



A new paradigm: proactive biological control of invasive insect pests

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Abstract Invasive insect pests are a significant and accelerating threat to agricultural productivity, they degrade wilderness areas, and reduce quality of life in urban zones. Introduction biological control, the introduction, release, and establishment of host-specific efficacious natural enemies, is an effective management tool for permanently suppressing invasive pest populations over vast areas, often to levels that may no longer cause economic or environmental damage. However, introduction biological control programs are reactive: they are only initiated after an invasive pest has established, spread, and is causing damage that requires mitigation. Host specificity and host range testing of natural enemies for use in an introduction biological control program against an invasive pest can take years to complete. During this time, the target pest population continues to increase, invades new areas, and inflicts damage. Proactive biological control research programs identify prior to their establishment pest species that have high invasion potential and are likely to cause economic or environmental damage once established. Natural enemies are selected, screened, and if sufficiently host-specific, approved for release in advance of the anticipated establishment of the target pest. Following

detection of the target pest and determination that incipient populations cannot be eradicated, natural enemies already approved for release are liberated into infested areas. This proactive approach to introduction biological control could significantly reduce project development time post-invasion, thereby lessening opportunities for pest populations to build, spread, and cause damage.

Keywords Classical biological control · Importation biological control · Invasive pests · Invasion bridgeheads · Natural enemies

Introduction

Invasive species are non-native organisms that have been deliberately or inadvertently introduced into areas outside of their native range by human activities, where, following permanent establishment, proliferation, and spread, cause adverse economic, ecological, and human-health impacts. Invasive non-native species are a perennial problem requiring escalating levels of human management to abate (Pyšek et al. 2020). Drivers for translocating species from their native range to new areas where they may become invasive include increasing volumes of exported and imported materials, human mobility, and land degradation (Seebans et al. 2018). Expanding agricultural and horticultural enterprises are also significant contributors (Paini et al. 2016; Seebans

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et al. 2017). Alarming, there appears to be no slowing of human-mediated movement of non-native species into new areas (Seebans et al. 2017). Increasing trade and tourism allow access to new regions that were previously isolated and enhanced accessibility is providing opportunities for additional species with invasive potential to be translocated from new source areas (Seebans et al. 2018).

To mitigate introduction risks, inspections of arriving goods and personal baggage at ports of entry are standard procedures for national biosecurity programs (Turner et al. 2021). However, given the vast volumes of goods moved by trade and tourism only a tiny fraction of material is inspected (Turner et al. 2021). Failure to inspect enables incursions by “unseen arrivals” that may be species known to be problematic (Turner et al. 2020) or “emerging alien species” which are relatively unknown species that have nascent invasion potential (Seebans et al. 2018). To avoid negative connotations associated with the noun “alien” the adjective “invasive” is used here to denote the non-native origin of the pest and its propensity for spreading and causing damage. Identifying “emerging invasive species” a priori is extremely challenging as there is likely no invasion history associated with the incipient pest (Paini et al. 2016), or it may be an unknown species new to science at the time of invasion (Hoddle et al. 2006).

Biosecurity preparedness relies in part on “horizon scanning” studies that attempt to identify “lurkers on the threshold” (Hoddle 2006) or “door-knocker” species (Seebans et al. 2018) that have high incursion risk, and are likely capable of causing significant negative impacts following establishment and spread (Hoddle 2006; Seebans et al. 2018). With respect to “horizon scanning” for potential invasive species, “invasion bridgeheads” (Lombaert et al. 2010) or “invasion hubs” (Florance et al. 2011), established invasive populations that act as sources of colonists for additional or secondary invasion events (Bertelsmeier et al. 2018) have been identified as predictable progenitors for intra- (Paini et al. 2010) and inter-continental spread of invasive pests (Correa et al. 2019).

