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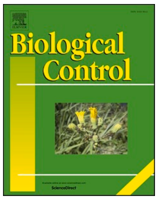

Guidelines and framework to assess the feasibility of starting pre-emptive risk assessment of classical biological control agents

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HIGHLIGHTS

- In this perspective paper we address the concept of pre-emptive biological control as a novel approach to enhance biocontrol preparedness.
- We highlight the importance of pre-emptive biological control and provide examples of pre-emptive biological control programmes conducted, or currently underway, against different high-risk pests.
- We define a set of aspects that should be considered when selecting a suitable target pest for pre-emptive biocontrol risk assessment.
- We provide a set of guidelines and a decision framework to assess the feasibility of conducting pre-emptive risk assessment for candidate biological control agents against high-risk arthropod pests.
- We comment on how the proposed guidelines and decision framework will provide biocontrol practitioners with a suitable tool to assess if biocontrol risk assessment against a high-risk pest could be initiated pre-emptively.

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ABSTRACT

Non-native invasive arthropod species threaten biodiversity and food security worldwide, resulting in substantial economic, environmental, social and cultural costs. Classical biological control (CBC) is regarded as a cost-effective component of integrated pest management programmes to manage invasive arthropod pests sustainably. However, CBC programmes are traditionally conducted once a pest has established in a new environment, and invariably all research needed to achieve approval to release a biological control agent can take several years. During that time, adverse impacts of the pest accelerate. A pre-emptive biocontrol approach will provide the opportunity to develop CBC for invasive pests before they arrive in the country at risk of introduction and therefore enhance preparedness. A critical aspect of this approach is that risk assessment is carried out *in advance* of the arrival of the pest. Implementing pre-emptive biocontrol risk assessment means that natural enemies can be selected, screened in containment or abroad and potentially pre-approved prior to a pest establishing in the country at risk, thus improving CBC effectiveness. However, such an approach may not always be feasible. This contribution defines the fundamental prerequisites, principles, and objectives of pre-emptive biocontrol risk assessment. A set of guidelines and a decision framework were developed, which can be used to assess the feasibility of conducting a pre-emptive risk assessment for candidate biological control agents against high-risk arthropod pests.

1. Introduction

Non-native invasive species threaten global biodiversity and food security resulting in substantial economic costs reported to be in excess of US$100 billion annually (Jardine and Sanchirico 2018). Approximately 480,000 non-native species have been introduced into different ecosystems worldwide, and the threat posed by invasive species is increasing due to the globalisation of trade, tourism, and climate change (CABI 2019; Paini et al. 2016). Measures have been introduced for the prevention and early detection of invasive species, but management tends to be reactive once the pest arrives and an outbreak is discovered. The first management practices are usually aimed at eradication, but if this is unsuccessful, the pest establishes and strategies switch to population control and slowing down the spread of the invasive species (Fleming et al. 2017; Harris et al. 2018; Robertson et al. 2020).

Identifying future risks, and preparing to manage those risks, is becoming increasingly important to help mitigate the impact that invasive species have on native ecosystems once established in a new environment. Classical biological control (CBC), the introduction of a non-indigenous biological control agent (BCA) aiming at permanent control of the target pest, is recognised as a key strategy for managing invasive insect pest populations (Hajek 2004; Van Driesche et al. 2008), and since the late 1800 s there have been over 6000 introductions of more than 2000 insect BCAs world-wide to control over 500 insect pests (Kenis et al. 2017). Such introductions have resulted in the successful control of 29% of the pests being targeted, which highlights the effectiveness of CBC (Kenis et al. 2017).The deliberate introduction of an exotic BCA is subject to regulatory measures, including a rigorous risk assessment and review process (Castella et al. 2022; Ehlers et al. 2020; Barratt and Ehlers 2017; Barratt et al. 2018), and invariably all research required to achieve approval for the introduction and release of a BCA can take several years. As a result, CBC programmes are traditionally implemented once a pest is established and widespread in an invaded range.

The implementation of a pre-emptive biological control approach could accelerate the response to high-risk biosecurity threats since natural enemies can be selected, screened and pre-approved for release in the eventuality of a pest invasion (Hoddle 2023). This novel approach to the screening and registration process for classical biocontrol agents could expedite the response to invasive pests with biocontrol implemented more promptly following the arrival of the pest in a new area (Hoddle 2023; Conti et al. 2021). Accordingly, a pre-emptive biocontrol strategy could lead to a significant reduction of pest population densities and rates of spread during an early stage of invasion, resulting in reduced environmental and economic impacts (Hoddle 2023). After applying the pre-emptive strategy, a quick extensive biocontrol release could then be possible in the event of an incursion, which may even contribute to the successful eradication of a pest population while still within a small, confined area (Charles et al. 2019). However, not all pest species may be suitable candidates for pre-emptive biocontrol, and a number of factors (e.g., the likelihood of an invasion and the availability of effective natural enemies) need to be considered before embarking into extensive biocontrol programmes. As a first step, the fundamental prerequisites, principles and objectives of best-practice pre-emptive risk assessment need to be defined in order to assess the feasibility of starting pre-emptive biocontrol risk assessment for high-risk pests.

This contribution provides examples of pre-emptive biological control programmes conducted, or currently underway, against different high-risk pests (Section 2), defines a set of aspects that should be considered when selecting a suitable target pest for pre-emptive biocontrol risk assessment (Section 3), and then provides a set of guidelines and a decision framework that can be used to assess the feasibility of conducting pre-emptive risk assessment for candidate BCAs against high-risk insect pests (Section 4). We conclude by commenting on how the proposed guidelines and decision framework will provide biocontrol practitioners with a suitable tool to assess if classical biological control risk assessment against a high-risk pest could be initiated pre-emptively, which will facilitate a successful, informed, and responsible implementation of this novel approach.

2. Current status of pre-emptive biocontrol worldwide

2.1. Pre-emptive biocontrol against BMSB – The New Zealand example

The pest - potential risk and impact: The brown marmorated stink bug (BMSB), *Halyomorpha halys* Stål (Hemiptera: Pentatomidae) is a highly invasive pest known to attack a wide range of fruit and vegetable crops worldwide (Leskey & Nielsen 2018). The pest is native to East Asia and has invaded and spread through Eurasia and North and South America (Hoebeke & Carter 2003; Leskey & Nielsen 2018). BMSB has been regularly intercepted at the New Zealand border since 2014 (Ormsby 2018) but has not yet been established there. In 2015, pre-emptive research was initiated to investigate biocontrol options for BMSB in preparedness for a potential incursion into New Zealand

(Charles et al. 2019). This novel pre-emptive approach was started in response to the severe economic threat the pest is considered to pose to New Zealand's primary horticultural sector (Conti et al. 2021). There may also be a potential risk to New Zealand's native plants (Duthie 2012).

