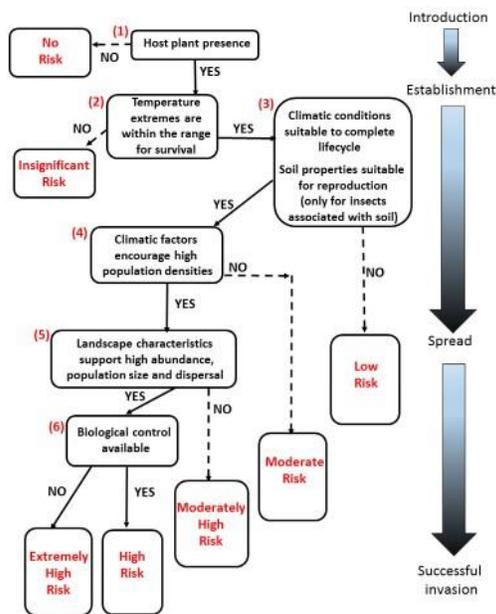
population size and dispersal. To understand which pass to take, we have to address the question: "What landscape characteristics are known to increase the population size and dispersal capacity of the species?" and, "Is at least one of these landscape characteristics present in the PRA area?" If the answer is 'yes', we can move to Box 6 and look at the availability of biocontrol agents effective against the pest. This includes commercial biocontrol agents, approved for usage in the PRA area, as well general predators, like spiders, crickets, ground beetles, jumping spiders and katydids present in the PRA area, and shown to be effective in reducing pest population size during the laboratory and/or field trials (e.g., Morrison et al. 2016).

In order to demonstrate how this flowchart works we will apply it to two pests, carrot weevil (CW), *Listronotus oregonensis* and brown marmorated stink bug (BMSB), *Halyomorpha halys*, in Nova Scotia (NS). While carrot weevil is well established in Nova Scotia, brown marmorated stink bug is not and the risk level is not yet determined. Brown marmorated stink bug is established in southern Ontario (Garipey et al. 2014) and recently confirmed in Quebec (Choinard et al. 2017). It should be noted that this approach assesses only the environmental impact of pests that has to be integrated with crop impact in order to obtain the overall risk level. This could be done through the application of the matrix method introduced by Holt et al. (2014), which represents an extension of one

of DEXi multi-attribute decision models. Risk levels used in the flowchart can also be converted to the probability percentage following IPCC guidelines (IPCC 2010).

RESULTS

Case 1: Carrot weevil

Box 1 – *Host plant preference*

The first box requires the evaluation of NS as having the appropriate host plants to support carrot weevil. NS has similar plant flora to other Eastern provinces and produces carrots commercially, providing ample hosts for CW host range (presence of carrots) (Box 1 - YES).

Box 2 – *Temperature extremes*

Using published data on upper and lower thermal limits we identified that temperature extremes in this region are within carrot weevil range for survival (Box 2 – YES). Although the temperature thresholds for the survival of adult carrot weevils remain unknown, it was demonstrated that in Clinton County (Michigan, USA) CW was able to survive soil temperatures as low as -7 °C which is well outside the extreme temperature range estimated for soil layers at 5cm depth in NS (Grafius and Collins 1986). Carrot weevil are known to overwinter in the top 5 cm of soil, protecting them from extremely low air temperatures. This is particularly relevant in areas with relatively deep snow cover and often long snow cover duration, like NS, where carrot weevil are also protected from a long-term exposure to sub-lethal temperatures (Grafius and Collins 1986).

Box 3 – *Climatic conditions and soil properties suitability to complete lifecycle*

Examination of climatic conditions in NS suggests they are conducive to the completion of species life cycle (Box 3 - YES). Lower and upper temperature thresholds for carrot weevil development are 6.7 °C and 32 °C, respectively, which is within the diurnal temperature variation in late May- September. In NS, carrot weevils usually complete their lifecycle by early August (Simonet and Davenport 1981; Boivin 1999). Soil properties (e.g., sandy loam) do not restrict the carrot weevil movement, favour its borrowing activity, and likely do not negatively affect the reproductive cycle of this species (Bykova and Blatt 2018).

