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Risk Assessment

Invasion risk of non-native insects to agricultural lands: a screening for Croatia

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Abstract

Increasing global trade in agricultural and horticultural products coupled with climate change are amongst the main drivers of the global spread of non-native insect species. This trend has substantial impacts on agroecosystems and economies in general. The aim of this study was to screen non-native insect species for their risk of invasiveness in Croatian agricultural lands under current and future climatic conditions. The invasion risk of 18 extant and eight horizon species was determined with a high level of confidence. Of the 26 species screened, 65.4% and 92.3% were ranked as high (or very high) risk under current and future climate conditions, respectively. The results of this study are expected to help policy makers to prioritise the management of both extant and horizon non-native insect species and to assist decision-makers in identifying candidate species for comprehensive, follow-up risk assessment. It is anticipated that the present findings will also contribute to the refinement of national legislation to control and regulate more effectively the spread of non-native insect species in Croatia also accounting for changing climatic conditions.

Key words: climate change, invasive species, Terrestrial Animal Species Invasiveness Screening Kit (TAS-ISK)

Introduction

Biological invasions by non-native terrestrial arthropods, combined with the effects of climate change, pose a substantial threat to native biodiversity, economies, society and the global environment, with agriculture being particularly vulnerable (Ward and Masters 2007; Hulme et al. 2009; Kenis and Branco 2010; Skendžić et al. 2021b; Montgomery et al. 2023). Over the last two centuries, thousands of non-native species have been introduced worldwide either deliberately or accidentally, including to Europe (Nentwig 2007; Hulme et al. 2009). This has resulted in a wide range of negative environmental impacts involving every year costly measures for rehabilitation (Bacon et al. 2012).

The international trade of agricultural and horticultural products combined with the expansion in human mobility has increased the frequency of introduction and spread of non-native terrestrial arthropods at the global scale (Kenis et al. 2007; Hulme et al. 2009; Montgomery et al. 2023). For Europe, this is documented in databases listing some 1590 established species of non-native terrestrial arthropods (Kenis and Branco 2010). Around 50% of these species are phytophagous and belong mainly to the orders Coleoptera and Hemiptera (Roques et al. 2009). Most non-native terrestrial arthropods are recognised as serious pests for agricultural crops with impacts involving yield losses and increased management costs (Kenis and Branco 2010; Hoffmann and Broadhurst 2016; Fried et al. 2017; Diagne et al. 2021). Moreover, many non-native terrestrial arthropods are known to be a pervasive threat to biodiversity, with impacts including predation, parasitism, hybridisation, competition for resources and space, and disease transmission (Kenis et al. 2009; Kenis and Branco 2010).

To counter this global threat, it is crucial to identify those non-native species at higher risk of invasion before their arrival or at an early stage of introduction in order to implement successful management measures of control. This requires an in-depth understanding of the invasion process, including knowledge of introduction pathways, establishment mechanisms, species life cycles and habitat features that favour invasion (Kenis et al. 2007). In Europe, one successfully implemented approach is horizon scanning, which facilitates the collection of information on risks and impacts by those non-native species that are not yet present in the target area (i.e. horizon species) and provides valuable support for management (Roy et al. 2014, 2019). To capture the above aspects, several horizon scanning studies of non-native pests across European countries have recently been conducted at both the regional (Roy et al. 2014, 2019) and national level (Roy et al. 2014; Lucy et al. 2020; Peyton et al. 2020; Kenis et al. 2022; Cano-Barbacil et al. 2023; Dawson et al. 2023).

Within the European and Mediterranean regions, incidents of quarantine pests are recorded in the central communication database of the European and Mediterranean Plant Protection Organization (EPPO: Bacon et al. 2012). The EPPO A1 list includes pests that are not currently present in the EPPO region, whereas the EPPO A2 list includes pests that are present in limited geographical areas within the EPPO region. The third EPPO list, known as the Alert List, serves as a warning mechanism for EPPO member countries and highlights specific pests that pose potential risks and require early attention. From the Alert List, EPPO selects candidates that are subject to a pest risk analysis (EPPO 2024). In 2019, the European Commission established a list of priority quarantine pests for the European Union to which existing legislation must adhere. The current list includes 20 pests of which 17 are insects (EC 2019).

In Croatia, there has been a remarkable increase in the annual introduction of new non-native arthropods (mainly insects), especially in the period 2007–2012 (Matošević and Pajač Živković 2013). However, there is currently no officially recognised inventory of non-native insect species in the country, with the Global Biodiversity Information Facility database reporting the occurrence of 139 non-native arthropods (Roy et al. 2020). According to the last comprehensive and reference-based survey of non-native phytophagous insect and mite species on woody plants in Croatia, 101 of these species (98 insects from six Orders and three mites from the Subclass Acarina) have been recorded (Matošević and Pajač Živković 2013). These species are dominated by Hemiptera (56.4%), Lepidoptera (14.9%) and Hymenoptera (12.9%). Meanwhile, the continued appearance and spread of non-native insects in Croatia has manifested in notable cases, including the orange spiny whitefly *Aleurocanthus spiniferus* (Quaintance, 1903) (Paladin Soče et al. 2020), the polyphagous brown marmorated stink bug *Halyomorpha halys* (Stål, 1855) (Pajač Živković et al. 2021, 2023) and the South American tomato moth *Tuta absoluta* (Meyrick, 1917) (Jurković et al. 2013). Also, some newly established species have become economic pests, such as the spotted-wing drosophila *Drosophila suzukii* (Matsumura, 1931) (Pajač Živković et al. 2019).