The biocontrol candidate selected: BMSB is attacked by a number of egg parasitoids worldwide, of which most belong to three families: Encyrtidae, Eupelmidae and Scelionidae (Abram et al. 2017). In its native range of Asia, parasitoids within the genus *Trissolcus* (Scelionidae) are deemed to be the most effective parasitoids of BMSB (Lee et al. 2013), with the samurai wasp *Trissolcus japonicus* Ashmead (Hymenoptera: Scelionidae) considered the principal natural enemy of the pest (Yang et al. 2009; Lee et al. 2013; Zhang et al. 2017). Therefore, *T. japonicus* was identified as the most suitable candidate BCA for BMSB in New Zealand. Its potential host range in New Zealand was investigated using parasitoids originating from parasitised BMSB egg masses imported into containment from the USA (Charles et al. 2019).

Pre-emptive risk assessment in containment: Host testing of New Zealand's non-target Pentatomidae species included eight taxa from the subfamilies Asopinae and Pentatominae (Charles et al. 2019). New Zealand has eight species and two subspecies of Pentatomidae, of which one species and two subspecies are endemic, three are native, and four are exotic. The single endemic species, *Hypsithocus hudsonae* Bergroth and one of the sub-species, *Cermatulus nasalis turbotti* Woodward, could not be collected from the field for pre-emptive risk assessment testing. The host specificity testing, therefore, included most of the remaining species (Charles et al. 2019). Egg masses of the pentatomids were exposed to *T. japonicus* in the quarantine laboratory between 2015 and 2017. The parasitoid successfully attacked all egg masses except those of *Nezara viridula* Linnaeus (the green vegetable stinkbug) (Charles et al. 2019). Parasitism rates (percentage egg masses parasitised by *T. japonicus*) of the non-target hosts ranged between 18% (*Cermatulus nasalis hudsoni* Woodward) and 96% (*Glaucias amyoti* Dallas) (Charles et al. 2019). Although the results indicated that the members of the Pentatomidae tested were all likely to be within the physiological host range of *T. japonicus*, modelling simulations showed that a distribution overlap of *T. japonicus* with the endemic *H. hudsonae* and with some of the other non-target pentatomid species (e.g., *C. nasalis hudsoni*), was unlikely. This is due to the disparate potential distribution ranges of the native Pentatomidae species and the parasitoid (Avila & Charles 2018).

Application for BCA release: An application for approval to release *T. japonicus* into New Zealand was made to the Environmental Protection Authority (EPA) in March 2018. The application to support this proposed release included the host range testing results and modelling simulations predicting both the potential distributions of BMSB and *T. japonicus* and the potential overlap with the distribution of non-target Pentatomidae species. Information on the economic, social and cultural benefits was also provided (EPA 2018). In August 2018, the EPA approved *T. japonicus* for release in New Zealand, subject to conditions (EPA 2018). The decision was made due to the anticipated high economic, environmental, social and cultural impacts associated with the potential introduction of BMSB, which outweighed the potential risks to native pentatomid species. The pre-approval to release *T. japonicus* in the event of BMSB arriving in New Zealand was a world first and an important outcome for biocontrol in the country as it enhanced its preparedness for a potential BMSB incursion.

2.2. Pre-emptive biocontrol in Australia

Pre-emptive biocontrol in Australia has also focused on identifying and selecting candidate BCAs before the arrival of the relevant pest in the country. Examples include pre-emptive biocontrol programmes for the Russian wheat aphid (RWA) *Diuraphis noxia* Kurdjumov (Hemiptera: Aphididae) (Aeschlimann & Hughes 1992) and BMSB (Caron et al. 2021). The parasitoid *Aphelinus varipes* Förster (Hymenoptera: Aphelinidae) was imported, reared and released in Australia as part of a pre-emptive biocontrol approach against the RWA to determine its capacity to establish in the local climate regardless of the absence of RWA (Aeschlimann & Hughes 1992). However, the parasitoid did not establish (Hughes et al. 1994). For this pre-emptive biocontrol programme against RWA, the literature fails to indicate whether or not any form of pre-release risk assessment was conducted. In the other example, *T. japonicus* was considered unsuitable for biocontrol of BMSB in Australia due to its wide host range and Australia's high pentatomid diversity. Focus was turned to another BCA of BMSB, *Trissolcus mitsukurii* Ashmead (Hymenoptera: Scelionidae), which is already established (Caron et al. 2021).

2.3. Other examples of pre-emptive biocontrol

In the following examples, the term pre-emptive biocontrol is used synonymously with other expressions, such as "proactive biocontrol" in recent publications (Hoddle 2020; Gómez-Marco et al. 2023, Hoddle 2023). All examples involve identifying and selecting potential BCAs for pre-emptive biocontrol. However, no published examples (other than the one from New Zealand) are currently available for a complete pre-emptive biocontrol risk assessment.

Pre-emptive biocontrol in the USA: Scientists in California have been particularly active in pre-emptive biocontrol, recognising the benefits of this approach to pest management. In 2018, a new programme was started by the California Department of Food and Agriculture (CDFA) with a focus on pre-emptive ("proactive") biocontrol (Hoddle 2023). The programme aims to establish a list of high-risk target pests, followed by selecting and assessing candidate BCAs for the pests. Ultimately, a collection of US Department of Agriculture Animal and Plant Health Inspection Service (USDA-APHIS) release permits (conditional to risk assessment results) will be issued and renewed when required (Hoddle 2023). Unlike in New Zealand, the USA examples have focused mostly on the identification or selection of the candidate BCAs prior to the arrival of the pest, with little focus on risk assessment. Examples include pre-emptive biocontrol programmes for the avocado seed moth [*Stenoma catenifer* Walsingham (Lepidoptera: Depressariidae)] (Hoddle & Hoddle 2008, 2012), the avocado seed weevil [*Heilipus lauri* Boheman (Coleoptera: Curculionidae)] (Hoddle 2020), the tomato leafminer [*Tuta absoluta* Meyrick (Lepidoptera: Gelechiidae)] (CDFA 2022), and spotted lanternfly [SLF; *Lycorma delicatula* White (Hemiptera: Fulgoridae)] (CDFA 2022). The latter example is the only one that we are aware of, where host range testing of a candidate BCA has been initiated in anticipation of the eventual establishment of the pest in California, although SLF arrived and established in the northeast USA back in 2014 (Gómez-Marco et al. 2023).

Pre-emptive biocontrol in Canada: Although *L. delicatula* is not yet present in Canada, the pest is recognised as a potential threat to the country's fruit trees, grape and forestry production (CFIA 2021). Recent detections in New York State (USA) and climatic modelling suggest that the pest has the potential to establish in British Columbia and southern Ontario, prompting a pre-emptive biocontrol approach to SLF in Canada (CABI 2022). A collaborative project between Canada, China and Switzerland started in 2019 is currently investigating the natural enemies of SLF in its native China, with a focus on their host specificity and impacts to SLF populations (CABI 2022).