Amongst invasive species, some of the smallest and most difficult to detect are insects and mites, which can cause significant adverse impacts following establishment in non-native habitats (Boubou et al. 2012; Turner et al. 2021). Drivers for herbivorous arthropod (i.e., insects and mites) movement are

strongly linked to trade in live plants (Liebhold et al. 2012), which is also a source of invasive weed species (Bradley et al. 2012) and plant pathogens (Liebhold et al. 2012), and agricultural exports (Paini et al. 2016; Lu et al. 2021). Examples of some important arthropod invaders that have undergone range expansion via invasion bridgeheads include: Asian citrus psyllid, *Diaphorina citri* Kuwayama (Hemiptera: Liviidae) (Luo and Agnarsson 2018), brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) (Cesari et al. 2017; Valentine et al. 2017), glassy-winged sharpshooter, *Homalodisca vitripennis* (Germer) (Hemiptera: Cicadellidae) (Hoddle and Morgan 2022), obscure mealybug, *Pseudococcus viburni* (Signoret) (Hemiptera: Pseudococcidae) (Correa et al. 2019), palm weevils, *Rhynchophorus* spp. (Coleoptera: Curculionidae) (Rugman-Jones et al. 2013), spotted lanternfly, *Lycorma delicatula* (White) (Hemiptera: Fulgoridae) (Du et al. 2021), red tomato spider mite, *Tetranychus evansi* Baker and Pritchard (Trombidiformes: Tetranychidae) (Boubou et al. 2012), and western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae) (Yang et al. 2012; Reitz et al. 2020).

“Horizon scans” have highlighted “invasion bridgeheads” as an important phenomenon driving the biogeography, and regional, national, and international flow of invasive species (Bertelsmeier et al. 2018; Bertelsmeier and Ollier 2021; Ricciardi et al. 2021). Collaborative identification and mitigation of invasion bridgeheads (Ricciardi et al. 2021) may lessen threats to agricultural trade partners (Paini et al. 2016; Huron et al. 2022) and possibly aid in the identification of native range areas from which invasive populations originated (Luo and Agnarsson 2018; Correa et al. 2019). This, in turn, may enable location of natural enemies adapted to invasive genotypes that originated in the native or invaded range, and to climatic conditions in invaded areas that could be used in introduction biological control programs for managing pest populations (Lara and Hoddle 2015).

Introduction biological control

Introduction biological control, also referred to as classical or importation biological control, is a tool that can be used for managing damaging populations

of invasive pests, and is most commonly employed against non-native pest insects and weeds (Hoddle et al. 2021). Specifically, introduction biological control is the deliberate collection, importation, release, and establishment of host-specific natural enemies (e.g., predators, parasitoids, or entomopathogens for arthropods, or herbivorous arthropods and plant pathogens for weeds) by qualified biological control scientists with the intent of suppressing pest populations to less damaging densities. Introduction biological control employs an upper trophic level organism (e.g., a parasitoid) to manage an invasive pest (e.g., herbivorous insect) occupying a lower trophic level. Introduction biological control programs are meticulously planned invasion projects in which a myriad of steps are carefully managed. These steps can include careful selection of a source population from within a circumscribed geographical location, management of the genetic constitution of populations of released natural enemies, precise records on numbers of individuals released and frequency of introductions, and judicious choice of release locations and times of year releases are made (Hoddle and Morgan 2022; Hoddle et al. 2022a). van Driesche et al. (2008) and Hoddle et al. (2021) provide overviews on the steps involved in developing introduction biological control programs.

Introduction biological control programs constitute a reactive management response to an invasive pest after it has become well-established, widespread, and problematic. Implementation is a multi-year process, during which time target pest populations continue to increase, spread, and inflict damage. The *D. citri* invasion into California, USA is an illustrative example of the time needed to develop an introduction biological control program for an invasive agricultural pest.

Case study: a reactive response to an invasion—development of an introduction biological control program for Asian citrus psyllid, *Diaphorina citri*, in California, USA

Diaphorina citri (Fig. 1a), native to the Indian subcontinent, is arguably the most destructive invasive pest affecting global citrus production because of its ability to acquire and vector a bacterium, *Candidatus Liberibacter asiaticus* (CLAs),