Non-native insect species have never been screened for their risk of invasiveness in Croatia. In conjunction with the recently introduced non-native insects mentioned above, there is a high potential for the invasion of species not yet present in this country such as the potato flea beetle *Epitrix cucumeris* (Harris, 1851), the fall armyworm *Spodoptera frugiperda* J.E. Smith, 1797, and the African citrus psyllid *Trioza erytreae* (Del Guercio, 1918), which have recently been reported in some European countries including Portugal and Spain (Boavida et al. 2013; Arenas-Arenas et al. 2019; Vives Moreno and Gastón 2020). The objectives of this study were twofold: (i) to conduct a risk screening of potentially invasive non-native insect species for Croatia that are already present on agricultural land; and (ii) to identify and screen additional invasive non-native insect species that could invade Croatia from neighbouring countries based on a horizon scanning (Table 1). It is expected that the results of this study will provide policy makers with important insights and help them to prioritise the control of non-native insect species on Croatian agricultural land. The present results will also shed light on which species should be subject to comprehensive, follow-up risk assessment (Baker et al. 2008; van Lenteren et al. 2007). This in turn can help improve national legislation regarding non-native insect species by emphasizing the prioritisation of monitoring and the implementation of rapid response measures (Roy et al. 2018). Of note, this study focuses on the screening component of the non-native species risk analysis process, which consists of three sequential steps: risk screening (or identification), risk assessment, and risk management and communication (Vilizzi et al. 2022a).

Table 1. Non-native insects screened with the Terrestrial Animal Species Invasiveness Screening Kit (TAS-ISK) for their invasion risk in agricultural lands of Croatia. The *a priori* categorisation follows the protocol of Vilizzi et al. (2022a): (1) Global Biodiversity Information Facility (GBIF: https://www.gbif.org/); (2) Global Invasive Species Database (GISD: www.iucngisd.org); (3) European Alien Species Information Network (EASIN: https://easin.jrc.ec.europa.eu/easin); (4) Google Scholar literature search. N = no impact/threat; Y = impact/threat; "–" = absent; n.a. = not applicable.

Species name	Common name	*A priori* categorisation				
		GBIF	GISD	EASIN	Google Scholar	Outcome
Extant						
Agrotis ipsilon (Hufnagel, 1766)	black cutworm	–	–	–	–	–
Aleurocanthus spiniferus (Quaintance, 1903)	orange spiny whitefly	N	–	N	Y	Invasive
Ceratitis capitata (Wiedemann, 1824)	medfly	Y	Y	Y	n.a.	Invasive
Corythucha ciliata (Say, 1832)	sycamore lace bug	N	–	Y	n.a.	Invasive
Cydalima perspectalis (Walker, 1859)	box tree moth	Y	–	N	n.a.	Invasive
Drosophila melanogaster Meigen, 1830	common fruit fly	–	–	–	–	–
Drosophila suzukii (Matsumura, 1931)	spotted-wing drosophila	N	–	Y	n.a.	Invasive
Grapholita molesta (Busck, 1916)	oriental fruit moth	N	–	Y	n.a.	Invasive
Halyomorpha halys (Stål, 1855)	brown marmorated stink bug	Y	–	Y	n.a.	Invasive
Harmonia axyridis (Pallas, 1773)	harlequin ladybird	Y	Y	Y	n.a.	Invasive
Nezara viridula (Linnaeus, 1758)	southern green shield bug	Y	–	Y	n.a.	Invasive
Ophraella communa LeSage, 1986	ragweed leaf beetle	N	–	N	n.a.	Non-invasive
Rhagoletis cingulata (Loew, 1862)	cherry fruit fly	N	–	Y	n.a.	Invasive
Rhagoletis completa Cresson, 1929	husk maggot	N	–	Y	n.a.	Invasive
Saissetia oleae (Olivier, 1791)	black scale	N	–	Y	n.a.	Invasive
Scaphoideus titanus Ball, 1932	American grapevine leafhopper	–	–	–	–	–
Tuta absoluta (Meyrick, 1917)	South American tomato moth	N	–	Y	n.a.	Invasive
Viteus vitifoliae (Fitch, 1855)	grape phylloxera	–	–	–	–	-
Horizon						
Aleurocanthus woglumi Ashby, 1915	citrus blackfly	N	–	–	n.a.	Non-invasive
Bactrocera dorsalis (Hendel, 1912)	oriental fruit fly	Y	–	N	n.a.	Invasive
Epitrix cucumeris (Harris, 1851)	potato flea beetle	–	–	–	–	–
Popillia japonica Newman, 1838	Japanese beetle	–	–	–	–	–
Rhagoletis pomonella (Walsh, 1867)	apple maggot	–	–	–	Y	Invasive
Spodoptera frugiperda J.E.Smith, 1797	fall armyworm	Y	–	N	n.a.	Invasive
Thaumatotibia leucotreta (Meyrick, 1913)	false codling moth	N	–	N	n.a.	Non-invasive
Trioza erytreae (Del Guercio, 1918)	African citrus psyllid	N	–	N	Y	Invasive