Box 4 – *Climatic conditions for high population density*

Here we are mainly interested in the existence of sustained warm periods that allow high offspring survival and, presumably, the completion of a second generation.

Temperatures not warming until late May, typical for NS, can decrease carrot weevil population densities due to late emergence timing, which is known to happen only after the accumulation of 127 degree-days above 7 °C (commonly late May in Nova Scotia) (Grafius and Collins 1986; Blatt, unpublished data). In addition, it was reported that when temperatures above adult activity threshold (15 °C) occurred later in the season, carrot weevil population size becomes significantly reduced (Grafius and Collins 1986). Late emergence might also lower carrot weevil ability to complete a second generation due to discrepancies in photoperiod and unfavorable thermal conditions. These conditions suggest that current seasonal conditions in NS might not be able to support high population densities of carrot weevils and species will likely show negative long-term population growth rate (Box 4 - NO). From this point, the estimated risk level for carrot weevil infestation in NS is **moderate** (Figure 2A), which corresponds to its current status in the province. The carrot weevil is present, can reproduce, but is not able to support high population densities (Blatt, unpublished data.).

Case 2: Brown marmorated stink bug

Nova Scotia is recognized as having many micro-climates. For the purposes of this evaluation, we considered the micro-climate that would be present in Halifax, a likely first entry point of goods from BMSB-infested areas. Other areas within NS would need a similar assessment.

Box 1 – *Host plant preference*

BMSB is a polyphagous insect feeding on 300+ species of hardwood and herbaceous plant species. NS contains many species recognized as suitable hosts for BMSB, hence, Box 1 - YES.

Box 2 – *Temperature extremes*

BMSB has been found to be very sensitive to low temperatures during its dormancy stage and showed low overwintering survival rates below 0 °C (Gariepy et al. 2014; Nielsen et al. 2016). However, sexually immature adults of BMSB overwinter in dead standing trees as well as man-made structures in urban areas (Cambridge et al. 2015), which allows them to survive winters in regions outside of their thermal survival range (Inkley 2012). As such, BMSB should survive winters in NS (Box 2 – YES). Nonetheless, given the temperature range required for BMSB to complete its lifecycle and the current temperature range for NS, it is unlikely they will be able to reproduce (Box 3 - NO). Laboratory and field experiments showed that BMSB development is not possible at or below 15 °C (Haye et al. 2014). Temperatures in July and August are regularly slightly below this threshold. Based on what is currently known about BMSB, we conclude that if introduced to NS at the current moment, BMSB would likely not be able to complete its lifecycle (May—September) and therefore assign it **low risk** level, assuming a possibility of species establishment in a controlled environment (Figure 2B). However, as summer temperatures in this region are projected to increase by 2 ° to 4 ° during the next several decades (Lines et al. 2006), the risk level of BMSB invasion will most likely change. This indicates that despite that BMSB has been assigned low risk level, it is still crucial to monitor this species and be prepared to address BMSB infestations in the near future.