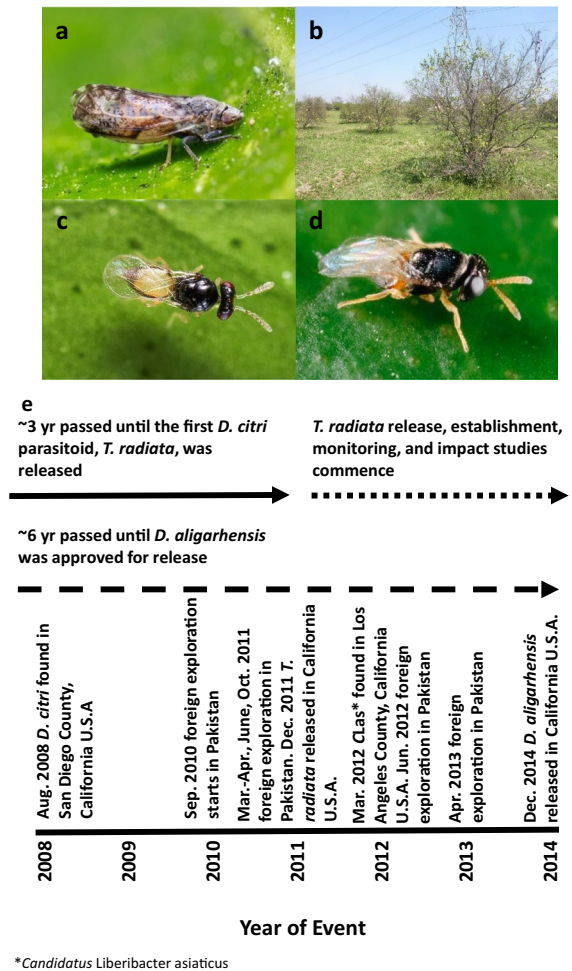


Fig. 1 Introduction biological control of **a** *Diaphorina citri*, the vector of *Candidatus Liberibacter asiaticus*, which causes a lethal citrus disease, **b** huanglongbing (also known as citrus greening) was initiated after *D. citri* invaded and established in California. *Diaphorina citri* was targeted with two nymphal parasitoids, **c** *Tamarixia radiata* and **d** *Diaphorencyrtus aligarhensis* sourced from Punjab Pakistan. **e** Development of this introduction biological control program was a years long process during which *D. citri* continued to spread. Photo credits: **a, c, d** Mike Lewis, University of California Riverside, USA; **b** Mark Hoddle, University of California Riverside, USA

which causes a lethal citrus disease known as huanglongbing or citrus greening (Fig. 1b) (Bové 2006; Grafton-Cardwell et al. 2013). In North America, *D. citri* established its first “invasion bridgehead” in Florida, USA in 1998 (Halbert and Manjunath 2004) and CLAs was first identified there in 2005 (Farnsworth et al. 2014). The subsequent economic impacts

of *D. citri*-CLAs on the Florida citrus industry have been considerable (Alvarez et al. 2016).

A second North American *D. citri* bridgehead was later reported from México in 2002, and importantly, for California, the presence of *D. citri* was confirmed in Tijuana, Baja California México in 2008. Tijuana is a large populous border city situated on the California-Mexican border. In 2009, CLAs was officially detected in México (Cortez-Mondaca et al. 2009). In 2008, *D. citri* was detected ~10 km north of Tijuana when established populations were found in San Diego County in California. Shortly thereafter, a larger and more widespread *D. citri* infestation was found in Los Angeles County (~120 km north of San Diego County) which was indicative of an earlier incursion event that had gone undetected (Hoddle et al. 2022a). In 2012, the first CLAs infected citrus tree was discovered in Los Angeles County California. The threat to California's ~\$7 billion USD per year citrus industry from *D. citri*-CLAs had now been realized, and the concern was would impacts be as severe as those observed in Florida (Hoddle et al. 2022a)?

The initial response plan to manage *D. citri* in California was insecticide-focused with the goal of containment and eradication. This program was, however, abandoned due to an inability to contain *D. citri* as it continued to spread over larger areas, with infested areas requiring repeat treatments, public disquiet with insecticide applications, and cost (>\$4.7 million USD) (Hoddle and Pandey 2014). The abandonment of insecticide application campaigns provided an opportunity to consider an alternative reactive response for *D. citri* management, introduction biological control, which commenced in 2010, two years after *D. citri* establishment was confirmed in California (Hoddle and Pandey 2014; Bistline-East et al. 2015; Hoddle et al. 2022a). Frustratingly, the introduction biological control project was not supported until insecticide management efforts ceased. The rationale for this decision was due to concern that a concurrent biological control program would detract support for insecticide use which may have resulted in refusals to participate in spray programs if biological control was viewed more favorably as an alternative management tactic.