This is an important distinction in the current context that is often overlooked in the literature and has led to confusion and misinterpretation (see Hill et al. 2020).

Materials and methods

To evaluate the risk of invasiveness of non-native insects for agricultural lands in Croatia (the risk assessment area), the screening involved 26 non-native species (Table 1). These species were selected based on the following criteria: (i) extant (n = 18), i.e. already present in the risk assessment area; and (ii) horizon (n = 8), i.e. not yet reported in, but likely to enter, the risk assessment area in the near future. Compilation of the extant species list was based on their presence in Croatia and their causing economic damage; 13 of these species were *a priori* invasive based on a comprehensive database search (Table 1). The horizon species were identified using the CABI ISC scanning tool (www.cabi.org/horizonscanningtool), the list of priority quarantine pests for the European Union (https://eurl-insects-mites.anses.fr/en/minisite/insects-and-mites/list-eu-quarantine-pests), and the list included in special monitoring programmes of the HAPIH (Center for Plant Protection: http://www.emynet.eu/research-group/hapih-team/) in Croatia. Additionally, the horizon species fulfilled the following criteria: (i) they are pests recorded and present in Europe, and (ii) they are agricultural pests.

Risk screening was undertaken with the Terrestrial Animal Species Invasiveness Screening Kit (TAS-ISK v2.4: Vilizzi et al. 2022c, 2025; available at www.cefas.co.uk/nns/tools/). This decision support tool complies with the "minimum standards" established by EC Regulation No. 1143/2014 on the prevention and management of the introduction and spread of invasive alien species (Roy et al. 2018). The TAS-ISK consists of 55 questions of which 49 comprise the Basic Risk Assessment (BRA) and six the Climate Change Assessment (CCA). The BRA addresses the biogeography/invasion history and biology/ecology of the screened species; the CCA requires the assessor to predict how future predicted climatic conditions are likely to affect the BRA with respect to risks of introduction, establishment, dispersal and impact. Two assessors (DČ and IM) screened 13 species each.

The screening process followed the standard protocol (Vilizzi et al. 2022a) with the assessors providing for each question a response, a confidence level and a justification (Vilizzi and Piria 2022). Upon completion of a species' screening, the BRA and BRA+CCA scores are computed. In both cases, a score < 1 indicates a "low risk" of the species being or becoming invasive in the risk assessment area, whereas a score ≥ 1 indicates a "medium risk" or a "high risk". Distinction between medium-risk and high-risk species is based on a calibrated threshold computed by Receiver Operating Characteristic (ROC) curve analysis (Vilizzi et al. 2022a, 2022b). An additional *ad hoc* threshold was also defined to distinguish within the species classified as high risk those carrying a "very high risk" of invasiveness (as per Britton et al. 2011). After computing the threshold, evaluation of the risk ranks to identify false or true and negative or positive outcomes was not applied to the medium-risk species because their evaluation in follow-up risk assessment depends on both management priorities and the availability of financial resources (Vilizzi et al. 2022a).

The *a priori* categorisation of species to implement ROC curve analysis followed the protocol by Vilizzi et al. (2022a). However, as five species categorised *a priori* as non-invasive achieved high BRA risk scores (≥ 35) and one *a priori* invasive species a relatively low BRA score (22), these were removed from the set of species used for calibration, which was then achieved using the remaining 20 species (Table 1). Rationale for this choice was based on the fact that a species considered to be non-invasive elsewhere outside its native range may achieve a high-risk score for a certain risk assessment area (as in the present case). Fitting of the ROC curve was with pROC (Robin et al. 2011) for R x64 v4.3.2 (R Development Core Team 2023). Permutational ANOVA following normalisation of the data was used to test for differences in the confidence factor (CF: see Vilizzi et al. 2022a)

Table 2. Risk outcomes for the non-native insects screened with the TAS-ISK for agricultural lands of Croatia. For each species, the following information is provided: *a priori* categorisation of invasiveness (N = non-invasive; Y = invasive: see Table 1), Basic Risk Assessment (BRA) and BRA + Climate Change Assessment (BRA+CCA) scores with corresponding risk ranks based on a calibrated threshold of 33 (M = Medium; H = High; VH = Very high, based on an *ad hoc* threshold ≥ 50: see text for details), classification (Class: FP = false positive; TP = true positive; "–" = not implemented as medium-risk: n.a. = non applicable: see text for details), CCA as difference between BRA+CCA and BRA scores, and confidence factor (CF). Risk outcomes for the BRA scores (within interval): M, [1, 33[; H]33, 50[; VH [50, 72]. Risk outcomes for the BRA+CCA scores: M [1, 33[; H]33, 50[; VH [50, 82]. Note the reverse bracket notation indicating an open interval.