DISCUSSION

There is a need for quick, locally relevant risk assessment methods which can facilitate scientific and efficient pest control evaluations (Andersen et al. 2004, 2005). The approach presented here can be used as a standalone tool as well as a basis for a new rapid PRA model. During the past decade, pest risk analysis, a dynamic and constantly evolving field, has advanced considerably with the development of rapid PRA schemes, such as FinnPrio scheme of Finland (Heikkilä et al. 2016), EPPO Express PRA scheme (EPPO 2012), rapid PRA of the UK (Baker et al. 2014), Quick Scan PRA scheme of the Netherlands (van der Gaag et al. 2017) and the Prioritizing method of France (Moignot and Reynaud 2013). These schemes take multiple criteria/level approach, consider the complexity underlying the invasion process and, although cannot replace a detailed PRA, allow fast prioritization of actions. FinnPrio, for example, uses multiple choice questions that assign points used to produce the probability distributions of the final scores. It takes into account climatic suitability and species capacity to overwinter and reproduce; however, unlike our method, does not separate establishment and spread components (Heikkilä et al. 2016). The UK scheme, by contrast, evaluates these components separately and looks at the mobility of the organism (e.g., insect flight capacity, dispersal mode, mobility vector) in order to rate the spread (Baker et al 2014). Another rapid PRA –the Prioritizing method, developed by ANSES Health Pest Laboratory (France), identifies 24 test criteria that are organized into 5 blocks (metacriteria), three of which correspond to major invasion stages and the other two are dedicated to the impact on crops, environment and society (Moignot and Reynaud 2013). Similar to

Figure 2. Determining the preliminary level of risk for (A) carrot weevil, *Listronotus oregonensis*, and (B) brown marmorated stink bug, *Halyomorpha halys*, in Nova Scotia using the process flowchart.
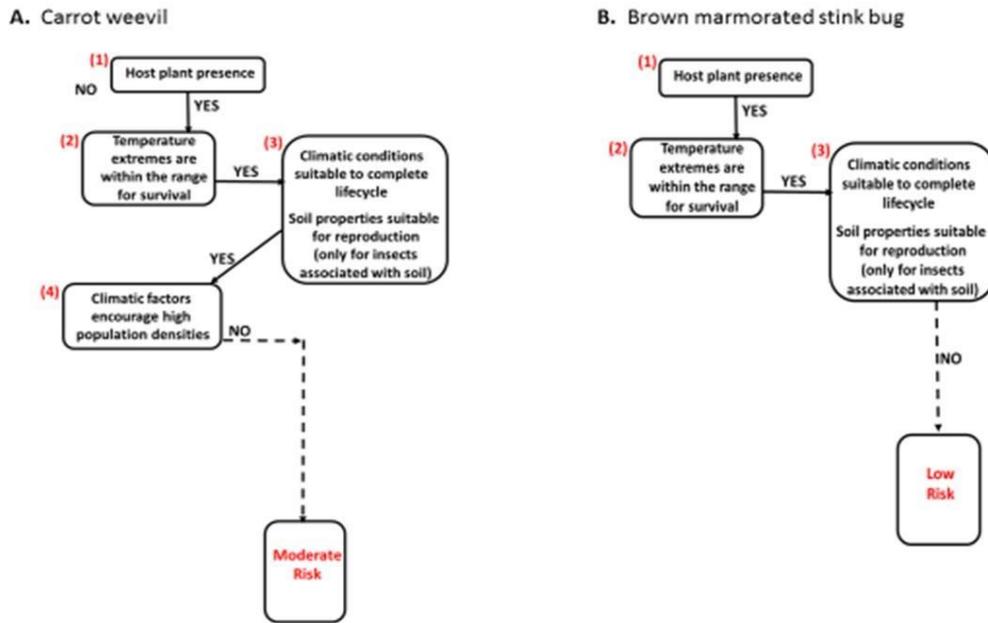
our approach, it considers eco-climatic conditions for species development, species reproduction strategies and takes into account invasion barriers identified in a unified framework for biological invasions (Blackburn et al. 2011); yet, is not as focused on species physiology.

Over the past decades, our understanding of insect pest physiology has advanced considerably bringing new opportunities for improvements in PRA process, particularly on a local scale. Although there is still much to learn regarding physiological responses of insects to climatic variables and ways to incorporate important physiological parameters into PRA frameworks, the field is currently in an exciting transitional period in which new methods are being applied to improve the quality of risk assessment process and make it more scientific.