Pre-emptive biocontrol in the UK: Emerald ash borer [EAB; *Agrilus planipennis* Fairmaire (Coleptera: Buprestidae)] is considered a major threat to ash trees in the UK and preparations to allow for CBC for the management of this beetle in the event of an incursion or establishment in the UK are ongoing. Three hymenopteran parasitoids BCAs, *Tetrastichus planipennisi* Yang (Hymenoptera: Eulophidae), *Oobius agrili* Zhang and Huang (Hymenoptera: Encyrtidae) and *Spathius galinae* Belokobylskij and Strazanac (Hymenoptera: Braconidae), which have been released in North America for EAB control (Duan et al. 2018), and a fourth parasitoid species, the braconid *Spathius polonicus* Niezabitowski, that appears to have forged an association by natural means in European Russia (Orlova-Bienkowskaja & Belokobylskij 2014), have been selected as potential candidates for release should EAB establish in the UK. Pre-emptive risk assessments to support licence applications for the release of these non-native parasitoids were drafted in 2019 (for *T. planipennisi*, *O. agrili* and *S. galinae*) and 2021 (for *S. polonicus*) and have identified several uncertainties (e.g., climatic matching to the UK, host-specificity, potential to hybridise with native parasitoids) that require addressing before the application for a licence to release can be submitted. Research is currently underway (including host range testing started in 2022 for the four parasitoids species against native UK *Agrilus* species) to obtain the additional data required, with the intention of submitting the risk assessments for pre-emptive approval of the BCAs once all the data have been acquired.

3. Selecting a suitable target pest for pre-emptive biocontrol risk assessment

3.1. Selection of high-risk pests from existing pest lists

A high-risk pest is defined as an organism that could cause significant detrimental environmental, economic and/or socio-cultural impacts if it were to become established in the country at risk of introduction. In general, the likelihood that a pest will be categorised as ‘high risk’ is higher if the pest is polyphagous, especially if it can cause substantial damage to a number of significant commercial and/or protected (rare or native/endemic) species (Mannion 2003). Other important aspects that may result in a high-risk classification include regular border interceptions, a lack of or very few natural enemies in the new environment, a known ability to transmit diseases, a difficult identification, a short life cycle and a rapid reproductive rate, high dispersal ability, and potential climatic suitability of the receiving environment (Mannion 2003).

Fundamentally, not all pests are high-risk but the risk level may shift over time with changing circumstances. For example, a number of government agencies and industry groups within New Zealand have compiled lists of priority/ high-risk pests that would pose a threat if they established (MPI 2022; GIA 2022). Similarly, the European Union (EU) has identified 20 priority pests (16 of which are insects) for the EU territory, based on their ability to cause severe economic, social and environmental problems (EU 2019a). Australia has developed the National Priority Plant Pests list (DAFF, 2019), which includes 42 exotic pests (single species or group of species), and the National Priority List of Exotic Environmental Pests, Weeds and Diseases that includes 168 species (DAFF 2020) posing serious biosecurity threats. The UK has developed the UK Plant Health Risk Register providing information (e.g., host range, distribution and regulatory status) for more than 1000 plant pests and assigning to each a numerical score summarising the risk and threat posed to the UK (Defra 2022). The lists in these countries provide a good starting point when selecting a target pest for which to conduct a pre-emptive biocontrol feasibility assessment.

3.2. Background information on the selected target pest

In the following section, we discuss the essential information and underpinning attributes of the target pest that are considered important when conducting a feasibility assessment to initiate a pre-emptive biocontrol risk assessment. These include the regulatory pest status, pest distribution, risk of arrival and establishment in the country at risk, host range, biology and ecology, taxonomy and related species, existing monitoring and control methods and potential impacts in the country at risk.

This information can be gathered from a number of sources including, but not limited to, scientific literature and reports, pest risk analysis reports (conducted by regulatory agencies and/or national/ regional plant protection organisations), pest records and databases, maps and models, and online information and data sources. Consultation with subject experts both in the country at risk and abroad is also essential and may provide vital information that is unavailable in published form.

Regulatory pest status in invaded range and in the country at risk of introduction: The regulatory status refers to the status given to a pest by regulatory authorities/government agencies within a given area, state or country. Some countries have established online registers, databases or lists that provide information regarding the status of a given pest, including whether it is present or absent and regulated or non-regulated within the area of interest. For example, The Official New Zealand Pest Register, administered by the Ministry for Primary Industries (MPI), is a database of pests that are regulated in New Zealand (Biosecurity NZ 2022). The database provides the regulatory status of a pest (regulated, non-regulated or not assessed), whether the pest is unwanted (yes or no) and whether the pest is notifiable (yes or no). In Europe, regulated pests of plants are included in the Commission Implementing Regulation (EU) 2019/2072, an implementing act of Regulation (EU) 2016/2031. Annex II of the Commission sets out a list of quarantine pests for the Union, and Annex IV contains a list of regulated non-quarantine pests (EU 2019b). An amendment of the lists was published in 2021 (EU 2021). The European and Mediterranean Plant Protection Organization (EPPO) recommends that its 52 member countries to regulate pests that are absent (A1 species) and present (A2 species) from the EPPO region. These species are detailed in the EPPO Global Database (EPPO 2023). The UK Plant Health Risk Register provides similar information, enabling industry and stakeholders to prioritise action against pests and diseases that threaten UK crops, trees, gardens, and countryside (Defra 2022). Regulatory status information will assist in selecting and prioritising high-risk pests for a feasibility assessment to initiate a pre-emptive biocontrol risk assessment.

Key considerations:

- Is the selected pest considered a pest in its native range?
- What is the regulatory status of the pest in non-native regions?
- What is the regulatory status of the pest in the country at risk of introduction?

Worldwide range and potential distribution in the country at risk of introduction: The worldwide range of a pest species describes the occurrence and arrangement of the pest across the globe. Within their range, the distributions of pest species are known to be regulated by both abiotic and biotic factors and the complex interactions between them (Worner et al. 2013). While temperature is undoubtedly the most important abiotic factor affecting insect pest distribution (Bale et al.

2002), other factors, such as relative humidity and rainfall, may also play an important role (Schoonhoven et al. 2005). Biotic factors affecting distribution include the presence of hosts/food sources, and species interactions such as predation/parasitism and competition (Schowalter 2022; Pedigo et al. 2021).

The current distribution of a pest refers to its known distribution at the present time. For high-risk pests, relatively accurate observed distribution maps are typically available, especially if the species has already become invasive in other countries (e.g., Nair & Peterson 2023; Orlova-Bienkowskaja & Volkovitsh 2018; Kriticos et al. 2017). Understanding the worldwide distribution of a pest is important when conducting a feasibility assessment to initiate a pre-emptive biocontrol risk assessment. Based on the known distribution and considering the biology/ecology of the pest, the potential distribution in the country at risk can be estimated using climate matching tools and ecoclimatic models such as CLIMEX (Sutherst 2003; Kriticos et al. 2015) or MaxEnt (Tepa-Yotto et al. 2021; Fischbein et al. 2019). This can subsequently be compared to the potential distribution of the selected BCA to establish whether there is an overlap between the target pest and the candidate BCA.

Key considerations:

- What is the current worldwide distribution of the pest?
- Has the pest a localised distribution, or is it spreading to new bioclimatic zones?
- Is there any existing information regarding the pest's potential distribution in the country at risk (e.g., based on modelling)? If not, is it possible (data availability) to perform bioclimatic modelling to make such predictions (e.g., as part of the feasibility assessment)?