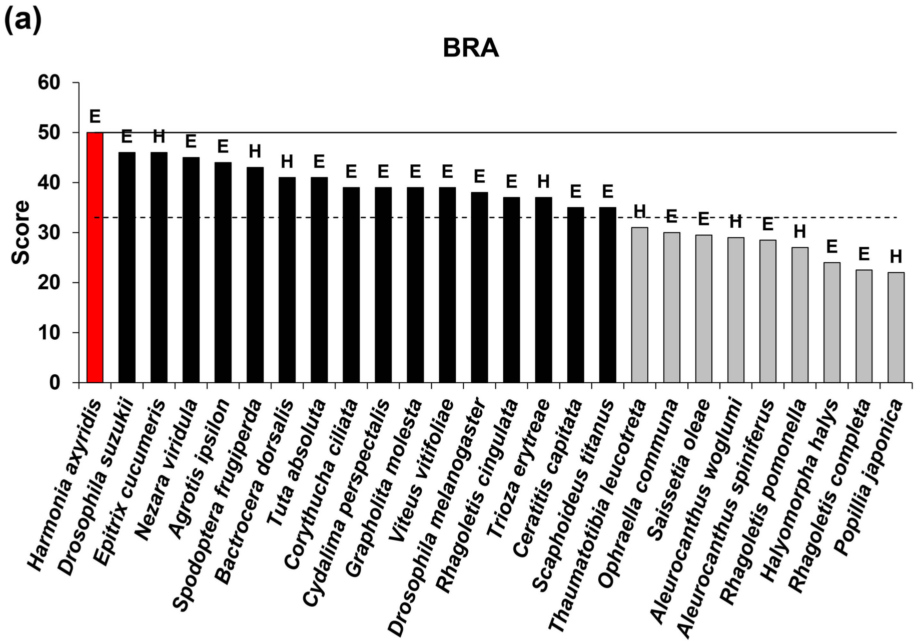
Species name	*A priori*	BRA			BRA+CCA			CCA	CF		
		Score	Rank	Class	Score	Rank	Class		Total	BRA	CCA
Extant											
Agrotis ipsilon	n.a.	44.0	H	n.a.	50.0	VH	n.a.	6	0.77	0.76	0.83
Aleurocanthus spiniferus	Y	28.5	M	–	38.5	H	TP	10	0.73	0.71	0.88
Ceratitis capitata	Y	35.0	H	TP	35.0	H	TP	0	0.74	0.73	0.75
Corythucha ciliata	Y	39.0	H	TP	45.0	H	TP	6	0.68	0.71	0.42
Cydalima perspectalis	Y	39.0	H	TP	45.0	H	TP	6	0.78	0.76	0.96
Drosophila melanogaster	n.a.	38.0	H	n.a.	42.0	H	n.a.	4	0.78	0.80	0.63
Drosophila suzukii	Y	46.0	H	TP	46.0	H	TP	0	0.73	0.72	0.75
Grapholita molesta	Y	39.0	H	TP	45.0	H	TP	6	0.73	0.75	0.54
Halyomorpha halys	Y	24.0	M	–	36.0	H	TP	12	0.77	0.74	1.00
Harmonia axyridis	Y	50.0	VH	TP	56.0	VH	TP	6	0.79	0.80	0.71
Nezara viridula	Y	45.0	H	TP	51.0	VH	TP	6	0.79	0.79	0.75
Ophraella communa	N	30.0	M	–	36.0	H	FP	6	0.69	0.70	0.58
Rhagoletis cingulata	Y	37.0	H	TP	37.0	H	TP	0	0.75	0.76	0.75
Rhagoletis completa	Y	22.5	M	–	22.5	M	–	0	0.65	0.64	0.75
Saissetia oleae	Y	29.5	M	–	29.5	M	–	0	0.68	0.70	0.50
Scaphoideus titanus	n.a.	35.0	H	n.a.	35.0	H	n.a.	0	0.78	0.75	1.00
Tuta absoluta	Y	41.0	H	TP	47.0	H	TP	6	0.79	0.79	0.75
Viteus vitifoliae	n.a.	39.0	H	n.a.	39.0	H	n.a.	0	0.82	0.80	1.00
Horizon											
Aleurocanthus woglumi	N	29.0	M	–	41.0	H	FP	12	0.81	0.79	1.00
Bactrocera dorsalis	Y	41.0	H	TP	53.0	VH	TP	12	0.75	0.75	0.75
Epitrix cucumeris	n.a.	46.0	H	n.a.	58.0	VH	n.a.	12	0.73	0.71	0.88
Popillia japonica	n.a.	22.0	M	n.a.	34.0	H	n.a.	12	0.77	0.74	0.96
Rhagoletis pomonella	Y	27.0	M	–	39.0	H	TP	12	0.70	0.70	0.75
Spodoptera frugiperda	Y	43.0	H	TP	55.0	H	TP	12	0.79	0.77	0.96
Thaumatotibia leucotreta	N	31.0	M	–	43.0	H	FP	12	0.68	0.70	0.50
Trioza erytreae	Y	37.0	H	TP	49.0	H	TP	12	0.72	0.70	0.88