ACKNOWLEDGEMENTS

REFERENCES

Alexander, J.M., Kueffer, C., Daehler, C.C., Edwards, P.J., Pauchard, A., Seipel, T., and MIREN Consortium. 2011. Assembly of non-native floras along elevational gradients explained by directional ecological filtering. Proceedings of National Academy of Science USA **108**: 656–661.

Ali Ahmed, D., Soltani, N., Kellouche, A., and Mazouzi, F. 2007. Effects of the soil texture and the burying depth of the larvae on some biological parameters of *Ceratitis capitata* (Diptera: Trypetidae). African Journal of Agricultural Research **2**: 105–111.

Andersen, M.C., Adams, H., Hope, B., and Powell, M. 2004. Risk assessment for invasive species. Risk Analysis **24**: 787–793.

Andersen, M.C. 2005. Potential applications of population viability analysis to risk assessment for invasive species. Human and Ecological Risk Assessment **11**: 1083–1095.

Canadian Food Inspection Agency (CFIA) 2011. Pest risk assessment guidelines. Canadian Food Inspection Agency, Government of Canada.

Baker, R.H.A., Cannon, R.J.C., and MacLeod, A. 2003. Predicting the potential distribution of alien pests in the UK under global climate change: *Diabrotica virgifera virgifera*. *In* Proceedings of the British Crop Protection Conference - Crop Science and Technology, Glasgow, November 10-12, 2003. pp. 1201–1208.

Baker, R.H.A., Anderson, H., Bishop, S., MacLeod, A., Parkinson, N., Tuffen, M.G. 2014. The UK Plant Health Risk Register: a tool for prioritizing actions. EPPO Bulletin 44(2): 187–194. Available at https://onlinelibrary.wiley.com/doi/pdf/10.1111/epp.12130 (accessed 15 July 2018).)

Baker, R.H.A., Brunel, S., MacLeod, A., Kriticos, D. 2011. Deliverable 3.3 Protocol for mapping endangered areas: Annex 2G instructions for the use and Interpretation of CLIMEX. Available at:https://secure.fera.defra.gov.uk/pratique/downloadItem.cfm?id=749 [Accessed Sept 11 2016]

Battisti, A., Stastny, M., Netherer, S., Robinet, C., Schopf, A., Roques, A., and Larsson, S. 2005. Expansion of geographic range in the pine processionary moth caused by increased winter temperatures. Ecological Applications **15**: 2084–2096.

Bhar, R. and Fahrig, L. 1998. Local vs. landscape effects of woody field borders as barriers to crop pest movement. Conservation Ecology **2**: 3.

Björklund, N., Nordlander, G., and Bylund H. 2003. Host-plant acceptance on mineral soil and humus by the pine weevil *Hylobius abietis* (L.). Agricultural and Forestry Entomology **5**: 61–65.

Blackburn, T.M., Pyšek, P., Bacher, S., Carlton, J.T., Duncan, R.P., Jarošík, V., Wilson, J.R.U., and Richardson, D.M. 2011. A proposed unified framework for biological invasions. Trends in Ecology and Evolution **26**: 333–339.

Boivin, G. 1999. Integrated management for carrot weevil. Integrated Pest Management Review **4**: 21–37.

Bykova, O. 2012. Mechanism controlling the distribution of two invasive species, PhD dissertation, University of Toronto, Toronto, Ontario, Canada.

Bykova, O., and Blatt, S. 2018. Effect of soil type on carrot weevil movement behaviour. Journal of Insect Behaviour **31**: 321–333.

Cambridge, J., Payenski, A., and Hamilton, G.C. 2015. The distribution of overwintering brown marmorated stink bugs (Hemiptera: Pentatomidae) in college dormitories. Florida Entomologist **98**: 1257–1259.

Canadian Forest Service (CFS). 2015. National Forest Pest Strategy. Pest risk analysis framework. User's guide. Canadian Council of Forest Ministers, Ottawa, Ontario.