The biological control program for *D. citri* sourced two species of nymphal parasitoid, *Tamarixia radiata* (Waterston) (Hymenoptera: Eulophidae) (Fig. 1c)

and *Diaphorencyrtus aligarhensis* (Shafee, Alam and Agarwal) (Hymenoptera: Encyrtidae) (Fig. 1d) from Punjab Pakistan, part of the putative native range of this pest, and an area with a ~70% climate match with major citrus production areas in California's Central Valley (Hoddle et al. 2022a). Following release, approximately three years after detection of *D. citri* in California (Fig. 1e), *T. radiata* established readily, spread quickly, and *D. citri* densities declined by >70% after releases began (Hoddle et al. 2016; Kistner et al. 2016; Milosavljević et al. 2021). *Diaphorencyrtus aligarhensis*, collected at the same time as *T. radiata*, was evaluated for safety, and was then approved for release by Federal regulatory authorities approximately six years after *D. citri* was detected in California (Fig. 1e). This parasitoid failed to establish despite releases of >700,000 individuals (Hoddle et al. 2022a; Milosavljević et al. 2022).

Given that *D. citri* invasion bridgeheads existed in Florida (1998) and México (2002) and that this insect is a notorious global citrus pest with high invasion potential, a retrospective question that deserves consideration is: "Could advance *D. citri* biological control preparedness in California have been better?" In hindsight, proactive actions to prepare an introduction biological control program in advance of the anticipated incursion and establishment of *D. citri* in California would have been justified. Such activity, if undertaken when *D. citri* invasion bridgeheads had been identified in Florida and México, would have permitted a more rapid biological control response to managing the *D. citri* incursion in California which could have slowed spread and reduced pest densities, with a possible concomitant reduction in incidences of vector-disseminated CLAs. Having host-specific natural enemies already selected and permitted for release prior to the establishment of a target invasive pest is the core concept underlying proactive biological control (Hoddle et al. 2018).

Proactive biological control research: a deep dive into development and application

Selecting targets for proactive biological control research programs can be achieved by conducting "horizon scans" for "door knocker" species that have already established invasion bridgeheads and are exhibiting a propensity for spread. In California,

for example, around 9–10 new macroinvertebrate species (i.e., insects, mites, spiders, terrestrial crustaceans, mollusks) establish per year. The majority of these non-native organisms are primarily plant feeding insects, of which, approximately three or so each year will become pests requiring management (Dowell et al. 2016). Importantly, approximately 44% of invaders that establish in California originate from invasion bridgeheads established elsewhere in the USA and Canada (Dowell et al. 2016). Tracking establishment and spread data is a prudent practice for identifying new invasive threats. In this regard, spotted lanternfly, *L. delicatula*, is a serious threat of spreading within North America and poses a significant invasion risk to other countries (Wakie et al. 2020; Huron et al. 2022).

Horizon scans for known “door knocker” species

Lycorma delicatula, native to China, established in South Korea in 2004 (Park et al. 2013), in Japan in 2009 (Nakashita et al. 2022), and the northeast USA in 2014 (Urban 2019). This polyphagous lanternfly is a pest of perennial agricultural crops (i.e., grapes and walnuts) and it was a target for introduction biological control in South Korea with an egg parasitoid, *Anastatus orientalis* Yang and Choi (Hymenoptera: Eupelmidae), sourced from China (Seo et al. 2019). Subsequently, *A. orientalis* sourced directly from China, was imported into the USA as a potential biological control agent of *L. delicatula*. Because *L. delicatula* is widely established on the east coast of the USA and numerous invasion bridgeheads are forming in the Midwest (e.g., Indiana), “horizon scanning” determined that this pest poses a significant invasion threat to California specialty crops (e.g., nuts, grapes, kiwifruit). Consequently, *A. orientalis* host range and host specificity were assessed prior to established populations of *L. delicatula* being detected in California (Gómez Marco et al. 2023).