between the BRA and BRA+CCA using a Bray-Curtis dissimilarity measure, 9999 unrestricted permutations of the raw data, and with statistical effects evaluated at $\alpha = 0.05$.

Results

The ROC curve analysis provided a threshold of 33 and an AUC of 0.7255 (0.5107–0.9403 95% CI). The threshold was therefore used for calibration of the BRA and BRA+CCA scores to distinguish between medium- and high-risk species under current and predicted climate conditions, respectively (Table 2). The TAS-ISK reports for the 26 screened species are provided in Supplementary material Appendix 1.

Based on the BRA scores (Table 2, Figure 1a), 17 (65.4%) species were ranked as high risk and 9 (34.6%) as medium risk. Of the 17 species categorised *a priori* as invasive, 12 were ranked as high risk (true positives), whereas none of the three species categorised *a priori* as non-invasive was



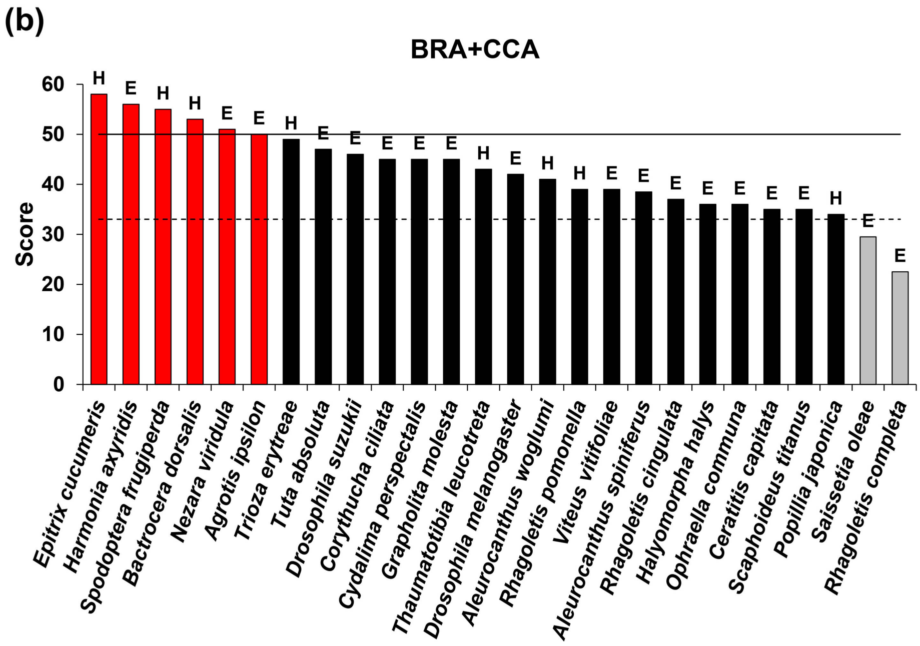


Figure 1. Risk outcome scores for the non-native insects (E = Extant; H = Horizon) screened with the Terrestrial Animal Species Invasiveness Screening Kit (TAS-ISK) for agricultural lands of Croatia. (a) Basic Risk Assessment (BRA) scores; (b) BRA + Climate Change Assessment (BRA+CCA) scores. Red bars = very high-risk species; Black bars = high-risk species; Gray bars = medium-risk species; Solid line = very high-risk (VH) threshold; Hatched line = high-risk (H) threshold. Thresholds as per Table 2.

ranked as high risk. Of the six species excluded from the *a priori* categorisation, five were ranked as high risk. Of the nine medium-risk species, three were *a priori* non-invasive, five invasive, and one not categorised.

Based on the BRA+CCA scores (Table 2, Figure 1b), 24 (92.3%) species were ranked as high risk and 2 (7.7%) as medium risk. Of the *a priori* invasive species, 15 were ranked as high risk (true positives), and all *a priori* non-invasive species were ranked as high risk (false positives). All six species excluded from *a priori* categorisation were ranked as high risk. Of the nine medium-risk species, three were *a priori* non-invasive, five invasive, and one not categorised.