Coroian, C.O., Mũnoz, I., Schlüens, E.A., Paniti-Telesky, O.R., Erler, S., Furdui, E.M., Mărghitaş, L.A., Dezmirean, D.S., Schlüns, H., de la Rúa, P., and Moritz, R.F. 2014. Climate rather than geography separates two European honeybee subspecies. Molecular Ecology **23**: 2353-2361.

Crawley, M.J. 1986. The population biology of invaders. Philosophical Transactions of the Royal Society of London, B 314: 711–731.

Dowell, R.V. and Wood, T.K. 2014. Influence of freezing temperatures on the distribution of *Umbonia crassicornis* (Hemiptepa: Membracidae) in Florida. Florida Entomologist **97**: 317–319.

Dunning, J.B., Danielson, B.J., and Pulliam, H.R. 1992. Ecological processes that affect populations in complex landscapes. Oikos, **65**: 169–175.

EPPO. 2012. Decision support scheme for an Express Pest Risk Analysis. EPPO Bulletin 42: 457–462. Available at https://onlinelibrary.wiley.com/doi/epdf/10.1111/epp.2591 [accessed 1 August 2018]

Elith, J. 2014. Predicting distributions of invasive species. *In* Risk-based decisions for biological threats. *Edited by* T.R. Walshe, A. Robinson, M. Nunn and M.A. Burgman. Cambridge University Press. pp x–y.

Engel, K.R., Tollrian, R., and Jeschke, J.M. 2011. Integrating biological invasions, climate change and phenotypic plasticity. Communicative and Integrative Biology **4**: 247–250.

Environment Canada. 2015. Canadian climate normals, 1981-2010, Ontario, Canadian Climate Program [online]. Available from http://climate.weather.gc.ca/climate_normalsé [accessed 1 May 2015].

Fahrig, L., and Jonsen, I. 1998. Effect of habitat patch characteristics on abundance and diversity of insects in an agricultural landscape. Ecosystems, **1**: 197–205.

Food and Agriculture Organization (FAO). 2017. Pest risk analysis for quarantine pests. ISPM No. 11, FAO, Rome.

Flitters, N.E., and Messenger, P.S. 1965. Effect of temperature and humidity on development and potential distribution of the Mexican fruit fly in the United States. USDA Technical Bulletin 1330.

Gariepy T.D., Haye T., Fraser H., and Zhang J. 2014. Occurrence, genetic diversity, and potential pathways of entry of *Halyomorpha halys* in newly invaded areas of Canada and Switzerland. Journal of Pest Science **87**: 17–28.

Gevney, M., and Worner, S.P. 2006. Prediction of global distribution of insect pest species in relation to climate by using an ecological informatics method. Journal of Economic Entomology **99**: 979–986.

Grafius, E., and Collins, R.D. 1986. Overwintering sites and survival of the carrot weevil, *Listronotus oregonensis* (Coleoptera: Curculionidae). Environmental Entomology **15**: 113–117.

Gutierrez, A.P., Ponti, L., Hoddle, M., Almeida, R.P.P., and Irvin, N.A. 2011. Geographic distribution and relative abundance of the invasive glassy-winged sharpshooter: effects of temperature and egg parasitoids. Environmental Entomology **40**: 755–769.

Haye T., Abdallah S., Gariepy T.D., and Wyniger D. 2014. Phenology, life table analysis and temperature requirements of the invasive brown marmorated stink bug, *Halyomorpha halys*, in Europe. Journal of Pest Science **87**: 407–418.

Heikkilä, J., Tuomola, J., Pouta, E., Hannunen, S. 2016. FinnPRIO: a model for ranking invasive plant pests based on risk. Biological Invasions **18**: 1827–1842.

Held, D., and Ray, C. 2009. Asiatic garden deetle *Maladera castanea* (Coleoptera: Scarabaeidae) grubs found in damaged turf in Alabama. The Florida Entomologist **92**(4): 670-672.