Similar proactive biological control research efforts were initiated against *H. vitripennis* by New Zealand (Groenteman et al. 2015) and Australia (Rathe et al. 2012; 2014) and for *H. halys* by New Zealand (Charles et al. 2019). *Homalodisca vitripennis*, native to southeastern USA and northeast México, invaded California sometime in the 1980’s and became a significant pest because it vectored a xylem-limited bacterium, *Xylella fastidiosa* Wells

et al. (Xanthomonadaceae), the causative agent of the lethal grape malady, Pierce’s disease (Hoddle and Morgan 2022). *Homalodisca vitripennis* was identified as a significant incursion threat for New Zealand and Australia following establishment of invasion bridgeheads in the South Pacific. The first bridgehead established in French Polynesia (1999) possibly due to importation of infested nursery stock from California. Established *H. vitripennis* populations were then detected in Hawaii (2004), Easter Island (2005) and the Cook Islands (2007) (Hoddle and Morgan 2022). Movement of live plants infested with *H. vitripennis* from areas with invasion bridgeheads was the most likely conduit for translocating this pest to new areas within the South Pacific (Petit et al. 2009). Consequently, high levels of tourism between New Zealand and Australia with *H. vitripennis* infested areas (e.g., French Polynesia) was a recognized incursion pathway for those two countries. Additionally, ecological niche modeling indicated New Zealand and Australia had climates suitable for *H. vitripennis* to persist year round, should it establish, thereby potentially threatening important agricultural industries such as wine grape production (Hoddle 2004a).

In the absence of effective natural enemies, *H. vitripennis* populations reached astounding densities in French Polynesia (Grandgirard et al. 2007a, 2008, 2009). An introduction biological control program targeting *H. vitripennis* in French Polynesia with an egg parasitoid, *Cosmocomoidea ashmeadi* (Girault) (Hymenoptera: Mymaridae), provided rapid and spectacular suppression of this pest within seven months of release (Grandgirard et al. 2008; 2009). High and persistent levels of suppression by *C. ashmeadi* in all invaded regions in the South Pacific resulted in cessation of *H. vitripennis* spread throughout this area (Weber et al. 2021; Wyckhuys et al. 2021; Hoddle and Morgan 2022). The success of this program significantly reduced incursion risks to New Zealand and Australia from areas with established *H. vitripennis* populations because the threat likelihood from illegal movement of infested plant material (Hoddle and Morgan 2022) or accidental transportation of adults in aircraft (Rathe et al. 2015) was diminished. *Cosmocomoidea ashmeadi* is host-specific to members of Proconiini (Boyd and Hoddle 2007; Grandgirard et al. 2007b), a cicadellid tribe restricted to the Americas. Because species of Proconiini do not naturally occur in New Zealand (and Australia), Charles (2012)

proposed that *C. ashmeadi* should not be subjected to non-target host testing prior to use in New Zealand should this parasitoid be needed for biological control of *H. vitripennis*.

Brown marmorated stink bug, *H. halys*, native to China, Japan, Korea, and Taiwan has successfully invaded Canada, the USA, Europe, and Chile (Charles et al. 2019). This polyphagous pest is a significant threat to horticultural industries, such as kiwifruit, grapes, and apples, which are major crops in New Zealand (Fraser et al. 2017; Charles et al. 2019). Ecological niche modeling indicates that *H. halys* has significant capacity to continue to expand its range and this pest has been intercepted numerous times entering New Zealand, indicating that it may be prudent to prepare in advance for the eventual establishment of this pest (Fraser et al. 2017; Avila and Charles 2018; Yanow et al. 2021). The egg parasitoid, *Trissolcus japonicus* (Ashmead) (Hymenoptera: Scelionidae), a natural enemy of *H. halys*, has been proactively screened and approved for use in a proactive biological control program against this pest in New Zealand should it establish (Charles et al. 2019). Even though evidence of attack to New Zealand native species exists (Saunders et al. 2021) the probable benefits from biological control of *H. halys* with *T. japonicus* were determined to outweigh risks to non-target species (Charles et al. 2019).