Based on an *ad hoc* threshold ≥ 50, the harlequin ladybird *Harmonia axyridis* (Pallas, 1773) was ranked as very high risk for both the BRA and BRA+CCA, and an additional five species for the BRA+CCA only [i.e. *Epitrix cucumeris*, *Spodoptera frugiperda*, oriental fruit fly *Bactrocera dorsalis* (Hendel, 1912), southern green shield bug *Nezara viridula* (Linnaeus, 1758), black cutworm *Agrotis ipsilon* (Hufnagel, 1766)] (Table 2, Figure 1). The number of species ranked as high (and very high) risk increased from 17 (65.4%) under the BRA to 24 (92.3%) under the BRA+CCA. The CCA resulted in an increase in the BRA score (cf. BRA+CCA score) for 19 (73.1%) species and in no change for 7 (26.9%) (Table 2).

The mean CF_{Total} was 0.745 ± 0.009 SE, the mean CF_{BRA} 0.741 ± 0.008 SE and the mean CF_{CCA} 0.777 ± 0.034 SE, hence in all cases indicating high confidence (Table 2). There was no difference between mean CF_{BRA} and mean CF_{CCA} ($F^{\#}_{1,50}$ = 1.07, $P^{\#}$ = 0.314; # = permutational value).

Discussion

Risk outcomes

This study is the first to provide an extensive risk screening of extant and horizon non-native insects for a European country (Croatia) and is also the first calibrated application of the TAS-ISK. The invasiveness risk of 26 extant and horizon non-native insect species posing a threat to agricultural lands in Croatia was identified with a high level of confidence under both current (BRA) and predicted climate change conditions (BRA+CCA). Although lack of knowledge of species' responses under predicted global warming scenarios may lead to significantly lower confidence in answering the CCA questions relative to the BRA questions (see Vilizzi et al. 2022a), insects are generally known to respond positively to warmer summer temperature conditions, especially when introduced from (native) areas characterised by a temperate climate (Harvey et al. 2023). In this study, this increased the confidence in responses to the questions pertaining to climate change, which was not significantly different from the confidence in responses to the questions relative to current climate conditions. Under these conditions, of the 18 extant non-native insects, 13 were ranked as high risk, and of the eight horizon species, four were also ranked as high risk. However, the latter species increased to seven under predicted climate change scenarios. The prevalence of invasive species underlines the generally invasive nature of insects, which is attributable to a number of key factors including: (i) high reproductive rates allowing the rapid establishment of populations; (ii) a wide range of food preferences favouring exploitation of resources in newly colonised areas; (iii) a small size favouring inconspicuous establishment; (iv) broad climatic tolerance increasing the chance of invasion and survival during transport; and (v) absence of predators contributing to their dominance in invaded areas (Pitt and Witmer 2014; Venette and Hutchison 2021).

Among the extant species, *Harmonia axyridis* was identified as the most invasive. This outcome aligns with its status as the world's most hazardous and widespread non-native coccinellid (Roy et al. 2006, 2016). This species was introduced to Europe in the 1980s as a biological control agent for aphids and released on a large scale (Roy and Migeon 2010). Due to its polyphagous nature, *H. axyridis* has spread rapidly throughout Europe (van Lenteren et al. 2007; Roy and Migeon 2010). In Croatia, this species is widespread and exhibits remarkable adaptability and invasiveness (Mičetić Stanković et al. 2011). Consequently, it has caused a decline in biodiversity in European ecosystems and poses a serious threat to native predators in Croatia (van Lenteren et al. 2007; Roy and Migeon 2010). All this underlines the urgent need for globally harmonised regulations for biological control agents (van Lenteren et al. 2007).

Among the other extant species whose level of risk increased from high (under current climate conditions) to very high (under predicted climate conditions), two species stand out, namely *Agrotis ipsilon* and *Nezara viridula*. Both species are known to be widespread polyphagous pests that cause damage to crop and have high economic impact on agricultural production (Barclay 2004; Ciceoi et al. 2017; Rodingpuia and Lalthanzara 2021; Lee et al. 2023). As a result of their global invasiveness, their very high-risk scores in this study were expected. In Croatia, *A. ipsilon* and *N. viridula* are dominant and widespread, and occasionally occur *en masse* causing damage to crop production (Maceljski 2002; Vratarić and Sudarić 2009; Majić et al. 2010; Lemic et al. 2016; Pintar et al. 2019). The recent effects of climate change, which have been characterised by frequent deviations in average temperatures and precipitation, have contributed to the increased occurrence of these pests in Croatia (Maceljski 2002; Pintar et al. 2019), and this is likely to increase further in the future.