Holt J, Leach AW, Schrader G, Petter, F., MacLeod, A., van der Gaag, D.J., Baker, R.H.A., and Mumford, J.D. 2014. Eliciting and combining decision criteria using a limited palette of utility functions and uncertainty distributions: illustrated by application to pest risk analysis. Risk Analysis **34**: 4–16.

Jackson, S.T., Betancourt, J.L., Both, R.K., and Gray, S.T. 2009. Ecology and ratchet of events: climate variability, niche dimensions and species distributions. Proceeding of National Academy of Sciences 106: 19685–19692.

Inkley, D.B. 2012. Characteristics of home invasion by the brown marmorated stink bug (Hemiptera: Pentatomidae). Journal of Entomological Science. **47**: 125–130.

Intergovernmental Panel on Climate Change (IPCC). 2010. Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties. IPCC Cross Working Group Meeting on Consistent Treatment of Uncertainties.

Karsten, M., Barton, M., Addison, P., Addison, M.F. and Terblanche, J.S. 2018. A synthesis for managing invasions and pest risks simultaneously for tephritid fruit flies in South Africa. Entomologia Experimentalis et Applicata. doi:10.1111/eea.1266.

Kearney, M., and Porter, W.P. 2009. Mechanistic niche modelling: combining physiological and spatial data to predict species' ranges. Ecological Letters **12**: 334–350.

Kenis, M., Rabitsch, W., Auger-Rozenberg, M.A., and Roques, A. 2007. How can alien species inventories and interception data help us prevent insect invasions? Bulletin of Entomological Research **97**:489–502.

Kinoshita, S., and Yagi, N. 1930. Notes on the northern limit of distribution of the paddy borer. Nihon Gakuzyutsu Kyokai Hokoku **6**: 546–548. (in Japanese)

Kukal, O., Ayres, M.P., and Scriber, J.M. 1991. Cold tolerance of pupae in relation to the distribution of swallowtail butterflies. Canadian Journal of Zoology **69**: 3028–3037.

Kumar, S., Neven, L.G., and Yee, W.L. 2014. Evaluating correlative and mechanistic niche models for assessing the risk of pest establishment. Ecosphere, **5**: 86.

Kriticos, D.J., Maywald, G.F., Yonow, T., Zurcher, E.J., Herrmann, N.I. and Sutherst, R.W. 2015. CLIMEX Version 4: Exploring the effects of climate on plants, animals and diseases. CSIRO, Canberra.

Lawton, J.H., and Brown, K.C. 1986. The population and community ecology of invading insects. Philosophical Transactions of the Royal Society of London, B 314: 607–617.

Li, C., Liu, H., Huang, F., Cheng, D.F., Wang, J.J., Zhang, Y.H., Sun, J.R., and Guo, W.C. 2014. Effect of temperature on the occurrence and distribution of Colorado potato beetle (Coleoptera: Chrysomelidae) in China. Environmental Entomology **43**: 511–519.

Lines, G., Pancura, M., and Lander, C. 2006. Building climate change scenarios of temperature and precipitation in Atlantic Canada using the Statistical Downscaling Model (SDSM). Science Report Series 2005-9, (October 2006 rev.), Meteorological Service of Canada Atlantic Region, Environment Canada, Dartmouth, NS.

Moignot, B., and Reynaud, P. 2013. Developing a methodology for the prioritization of pests in plant health. Euro Reference No 9: 5-9.

Møller, A.P. 2013. Long-term trends in wind speed, insect abundance and ecology of an insectivorous bird. Ecosphere, **4**: 1–11.

Morrison, W.R., Mathews, C.R. and Leskey, T.C. 2016. Frequency, efficiency, and physical characteristics of predation by generalist predators of brown marmorated stink bug (Hemiptera: Pentatomidae) eggs. Biological Control **97**: 120–130.