Risk of entry, establishment and spread of the selected pest: The risk of entry refers to the likelihood of a new pest entering the country at risk. Several factors determine the entry risk, including the number and frequency of border interceptions and the likely entry pathways. In New Zealand, pest risk analyses have been conducted by MPI for a number of high-risk pests. These documents provide an extensive risk assessment of each pest, including the likelihood of entry, establishment and spread in New Zealand. For the EU, the European Food Safety Authority (EFSA) has conducted numerous pest categorisations and pest risk analyses. EPPO also conducts pest risk analyses for the EPPO region, which can be found in the EPPO Global Database (EPPO 2023). Other sources of risk analysis data include scientific literature and reports, which may provide information on risk modelling.

Knowledge of the risk of entry of a given pest in the country at risk will assist in the selection and prioritisation of pests to target for a feasibility assessment to initiate a pre-emptive biocontrol risk assessment. In addition, understanding the genetic structure of the pest in its native and invaded ranges can highlight or confirm the origin of the invasive population and guide the strategy for its control (Estoup & Guillemaud 2010).

Key considerations:

- Are there existing risk assessments for the pest?
- Has the pest been intercepted at the border and/or post-border of the country at risk?
- Is there any information on the pathway of the interceptions (country, commodities)? Is the pathway active?
- How often, which life stages, what volumes and to what extent is the pest intercepted?
- Is there any existing information regarding the risk of establishment and spread based on modelling?
- Are there any DNA barcoding studies/databases available to help resolve the identity and origin of the pest, if unknown?

Host range (invaded and native) and potential hosts in the country at risk: The host range of an insect pest is defined as "the suite of host species capable, under natural conditions, of sustaining a specific pest or other organism" (FAO 2018). Information about the host range of a pest will also assist in the selection and prioritisation of pests to target for evaluation of the feasibility of initiating a pre-emptive biocontrol risk assessment. Information on the host range of a pest abroad can provide valuable information regarding its potential host range in the country at risk. The presence and abundance of known plant hosts and their distributions in the country at risk will affect the likelihood of pest establishment. In addition, knowledge of a pest's potential host range will assist in predicting its potential impacts on native plant species and ecosystems (Kenis et al. 2009).

Key considerations:

- Is the host range of the pest known?
- What is the known host range of the pest in its native range?
- What is the known host range of the pest in its invaded range?
- Is the pest polyphagous or specialised on a certain plant family (oligophagous) or species (monophagous)?
- Is the host range of the pest expanding?
- Which of the known host plants are present in the country at risk?
- Are there plants that are closely related to known host plants in the country at risk?
- Does the pest threaten commercial, protected, amenity or native wild plants in the country at risk?
- What is the type, frequency, and severity of damage caused by the pest?

Biology and ecology: When conducting a pre-emptive biocontrol feasibility assessment, information on the biology and ecology of the target pest will assist in predicting biological synchrony with a candidate BCA (i.e., life cycle duration, rate of reproduction, seasonal phenology, and overlap of generations between the target pest and a candidate BCA). It will also provide information on the dispersal ability of the pest compared to the candidate BCA. Any information regarding the ecology of the pest will also assist in understanding how the pest will affect the ecosystem and environment in the country at risk (e.g., habitat loss, modifying current food webs).

Key considerations:

- Life cycle duration, life cycle in relation to the growing season, rate of reproduction/ development, other life cycle parameters such as number of generations per year, temperature/day length requirements for development, diapause/cold hardiness
- Seasonal abundance of life stage(s) susceptible to attack by BCAs
- Dispersal ability (speed/ range), means of dispersal
- Does the pest vector have any plant diseases of concern?

Related species in the country at risk: Risk assessment for CBC agents involves an assessment of the potential impact of the BCA on non-target species in the new environment. The selection of the non-target species for host testing requires careful consideration. In general, traditional methods for non-target species selection that consider the taxonomy of the pest species and phylogenetic affinities, ecological affinities (e.g., niche overlap), biological factors (e.g., host range overlap, morphological likeness, behaviour), and socio-economic concerns (e.g., species of commercial, social or environmental importance) are a good starting point (Kuhlmann et al. 2006; Barratt et al. 2016). Another key element is the availability and rearing possibility of non-target species for robust host testing – some species may be rare or difficult to collect and rear (Kuhlmann et al. 2006; Barratt et al. 2016).

Understanding a target pest's taxonomy and phylogenetic affinities will provide important information when conducting a pre-emptive biocontrol feasibility assessment. By compiling a list of related species in the country at risk, the species can be ranked from the most closely related to the more distantly related. Rankings should also consider whether the related species are introduced, native or endemic to the country at risk. The list will highlight the number of potential non-target species and those most at potential risk from the BCA that should be included in a pre-emptive risk assessment. Selecting non-target species for BCA risk assessment is a challenging task, and therefore alternative methods, such as PRONTI (priority ranking of non-target invertebrates) (Todd et al. 2017; Barratt et al. 2016; Todd et al. 2015), could also be considered.

Key considerations:

- Has the phylogeny of the pest been investigated?
- Are there any closely related species in the country at risk?
- Are the related species introduced, native, endemic, or endangered?

Existing control methods, their effectiveness, and the risk of doing nothing: A number of tools for insect pest management are available worldwide (Dent & Binks 2020). Pest management options include chemical, microbial, biological, physical/mechanical, cultural and behavioural control, and host plant resistance.

Knowledge of existing management options used in areas where the target pest is present, particularly the use of biocontrol, will provide crucial information when conducting a pre-emptive biocontrol feasibility assessment. Of particular interest is whether biological control has been used successfully against the pest elsewhere, and the accessibility of the BCAs.

Key considerations:

- Has eradication of the pest been attempted in invaded countries? If so, were the eradication attempts successful?
- What, if any, management options (e.g., chemical, cultural, biological control) are used for the pest abroad?
- What is the effectiveness and ecological/economic cost of these management options?
- Are these management options feasible in the country at risk?
- Have CBC programmes been implemented abroad? If so, have they been successful?
- Where biocontrol has been successful, which species were used, and are they easily accessible for importation?

Potential environmental, economic, human health and safety, societal and community impacts: When assessing the potential impacts of insect pest invasions, environmental, economic, social and cultural values and community implications need to be considered (Pimentel et al. 2005; Skendžić et al. 2021; Venette & Hutchison 2021). Direct economic impacts of invasive pest species may include the cost of production losses and the cost of management (Colautti et al. 2006). Environmental impacts include effects on biodiversity and ecosystem integrity (Vilà et al. 2010). Invasive pest species may impact plant species (including native species) through herbivory and native and endemic insect species through competition or predation (Kenis et al. 2009). Other environmental or human/animal health impacts may include but are not limited to increased use of insecticides, production of allergens, or the ability of pest species to vector unwanted pathogens (Schaffner et al. 2013). Socio-cultural consequences of an insect pest also need to be considered. These may include the pest's preference to overwinter in fabricated structures (e.g., houses), unpleasant odours associated with the pest, and the impact on native plants, homes, and communities of importance to indigenous people.

Knowledge of the potential impacts of a given pest will therefore assist in its selection and prioritisation for pre-emptive biocontrol risk assessment.