The highest BRA+CCA scores among the horizon species were achieved by *Bactrocera dorsalis*, *Epitrix cucumeris* and *Spodoptera frugiperda*, which were all ranked as very high risk. Of these species, *B. dorsalis* and *S. frugiperda* are on the European Union's list of priority quarantine pests and are subject to Regulation (EU) 2019/1702 (EC 2019). *Bactrocera dorsalis* is curently transient in Italy as a neighbouring country of Croatia (Nugnes et al. 2018). As a result of its pronounced polyphagy and high reproductive capacity, this species poses the greatest threat to European orchards (Nugnes et al. 2018). A comprehensive risk assessment at the EU level has shown that the coastal regions of the Mediterranean Sea, including Croatia, are the most vulnerable to invasions by this species due to favourable eco-climatic conditions and the availability of host fruits able to support viable populations (De Villiers et al. 2016; European Food Safety Authority et al. 2019). *Epitrix cucumeris* is currently documented in two European countries, namely Portugal and Spain (Hoop et al. 2017). A comprehensive pest risk assessment carried out for the Euro-Mediterranean region for this species has shown that there is a high risk of further spread through the commercial transportation of potato tubers to other parts of Europe, including Croatia. Given this threat, emergency measures were taken in the EU in 2012 to reduce the risk of further introduction and spread of *E. cucumeris* (Eyre and Giltrap 2013; EPPO 2017). This species is currently on the EPPO A2 list of pests recommended for regulation as quarantine pests (EPPO 2017). *Spodoptera frugiperda* is restricted to limited areas of Europe. However, its marked polyphagy and migratory ability are rising concern about the possible impact of transient populations invading new areas where conditions are favourable for their establishment. A risk assessment for the Mediterranean coastal areas of Southern Europe has revealed that these regions are highly suitable for the establishment of this pest (Gilioli et al. 2023). This finding underscores the serious threat that the species poses to agricultural land along the Croatian coastline due to increasingly milder climates especially under scenarios of global warming.

Other horizon species that are on the European Union's list of priority quarantine pests and are of major importance for agricultural lands in Croatia are the Japanese beetle *Popilla japonica* Newman, 1838, the apple maggot *Rhagoletis pomonella* (Walsh, 1867), and the false codling moth *Thaumatotibia leucotreta* (Meyrick, 1913). In this study, these highly polyphagous invasive insects were ranked as medium risk under current climate conditions, but as high risk under predicted climate conditions. As they all have widespread host plants on European territory and could have better survival conditions due to changing climatic conditions, there is a high likelihood of their becoming invasive in Croatia.

Climate change

With a current temperature rise of 2.3 °C, Europe is the continent experiencing the fastest warming primarily due to human-related activities (WMO 2023). The effects of climate change extend across all European regions, although with differences in type and extent (Pajek et al. 2019). Climate projections based on the Köppen-Geiger system indicate a shift towards warmer temperate periods by 2050 characterised by hot and humid or warm summers, with Cfa, Cfb, and Csa climate types becoming predominant in Croatia (Rubel and Kottek 2010). This shift increases the likelihood of non-native insect species posing a threat to biodiversity, thereby emphasising the need for proactive management measures (Hughes et al. 2020).

Climate change contributes substantially to the spread of non-native insect species and poses a potential threat to the native fauna (Skendžić et al. 2021a). As climatic conditions continue to evolve, studies indicate an alarming trend. For example, this study has shown that under projected future climate scenarios, 92% of the screened insect species increased their risk scores under predicted climate change conditions. This increased risk suggests that non-native insect species may find increasingly favourable conditions for their establishment and spread as temperatures rise and precipitation patterns change, with potentially negative ecological consequences for the native ecosystems. These findings emphasise the urgency of implementing proactive measures and adaptive strategies to mitigate the potential ecological disruption associated with climate change and the spread of non-native species.

In the field of agriculture, climate change in Europe poses a complex challenge, particularly with regard to the management of invasive pests. Climate change can affect the distribution, abundance and behaviour of species, including insects, in various ways (Skendžić et al. 2021a, b). The present results suggest that climate-induced shifts in life cycles and phenology are closely associated with the invasive potential and behaviour of several non-native insect species. Changing climatic conditions can lead to changes in species life cycles and phenological events, making pest control strategies more complex and challenging to implement (Skendžić et al. 2021a, b).

Management and policy

Given the increasing frequency and damaging effects of insect invasions (as in the case of *Harmonia axyridis*: Roy et al. 2006, 2016), an economic and practical approach is represented by initiative-taking prevention. This includes surveillance and regulation during a species' introduction or establishment phase, starting with initiatives aimed at identifying and controlling transport vectors and routes (Venette and Hutchinson 2021). Thorough inspections, strict enforcement, systematic evaluation and continuous improvement of vectors and transport routes are essential components. In addition, climate-induced changes, including earlier field seasons, variable weather events and alterations in species survival, pose challenges to pest control strategies and diminish the effectiveness of current measures (Lin 2011; Lemic et al. 2024). These climatic shifts can lead to extended periods of pest activity, increased pest resistance and altered migration patterns. The specific impacts on these species vary depending on regional climate patterns, their adaptive capacity and interactions with local ecosystems (Hulme 2006; Aluja et al. 2014). Such variations necessitate the development of more adaptive and region-specific pest management strategies to maintain agricultural productivity and ecosystem health.