Müller, F., Baessler, C., Schubert, H., and Klotz, S. 2010. Long-term ecological research. Between theory and application. 1st Edition, Springler.

Nielsen, A.L., Chen, S., and Fleischer, S. 2016. Coupling developmental physiology, photoperiod, and temperature to model phenology and dynamics of an invasive Heteropteran, *Halyomorpha halys*. Frontiers in Physiology 7:165.

Papadopoulos, N.T., Katsoyannos, B.I., Carey, J.R., and Kouloussis, N.A. 2001. Seasonal and annual occurrence of the Mediterranean fruit fly (Diptera: Tephritidae) in Northern Greece. Annals of Entomological Society of America **94**: 41–50.

Pratt, P.D and Center, T.D. 2012. Biocontrol without borders: the unintended spread of introduced weed biological control agents Center. BioControl, **57**: 319–329.

Reid, RW. 1969. The influence of humidity on incubating bark beetle eggs. The Canadian Entomologist **101**: 182–183.

Rehman, A., Inayatullah, C. and Majid, A. 2002. Descriptive model to predict the outbreaks of yellow rice stem borer, *Scirpophaga incertulas*. Pakistan Journal of Agricultural Research **17**: 282–289.

Richardson, D.M., Pysek, P., Rejmánek, M., Barbour, M.G., Panetta, F.D., and West, C.J. 2000. Naturalization and invasion of alien plants: concepts and definitions. Diversity and Distributions **6**: 93–107.

Safranyik, L. 1978. Effects of climate and weather on mountain pine beetle populations. *In* Proceedings of Symposium on Theory and Practice of Mountain Pine Beetle Management in Lodgepole Pine Forests, April 25-27, 1978. *Edited by* A.A. Berryman, G.D. Amman, and R.W. Stark. Washington State University, Pullman, Washington. College of Forestry, Wildlife and Range Sciences, University of Idaho, Moscow, Idaho. pp 77–84.

Safranyik, L., and Wilson, B. 2006. The Mountain Pine Beetle: a Synthesis of its Biology and Management in Lodgepole Pine. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC. Available from https://www.for.gov.bc.ca/hfd/library/mpb/MPBBook-ofront.pdf [accessed 13 May 2019]

Shi, P., Zhong, L., Sandhu, H.S., Ge, F., Xu, X., and Chen, W. 2012a. Population decrease of *Scirpophaga incertulas* Walker (Lepidoptera Pyralidae) under climate warming. Ecology and Evolution **2**: 58–64.

Shi, P., Wang, B., Ayres, M.P., Ge, F., Zhong, L., and Li, B-L. 2012b. Influence of temperature on the northern distribution limits of *Scirpophaga incertulas* Walker (Lepidoptera: Pyralidae) in China. Journal of Thermal Biology **37**: 130–137.

Simonet, D.E., and Davenport, B.L. 1981. Temperature requirements for development and oviposition of the carrot weevil (Coleoptera, Curculionidae). Annals of the Entomological Society of America **74**: 312–315.

Sporleder, M., Tonnang, H.E.Z., Juarez, H., Gonzales, J.C., Carhuapoma, P., and Kroschel, J. 2013. Application and use of insect phenology modeling for invasive species for regional and global risk assessments under future climate change scenarios. *In* Potential invasive pests of agricultural crops, *Edited by* J. Peña. Wallingford, Oxon, UK: CABI. pp. 412–426.

Tantowijoyo, W., and Hoffmann, A.A. 2010. Identifying factors determining the altitudinal distribution of the invasive pest leafminers *Liriomyza huidobrensis* and *Liriomyza sativae*. Entomologia Experimentalis et Applicata **135**: 141–153.

Tillman, P.G. 2011. Influence of corn on stink bugs (Heteroptera: Pentatomidae) in subsequent crops. Environmental Entomology **40**: 1159–1176.