Key considerations:

- Does the pest cause economic impacts abroad? If so, to what extent?
- Does the pest have the potential to cause economic impacts in the country at risk? If so, to what extent (e.g., predicted crop production losses (yield/ quality), market access restrictions)?
- Does the pest cause environmental impacts abroad? If so, to what extent?
- Does the pest have the potential to cause environmental impacts in the country at risk? If so, to what extent?
- Does the pest cause social/cultural/nuisance impacts abroad?
- Does the pest have the potential to cause social/cultural/nuisance impacts in the country at risk? If so, to what extent?
- Does the pest cause human health impacts abroad?
- Does the pest have the potential to cause human health impacts in the country at risk? If so, to what extent?

4. Best practice and principles of pre-emptive biocontrol risk assessment: A guideline and framework to assess feasibility for implementation

As for conventional CBC programmes, it is paramount to first identify and select the most suitable natural enemies of the target pest to evaluate the feasibility of pre-emptive classical biocontrol risk assessment. In general, the selection should be made by considering a number of criteria, which may be related to the various ecological aspects of the BCA and the target pest, but also to the area of origin and potential introduction of both organisms, as well as biological control management practices in a given area (Kenis & Seehausen 2022). Some of the selection criteria are dictated by the laws and policies of the country of potential introduction, others are simply based on experience by biological control practitioners, and a few can actually be directly related to the successes of previous biological control programmes in other countries. For example, the decision to release *Torymus sinensis* Kamijo (Hymenoptera: Torymidae) for the control of *Dryocosmus kuriphilus* Yasumatsu (Hymenoptera: Cynipidae) in Italy was based on the success of releases in Japan and in the USA (Quacchia et al. 2008).

It is often difficult to determine what BCA-related factors lead to the success or failure of a biological control programme because additional factors relating to the target pest, its environment, or management practices also inevitably strongly influence the outcome (Seehausen et al. 2021). Therefore, selection criteria for prospective BCAs should always be placed in a broader context with consideration of these additional factors.

This section describes a series of aspects to consider when selecting the most suitable BCA to conduct a pre-emptive classical biocontrol risk assessment. These are then presented in a decision framework (see Appendix A), so that the feasibility of initiating pre-emptive biocontrol risk assessment can be readily gauged.

4.1. Selecting the most suitable BCA for pre-emptive biocontrol risk assessment

4.1.1. Availability of information about suitable BCA(s)

The first stage of a feasibility study is to determine whether there exist any natural that have the potential for use as a BCA against the target pest. Natural enemies that have already been identified as possible BCAs, or are being used as such elsewhere, should be considered first and information on BCA candidates needs to be gathered. Information can be obtained from a range of sources, such as the scientific literature, reports, expert consultation, and existing release applications from other countries.

If the target pest has not yet been considered for CBC elsewhere, information about the known natural enemies in the pest's area of origin should be compiled to identify possible BCAs. When existing literature and/or knowledge about natural enemies of the target pest are insufficient to determine a suitable candidate BCA for CBC, and cannot be determined through research activities, pre-emptive biological control risk assessment should be deemed unfeasible until such information becomes available. In this case, foreign explorations to characterise the natural enemy complex of the target pest in its native range should be considered. If a candidate BCA is found due to the exploration, a new feasibility study can be conducted.

Key considerations:

- Are any natural enemies of the target pest identified as suitable BCA (s) elsewhere, which could be considered for CBC in the potential area of introduction?

4.1.2. Background information about the selected BCA

Once a suitable BCA has been identified against the target pest, the following information should be compiled to ensure that it fulfils the necessary characteristics expected for a successful BCA. This information may be readily available if the natural enemy is already used in CBC programmes elsewhere. If not, a pre-emptive risk assessment for the BCA may still be feasible, providing the required information can be determined relatively easily from research activities, which would be conducted as part of the pre-emptive risk assessment process.

Taxonomic status and synonyms: Before any effort is made to compile the literature on the BCA, clarification of its current taxonomic status is vital to ensure that information about the correct species is searched and ultimately that the correct BCA is imported for pre-emptive risk assessment. Compiling information on the identity and taxonomic history of the proposed control agent is expected to be one of the first steps in the selection of BCA(s). This information can be gathered from literature sources, collection data, and the expertise of taxonomic specialists (Sands & Van Driesche 2004). Any past synonyms of the potential agent may, for example, indicate whether close relatives of the agent occur in the receiving range, providing a better definition of likely food web relationships or the potential likelihood of hybridisation between candidate BCA and close relatives. The synonymy may also provide information on the hosts of related species that might be important in the design of host-range tests (Barratt et al. 2017). Cryptic species and biotypes of a BCA may differ in characteristics necessary for the success of biological control programmes but could also cause further risk of non-target effects (Caltagirone 1985; Clarke & Walter 1995). Studies have shown that at the sub-species level, differences can occur in traits such as host specificity (Goldson et al. 2005, Derocles et al. 2016; Seehausen et al. 2020), climatic suitability (van den Bosch et al. 1970; Valente et al. 2017), encapsulation resistance (Pschorn-Walcher & Zinnert 1971), microhabitat preference (Kenis & Mills 1998; Seehausen et al. 2020), development and diapause requirements (Kenis et al. 1996), and several other characteristics (see examples in Caltagirone 1985; Hopper et al. 1993). Molecular tools are now readily available to identify and characterise the taxonomy of many potential BCAs, even at the sub-species level (Hoddle et al. 2015; Reeve & Seehausen 2019).

Key considerations:

- Has the taxonomic status of the selected BCA been defined?
- Are there any biotypes, strains, subspecies, or cryptic species that need to be considered?
- Are there any DNA barcoding studies/databases available to help resolve the identity of the potential BCA?

Geographic distribution, climatic suitability/similarity, and potential distribution overlap with target pest: Information on the native, adventive, and introduced distribution of the target pest and the potential BCA is vital as it will allow the assessment of climatic similarities between the known current distribution and the potential distribution in the receiving range. Useful information requirements on distribution of the target pest are discussed in section 3.2. Climate-based species distribution models can help to confirm that selected BCAs originate from areas that are climatically similar to the intended area of introduction, which increases the chances of biological control species or biotypes establishing and efficiently controlling the target (Hoelmer & Kirk 2005; Hoddle et al. 2015; Fischbein et al. 2019) because the selected BCA will be physiologically able to survive and reproduce without climate-related constraints in its new environment (Hufbauer & Roderick 2005; Barratt et al. 2017; Robertson et al. 2008; Kriticos et al. 2015, 2021). The better the climatic match with the donor environment, the higher chances of successful establishment in the new environment (Van Driesche et al. 2008).

Failures of past CBC programmes can be directly or indirectly related to climate-related causes (Van Driesche et al. 2008; Kriticos et al. 2015, 2021). Agent releases in unsuitable climates were found to account for a quarter of all establishment failures, while almost 10% of failures could be related to a mismatch in synchronisation between the BCA and the target pest (Stiling 1993). The latter is often due to inappropriate development rates and diapause cues of the BCA as a consequence of climatic differences between the native area and the area of introduction. Therefore, to increase the chances of establishment and target control by the potential BCA, only those BCAs that are expected to be climatically adapted to the area of intended introduction and that are predicted to have both a spatial and temporal (phenological) overlap with the target pest in the invaded environment, should be considered for a pre-emptive biological control risk assessment. If there is sufficient information available to predict the climatic suitability of the receiving country for the BCA in terms of its establishment, and spatial and phenological overlap with the target pest, it is recommended that this is done before proceeding to laboratory pre-emptive risk assessment.