Certain species ranked in this study as high risk (i.e. *Bactrocera dorsalis*, *Epitrix cucumeris*, and *Spodoptera frugiperda*) have an increased risk of spreading through transport and pose a potential threat to agricultural lands outside their current regions. Comprehensive information about transport routes is essential for conducting risk assessments, monitoring and effective management of non-native species (Hulme 2009). Prevention strategies that consider dispersal pathways and protocols specifically designed for the arrival of individual non-native species in specific regions are necessary to minimise negative impacts (Essl et al. 2015). Given the uncertainty associated with the establishment of invasive species, the application of preventive measures through border security and quarantine has proven to be the most effective management approach, especially for high-risk species (Venette et al. 2021). The increase in travel and trade increases the risk of insect invasion and requires advances in detection technologies and control methods (Myers et al. 2000). Of the aforementioned species, the potential spread of *E. cucumeris* is mainly influenced by the trade in potato tubers and poses a major threat to European regions, including Croatia. The countries with the largest gaps or weak border controls also have the highest numbers of established insects (Bacon et al. 2012). This is a particularly important issue in the EU, where the recent removal of borders in some countries (e.g. Croatia and Slovenia) has led to an increase in incidents involving the introduction of non-native species (Piria et al. 2017).

The Convention on Biological Diversity instructs member states to prevent, control or eradicate the introduction of invasive species that pose a threat to ecosystems (CBD 2023). Eradication involves the removal of invasive populations and contributes to the restoration of previously endangered areas. Successful eradication programmes require early detection, the susceptibility of the species' biology to control measures, sufficient eradication resources, public support and measures to prevent reinvasion (Pyšek and Richardson 2010). Governments can introduce quarantine measures that restrict the movement of certain goods or require treatments such as fumigation of imported material to prevent re-invasion. However, despite the efforts of governments, these measures cannot completely prevent the introduction of all invasive insect species, as global trade and passenger flows are constantly increasing and can overwhelm containment measures (Kompas et al. 2023). While the effort to prevent or eradicate invasive insects is laudable, it is an arduous and expensive undertaking that requires prioritisation of limited resources for eradication or control measures (Garnas et al. 2016; Liebhold et al. 2016; Riera et al. 2021).

The eradication of highly invasive and hazardous species such as *B. dorsalis* and *S. frugiperda* has been attempted in various regions of the world. Efforts to control and eradicate these species are often undertaken in response to a species' invasive nature and potential threat to agriculture and ecosystems (Liebhold et al. 2016; McLaughlin and Dearden 2019). However, the success of eradication efforts can vary, and the feasibility of complete eradication depends on factors such as species' reproductive capacity, dispersal mechanisms, available control methods and extent of infestation. *Bactrocera dorsalis*, for example, has been the target of eradication programmes in several countries (Seewooruthun et al. 1998; Itô 2005;

Ohno et al. 2009; Vargas et al. 2010; Leblanc et al. 2013; Manrakhan et al. 2015). These programmes usually involve the use of integrated pest management strategies, including the sterile insect technique, insecticides and quarantine measures (Seewooruthun et al. 1998; Manrakhan et al. 2015). On the other hand, *S. frugiperda* is a difficult species to control due to its rapid spread and resistance to certain pesticides. Various countries have taken measures to control its impact, but complete eradication is unlikely to succeed due to its migratory behaviour (Babendreier et al. 2022). The success of eradication measures often depends on the cooperation of international efforts, the use of integrated pest management methods and continuous monitoring. Despite all efforts, complete eradication is not always possible and management strategies usually focus on minimising the impact of a species and preventing its further spread (Gutierrez and Ponti 2013).

The EU has recognised the importance of combating invasive species and has introduced comprehensive strategies and regulations to prevent and control their spread (EC 2023). The EU Regulation on the Prevention and Management of the Introduction and Spread of Invasive Alien Species outlines measures for early detection, rapid eradication and effective management within the EU. In addition, the European Green Deal emphasises the importance of protecting biodiversity and promoting sustainable agriculture, which goes hand in hand with efforts to tackle the challenges posed by invasive species (EC 2023). The integration of European policies strengthens a unified response to the difficult task of managing invasive species in the region.

In conclusion, the increased risk of adverse impacts from invasive insects, exacerbated by climate change and reduced barriers to their successful colonisation, poses a significant global scientific and policy challenge. The results of this study emphasise the need for a thorough risk assessment of more potential pest species, as their management will become a priority concern in the future. Urgent international cooperation is essential to effectively contain and regulate the spread of these invasive species.

Author’s contribution

IPŽ and DL designed the concept; IPŽ, DL, LV and MP wrote the first draft of the manuscript; DČ and IM conducted the screenings; HVC inspected the data; LV analysed the data. All authors inspected and approved the final version of the manuscript prior to submission.

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Supplementary material

The following supplementary material is available for this article:

Appendix 1. TAS-ISK reports for the 26 insect species screened for their invasion risk in agricultural lands of Croatia.

This material is available as part of online article from:
http://www.reabic.net/journals/mbi/2025/Supplements/MBI_2025_Zivkovic_etal_SupplementaryMaterial.xlsx