Tran, J.K., Ylioja, T., Billings, R.F., Regniere, J., and Ayres, M.P. 2007. Impact of minimum winter temperatures on the population dynamics of *Dendroctonus frontalis*. Ecological Applications **17**: 882–899.

Ulrichs, C., and Hopper, K.R. 2008. Predicting insect distributions from climate and habitat data. Biocontrol, **53**: 881–894.

Ungerer, M.J., Ayres, M.P., and Lombardero, M.J. 1999. Climate and the northern distribution limits of *Dendroctonus frontalis* Zimmermann (Coleoptera: Scolytidae). Journal of Biogeography **26**: 1133–114.

Ungerer, M.J., Ayres, M.P., and Lombardero, M.J. 2003. Climate and northern distribution limits of *Dendroctonus frontalis* Zimmermann (Coleoptera: Scolytidae). Journal of Biogeography **26**: 1133–1145.

van der Gaag, D.J., van Leeuwen, G.C.M., Loomans, A.J.M., Potting, R.P.J. and Verhoeven, J.T.J. 2017. Prioritizing risks for plant health in the Netherlands: a method to rank pests according to their probability of introduction. EPPO Bulletin 47: 69–78.

van der Merwe, M., Chown, S.L., and Smith, V.R. 1997. Thermal tolerance limits in six weevil species Coleoptera, Curculionidae from sub-Antarctic Marion Island. Polar Biology **185**: 331–336.

Venugopal, P.D., Coffey, P.L., Dively, G.P. and Lamp, W.O. 2014. Adjacent habitat influence on stink bug (Hemiptera: Pentatomidae) densities and the associated damage at field corn and soybean edges. PLoS ONE, 9(10), e109917. http://doi.org/10.1371/journal.pone.0109917.

Vera, M.T., Rodriguez, R., Segura, D.F., Cladera, J.L., and Sutherst, R.W. 2002. Potential geographical distribution of the Mediterranean fruit fly, *Ceratitis capitata* (Diptera: Tephritidae), with emphasis on Argentina and Australia. Environmental Entomology **31**: 1009–1022.

Visser, D. and Niederwieser, F. 2012. Snout Beetle problem escalates, CHIPS, Technical News, 24–26.

Walther, G.R., Roques, A., Hulme, P.E., Sykes, M.T., Pysek, P., Kühn, I., Zobel, M., Bacher, S., Botta-Dukát, Z., Bugmann, H., Czúcz, B., Dauber, J., Hickler, T., Jarošík, V., Kenis, M., Klotz, S., Minchin, D., Moora, M., Nentwig, W., Ott, J., Panov, V.E., Reineking, B., Robinet, C., Semenchenko, V., Solarz, W., Thuiller, W., Vilà, M., Vohland, K., and Settele, J. 2009. Alien species in a warmer world: risks and opportunities. Trends in Ecology and Evolution **24**: 686–693.

Wakie, T.T., Yee, W.L. and Neven, L.G. 2018.Assessing the risk of establishment of *Rhagoletis cerasi* (Diptera: Tephritidae) in the United States and globally. Journal of Economic Entomology **111**: 1275–1284.

Wang, N., Li, Z., Wu, J., Rajotte, E.G., Wan, F., and Wang, Z. 2009. The potential geographical distribution of *Bactrocera dorsalis* (Diptera: Tephrididae) in China based on emergence rate models and ARCGIS. *In* IFIP International Federation for Information Processing, 293, Computer and Computing Technologies in Agriculture II, Volume 1. *Edited by* D. Li and Z. Chunjiang. Boston, Springer. pp. 399–411.

Williamson, M.H., and Fitter, A. 1996. The varying success of invaders. Ecology, **77**: 1661–1666.

Yoshio, M., and Ishii, M. 2001. Relationship between cold hardiness and northward invasion in the great mormon butterfly, *Papilio memnon* L. (Lepidoptera: Papilionidae) in Japan. Applied Entomology and Zoology **36**: 329–335.