Key considerations:

- Is information available about the BCA's current geographic distribution (i.e., native, naturalised, adventive, and introduced range)?
- Is information available about the BCA's ability to adapt to different environmental conditions?
- Are there any bioclimatic modelling studies available that could help to confirm climatic suitability/similarity between the BCA's donor and receiving environment?
- Are there any bioclimatic modelling studies for the target pest that could help to confirm potential distribution overlap with the BCA in the new environment?

- If no bioclimatic modelling studies are available, is it possible to develop a climatic suitability model for the selected BCA and the target pest? If yes, it is recommended that modelling studies are completed before proceeding to pre-emptive risk assessment. If no, pre-emptive risk assessment may not be feasible but should not necessarily be discounted on this basis alone.

Biology and ecology of the BCA: Basic knowledge of the biology and ecology of natural enemies may be the key to success in a biological control programme (DeBach & Rosen 1991; Van Driesche & Bellows 1996), and therefore an important aspect to consider when selecting a candidate BCA for pre-emptive biocontrol risk assessment. One of the essential traits of potential BCA agents is specificity to the target species in order to lower the risk of non-target attacks (Hajek et al. 2016; Van Driesche & Hoddle 2017). To date, the usual recommendation is to prioritise host-specific BCAs as they are less likely to cause direct and indirect non-target impacts and are expected to be more effective against the target host (van Lenteren 1995; Louda et al. 2003). However, many other biological and ecological attributes (e.g., efficient searching and dispersal ability, high parasitism or predation rate, high reproductive potential, good phenological synchrony with host, ability to survive at low prey densities, ability to adapt to a wide range of environmental conditions, competitive ability, freedom from hyperparasitism/competitors) need to be considered in a candidate BCA, to ensure its effectiveness against the target pest and biosafety (Hokkanen & Sailer 1985; DeBach & Rosen 1991; Van Driesche & Bellows 1996; Van Driesche et al. 2008; Heimpel & Mills 2017). For example, a BCA with physiological synchrony with its host and high reproductive potential is expected to complete more than one generation during each generation of the pest and produce large numbers of offspring, and therefore, significantly contribute to the control of the target pest. Similarly, to achieve reasonable control of the target pest, a BCA needs to be able to search for and locate hosts at low densities to prevent potential outbreaks. It is important to note that not all biological and ecological attributes mentioned above may be applicable to all BCAs (e.g., Mills 2001, 2006a, b), and therefore should not be generalised (Lane et al. 1999). When regarded as single factors, these attributes may be desirable and lead to higher chances of success in controlling the target pest. However, often the attributes are taken out of context, ignoring the complexity of factors that ultimately determine the outcome of biological control programmes. This becomes especially evident when the agent-related factors are analysed in the context of other factors that also impact the success of biological control programmes. For example, Stiling (1990) emphasised the greater importance of the climatological origin of the BCA when compared to numerous traits of the natural enemy. Gross et al. (2005) found that lower trophic level factors such as habitat type and the taxonomic order of the pest can determine the outcome of biological control programmes. Also, Seehausen et al. (2021) found that remarkably few agent-related factors influenced the success of BCAs. Still, several target traits and the number of repeated introductions of agents against univoltine targets significantly increased the success. Therefore, more than focussing on agent-related traits alone is needed and lower trophic level, as well as other aspects, such as climatic factors and regional biological control practices should be included in the selection process for BCAs.

Several aspects should also be considered in terms of a potential BCA's interaction with species other than the target pest and further potential hosts. First, information should be gathered about diseases, parasites, and parasitoids/hyperparasitoids of the potential BCA in its area of origin to avoid their accidental introduction into the area where releases are intended. Such unwanted species may not only decrease the efficiency of the BCA, but also affect other species in the area of introduction. In most cases, importing BCAs into a high-security quarantine laboratory, where rearing and thorough evaluation is conducted, can detect and eliminate contamination with unwanted organisms before release. Second, it is good practice not only to study the natural enemy complex of the target pest in its area of origin but also in its area of introduction (Hoelmer & Kirk 2005; FAO 2019). This may identify natural enemies of the pest that are already present and reduce the need to introduce an exotic BCA, and can also help to identify ecological niches in the natural enemy complex of the pest that should be filled in priority by the selected BCA. Lastly, information on native natural enemies closely related to the potential BCA should be gathered to assess the risk of hybridisation (Hopper & Wajnberg 2006). Hybridisation may not only reduce the efficiency of the BCA but also pose a risk to the biodiversity and functionality of the native ecosystem (Yara et al. 2007). While these aspects are certainly important to consider for the selection of a BCA and the feasibility of pre-emptive biological control risk assessment, they should always be put into the complete context of the planned biological control programme, a risk–benefit analysis, and the policies and circumstances of the country in which releases are planned.

Key considerations include whether there is information available about the BCA's:

- host specificity?
- searching and dispersal abilities?
- parasitism and predation rate?
- potential to act as a hyperparasitoid?
- reproductive potential?
- phenological synchrony with the target host?
- ability to survive at low host/prey densities?
- potential natural enemies that may be present in the area of introduction?
- closely related species in the area of introduction that may be at risk to hybridise with the BCA?

Known effectiveness of the BCA against the target host abroad from field and/or lab studies: Information on the performance and efficiency of the selected BCA against target pests in its native range and from laboratory-based tests for an existing or previous biological control programme (if any) should be available. However, laboratory data must be interpreted with caution because mortality rates of the host, functional responses and bio-ethology obtained under laboratory conditions may not be the same in the field (Fernández-Arhex and Corley, 2003). If existing biological control programmes have been in place for some time, there may be records available detailing the outcomes, including information about the success and failure in terms of the establishment of the BCA and control of the target pest (e.g., Greathead 1986; Greathead & Greathead 1992; Van Driesche & Bellows 1996). Analysing these data can help to increase the success of future biological control programmes (e.g., Seehausen et al. 2021). If not from intentional releases during biological control programmes, recorded effectiveness of the potential BCA in adventive ranges can also be very useful, especially to determine the natural enemy's behaviour in new environments (e.g., Abram et al. 2022).

Key considerations:

- Is information available about the BCA's performance and efficacy against the target host in its native range?
- Is information available about the BCA's performance, efficiency and efficacy against the target host in its adventive range if self-introduced?
- If any biocontrol programmes have been started with the selected pest abroad, is there information about their success or failure?

Availability of closely related BCA species that could be used as an alternative or in synergy: Any information on native or introduced BCAs in the receiving country could prove useful. For example, such information could be helpful in (1) assessing the potential of resident BCAs to be used in synergy with the candidate BCA to maximise biocontrol efforts and (2) detecting potential competition between resident BCAs and the candidate BCA, which could disrupt/hinder classical biocontrol. As already mentioned above, knowledge about the natural enemy complex both in the native and the intended introduction area is important to identify (1) all natural enemies to be considered as BCAs, (2) natural enemies already present in the area of intended introduction, and (3) ecological niches in the natural enemy complex of the pest in the invasive range that can be filled by a BCA (Hoelmer & Kirk 2005; Kenis et al. 2019). Although this is not an essential aspect of selecting a candidate BCA to conduct a pre-emptive biocontrol risk assessment, it will still provide valuable information to assess potential benefits or issues in future biocontrol programmes.

Key considerations:

- Is there any information on resident BCAs in the receiving environment that could be used as either alternative BCAs or in synergy with the candidate BCA?
- If BCAs are identified in the receiving environment, is information available about their potential to compete with the candidate BCA and potentially reduce its effectiveness?

4.2. *Challenges to be encountered during pre-emptive biocontrol risk assessment*

A number of challenges will need to be overcome to make pre-emptive biocontrol risk-assessment possible. Although these challenges usually relate to aspects of the risk assessment itself (e.g., the availability of sufficient information on existing non-target species), they can also relate to different aspects of the logistics of importing an exotic BCA into containment for pre-emptive biological control risk assessment under laboratory conditions (e.g., approvals to import BCA, source and shipping options for BCA). Here, we describe a number of challenges that should be considered when selecting the most suitable BCA for which to conduct pre-emptive biological control risk assessment.

4.2.1. *Non-target species to test*

Even though successful biological control introductions have been reported worldwide (Ryan 1990; Van Driesche et al. 2003; Grandgirard et al. 2008), concern exists regarding the potential biosafety risks that exotic BCAs might pose in a new environment. These are known as ‘non-target effects’, affecting species other than the target pest species (e.g. any native species or other introduced beneficial species) in the country of introduction (Follett & Duan 2000; Mack et al. 2000; Sheppard et al. 2003; Eilenberg 2006). For example, in New Zealand, applicants wanting to apply for an EPA approval to release a BCA need to provide sufficient information to enable the authority to make its decisions in accordance with the Hazardous Substances and New Organisms (HSNO) Act. This includes a risk assessment of the potential adverse effects which could follow from the introduction of a new organism, among other requirements (Barratt et al. 2017). Likewise, application procedures in many European countries such as England, The Netherlands and Switzerland require information on potential environmental risks (with a particular focus on non-target species) (Castella et al. 2022), based on the standards developed by the EPPO (Mason et al. 2017). Therefore, it is critical to collate enough relevant information on potential non-target species to assure that most of those selected for host testing can be included in a laboratory risk assessment in containment. It is also pertinent to make an informed selection of potential non-target species by considering their phylogenetic relationships with the target pest (see Section 3.2 for further details). If background information on the selected non-targets is insufficient and the minimum number of species to make a thorough risk assessment (this will depend on each country’s regulatory requirements; see Barratt et al. 2021, Castella et al. 2022) cannot be included in pre-emptive host testing in containment, then pre-emptive biocontrol risk assessment might be unfeasible. However, if the only constraint is the ability to test non-targets in containment, options to test in a collaborator’s containment facility abroad could be investigated.

Key considerations:

- Is there sufficient information about fauna closely related to the target pest to make an informed selection of non-targets to include in pre-emptive risk assessment tests?
- Is it possible to collect non-target species from the field or source them from a collaborator’s lab to do risk assessment in containment?
- Is it possible to establish non-target colonies for risk assessment? If not, would host testing with field-collected insects be feasible?
- Is it possible to test selected non-target species in a local containment facility? If not, is it possible to conduct host testing of non-targets in a collaborator’s laboratory abroad?

4.2.2. *Logistics*

A number of different logistical aspects needs to be considered when planning to import a BCA into containment for risk assessment, as these are often critical for the successful implementation of pre-emptive biocontrol risk assessment. For example, a suitable containment facility, as well as the corresponding permits/approvals from regulatory agencies, need to be available before the candidate BCA(s) can be imported into the receiving country to carry out pre-emptive biocontrol risk assessment. In New Zealand, for instance, the EPA is responsible for regulating the importation and development in containment and release of new organisms (including BCAs) under the HSNO Act (Ehlers et al. 2020). Once EPA approval to import into containment (to conduct BCA risk assessment) is obtained, it is essential to apply for and obtain the corresponding import permit from MPI, under the Import Health Standard (IHS), in order to import BCA(s) into the designated containment facility (Barratt et al. 2017). In Switzerland, the Federal Office for the Environment is responsible for approval of trials in contained facilities (FOEN 2012). If trials are approved, cantonal authorities are responsible for the supervision of the quarantine facilities. According to our knowledge, no special import permit is required. Yet, in Switzerland as well as in the other ratification countries, adherence to the requirements of the Nagoya protocol must be assured. Therefore, identifying a suitable containment facility and ensuring the corresponding permits/approvals from regulatory agencies can be obtained are crucial logistical aspects to make pre-emptive risk assessment feasible. If a suitable containment facility cannot be located and permits from regulatory agencies cannot be obtained, options for conducting pre-emptive risk assessment in a collaborator’s laboratory abroad could be investigated.

Another key aspect is the identification of a source from which to import the BCA(s). A reliable supplier/source needs to be clearly identified in order to get a constant supply of the selected BCA(s) to conduct a thorough pre-emptive risk assessment. Sources could be, for example, BCA colonies maintained in a research laboratory abroad, or a biocontrol company from which the BCA(s) could be purchased. If the BCA is not available commercially or via international collaborators, collection of the BCA from suitable areas should be assessed for feasibility as long as there is a rearing methodology already available in order to establish a colony. Once a supplier of the BCA has been confirmed, or the collection of the BCA from the field has been deemed feasible, the fastest shipping option possible needs to be identified to avoid any delays in delivering the BCAs into a designated containment facility in the receiving country. If no sources of the selected BCA(s) are found and rapid shipping options cannot be identified, then the initiation of pre-emptive risk assessment should be deemed unfeasible until a source becomes available or options for conducting pre-emptive risk assessment in a collaborator's laboratory abroad can be confirmed.

Key considerations:

- Is a suitable containment facility available for pre-emptive biocontrol risk assessment?
- Is it possible to get all permits needed from regulatory agencies to import the selected BCA for pre-emptive biocontrol risk assessment?
- Is there a rearing methodology for the BCA available?
- Is there a reliable collaborator/supplier identified to provide a constant supply of the candidate BCA for pre-emptive biocontrol risk assessment? If not, is it possible to collect the BCA from a suitable area for importation?
- Has a shipping option to expedite rapid transport of the BCA been identified?
- If any of the above are not feasible, can pre-emptive risk assessment be conducted in a collaborator's laboratory abroad?
- Is it possible to get approval to bring the target pest into containment to take part in the BCA's pre-emptive biocontrol risk assessment work?

5. Conclusion

Non-native invasive species threaten global biodiversity and food security, resulting in substantial economic costs. Although practices are in place in many countries for the prevention and early detection of invasive species, attempts at eradication or management tend to be reactive once the pest arrives and an outbreak is discovered. If the invasive pest establishes, long-term management is generally adopted for population suppression and slowing the rate of spread.

Identifying future risks and preparing to manage those risks are becoming increasingly important steps to help mitigate invasive species' impacts on ecosystems in new environments. CBC is a crucial strategy for managing invasive insect pest populations. However, the deliberate introduction of an exotic BCA depends upon an often lengthy research programme and biosafety risk assessment and is subject to regulatory approval. This gives additional time for an invasive pest to establish and spread. Therefore, a pre-emptive biocontrol risk assessment approach would help to enhance preparedness for a potential invasion of high-risk pest species. New Zealand's example of the pre-emptive biocontrol risk assessment conducted against BMSB, which led to the pre-approval to release *T. japonicus* in the event of BMSB arriving in the country, is considered a world first and a significant outcome for pre-emptive biocontrol. However, such a pre-emptive approach is unlikely to be feasible for all insect pests.

The guidelines and decision framework developed in this paper, to assess the feasibility of starting a pre-emptive biocontrol risk assessment, clearly define the fundamental principles and objectives of best practice for this pre-emptive approach, as well as the characteristics of a good candidate (target and BCA) for pre-emptive risk assessment. These guidelines and framework will provide biocontrol practitioners with the opportunity to assess if biocontrol risk assessment against a high-risk pest could be initiated pre-emptively, and will facilitate a successful, informed, and responsible implementation of this novel approach. We expect that successfully implementing the pre-emptive risk assessment guidelines and framework presented in this paper will ultimately enhance biological control preparedness efforts against high-risk biosecurity threats.

CRediT authorship contribution statement

Gonzalo A. Avila: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **M. Lukas Seehausen:** Methodology, Investigation, Writing – original draft, Writing – review & editing. **Vincent Lesieur:** Writing – review & editing. **Asha Chhagan:** Methodology, Investigation, Writing – original draft, Writing – review & editing. **Valerie Caron:** Methodology, Investigation, Writing – original draft, Writing – review & editing. **Rachel E. Down:** Writing – review & editing. **Neil Audsley:** Writing – review & editing. **Jana Collatz:** Writing – review & editing. **Tibor Bukovinszki:** Writing – review & editing. **Giuseppino Sabbatini Peverieri:** Writing – review & editing. **Rob Tanner:** Writing – review & editing. **Ramona Maggini:** Writing – review & editing. **Panagiotis Milonas:** Writing – review & editing. **Connor F. McGee:** Writing – review & editing. **Kiran Horrocks:** Writing – review & editing. **Annette Herz:** Writing – review & editing. **Kathleen Lemanski:** Writing – review & editing. **Gianfranco Anfora:** Writing – review & editing. **Luka Batistič:** Writing – review & editing. **Tanja Bohinc:** Writing – review & editing. **Nicolas Borowiec:** Writing – review & editing. **Mihaela Dinu:** Writing – review & editing. **Ana-Cristina Fatu:** Writing – review & editing. **Chiara Ferracini:** Writing – review & editing. **Maria-Vassiliki Giakoumaki:** Writing – review & editing. **Claudio Ioriatti:** Writing – review & editing. **Mark Kenis:** Writing – review & editing. **Žiga Laznik:** Writing – review & editing. **Chris Malumphy:** Writing – review & editing. **Marco V. Rossi Stacconi:** Writing – review & editing. **Pio Federico Roversi:** Writing – review & editing. **Stanislav Trdan:** Writing – review & editing. **Barbara I.P. Barratt:** Methodology, Investigation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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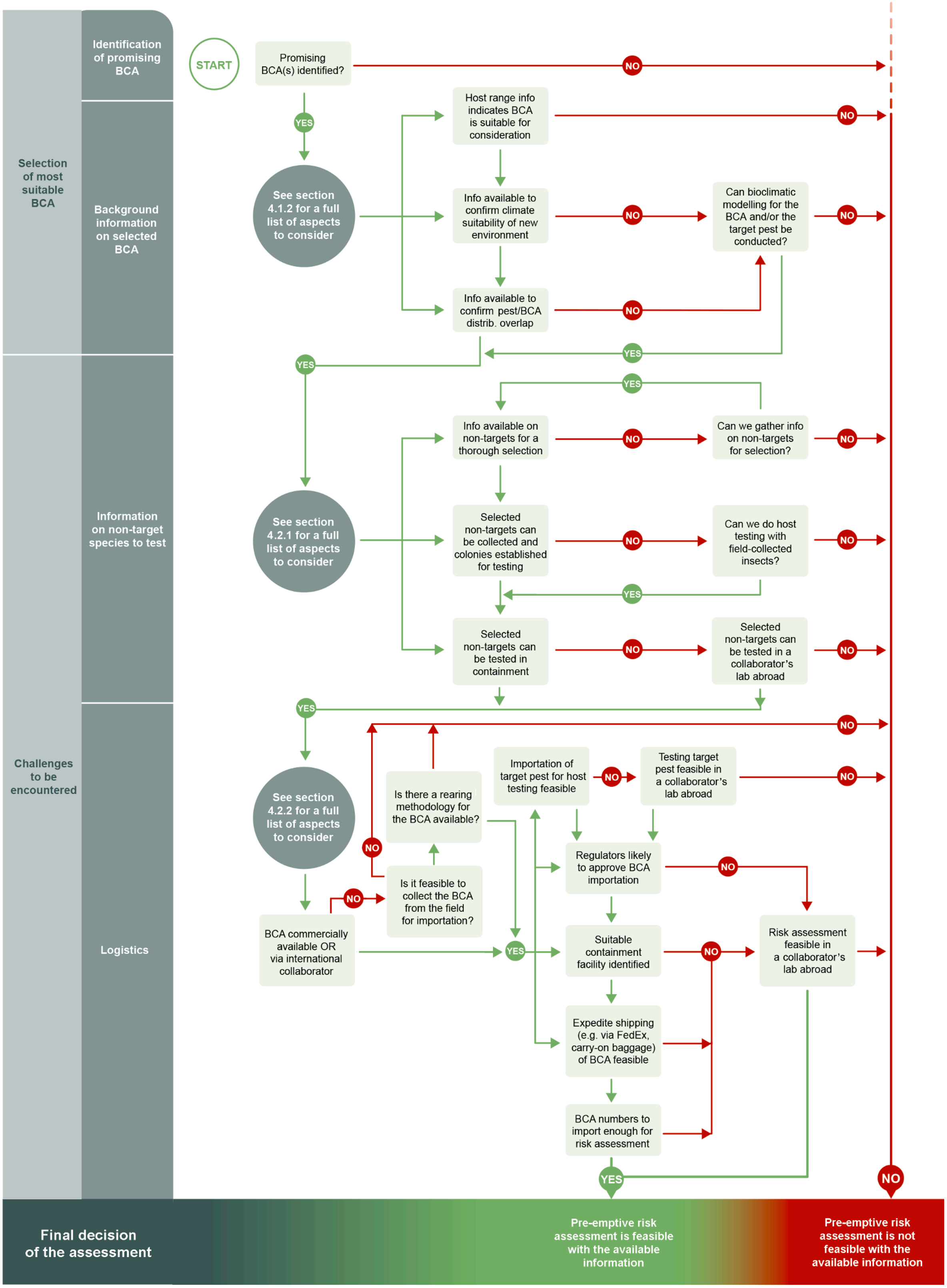
Appendix A



Framework to assess feasibility to start pre-emptive biocontrol risk assessment

Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocontrol.2023.105387.

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