Horizon scans for “wild cards” and “emerging invasive species”

Arguably, a more difficult challenge for developing a proactive biological control program would be identification of “wild card species” (i.e., unknown or unpredictable entities) that fall into the “emerging invasive species” category prior to them establishing “invasion bridgeheads” and becoming obvious “door knockers”. Emerging invasive insect threats, for example, could be recognized pests associated with agricultural crops that have high export volumes from source regions (e.g., Lu et al. 2021), or unknown or little studied pest species associated with a crop that is grown in the crop’s native or naturalized range, and from where there are high export volumes, and this crop, especially in the native range, has high levels of little studied native or endemic biodiversity associated with it (Hoddle 2004b; 2006). Avocado fruit, *Persea americana* Miller (Lauraceae) exports from

countries where this plant is native [e.g., México and Guatemala (Chanderbali et al. 2013)], naturalized in wilderness areas [e.g., Perú (Gray 1930)] where Lauraceae and *Persea* are well represented (León 2006) and specialist fruit feeding insects are likely present, or imports were restricted because of previous interceptions of fruit infested with quarantine-regulated pests that are avocado fruit specialists [e.g., Colombia (Hoddle et al. 2022b)] are possible sources of invasive avocado fruit pests. The previous scenarios illustrate three possible incursion routes by “wild card” or emergent invasive species: (1) high export volumes of fruit from regions where the crop is native or naturalized that may be infested with known species of fruit feeding pests, (2) unexpected “wild card” introductions by unknown or relatively poorly studied native or endemic pest species associated with fruit in native or naturalized regions, and (3) previous repeated interceptions of specialized fruit feeding pest species that has resulted in revocation of export privileges.

Avocados are an iconic California specialty crop with an annual value of approximately \$328-\$411 million USD (CAC 2022). Importantly, year round imports of fresh avocado fruit from México and Colombia and during March-October from Perú increases the likelihood of undetected incursions of fruit pests aligning with favorable conditions for establishment in California (i.e., suitable weather and availability of fruit stages vulnerable to attack). Even though these events co-aligning are probably very low, the “law of large numbers” states that a rare event with a low probability of occurrence in a small number of trials has a high probability of occurrence in a large number of trials (Shermer 2004; Hand 2014). Therefore, rare events, for example pest introductions resulting in establishment, may not be so uncommon when the number of times the rare event could happen is very large, such as the importation of hundreds of millions of avocado fruit from areas with known fruit feeding pests over long periods of time.

Two notorious specialist avocado fruit pests of quarantine importance for the USA are the avocado seed moth *Stenoma catenifer* Walsingham (Lepidoptera: Elachistidae) native to México, Perú, and Colombia (invasive in the Galápagos Islands), and the large avocado seed weevil, *Heilipus lauri* Boheman (Coleoptera: Curculionidae), native to México, absent in Perú, invasive in Colombia. Given the notoriety of these avocado fruit-feeding pests, it is surprising that

relatively little is known about their biology, ecology and behavior, and arguably monitoring and management plans are not well developed (Castañada-Vildózola et al. 2013; Hoddle and Parra 2013). California currently lacks specialist avocado fruit-feeding pests and establishment of fruit-feeding moths and weevils, for example, would cause significant industry upheaval.

A proactive approach to managing the threat posed by *S. catenifer* has resulted in the development of natural enemy inventories and life table studies documenting identities and impacts of natural enemy species that could be used in future introduction biological control programs (Hoddle and Hoddle 2008a, b, c, 2012). Additionally, the elucidation and optimization of field use of the moth's sex pheromone, an important detection and monitoring tool, has been completed (Hoddle et al. 2009a; 2011). A significant by-product of this work was the identification of previously unknown and undescribed pest species associated with avocado fruit (and their natural enemies) that could pose "wild card" incursion risks and records of first associations of described species with larval host foods (Hoddle 2008; Hoddle and Hoddle 2008c; Adamski and Hoddle 2009; Hoddle et al. 2009b; Brown and Hoddle 2010; Hoddle and Brown 2010; Gilligan et al. 2011).

Theoretically, should *S. catenifer* (or one of the discovered "wild card" species) be discovered in California tomorrow, an introduction biological control program could start rapidly as the groundwork on candidate natural enemy species in the native range has been completed. A similar proactive program is currently being developed for *H. lauri* to better position the California avocado industry (and production areas in Florida and Hawaii) should an incursion by this fruit pest result in establishment (Hoddle et al. 2022b,c).

A similar in-the-field approach to assess pestiferousness and invasion risks posed by little studied or unknown insect species (and plant pathogens) can be accomplished by surveying trees that are planted outside of their native ranges in botanic gardens, arboreta, as ornamentals in urban areas, or deliberately planted for observations in carefully designed "garden" experiments (Rathe et al. 2014; Groenteman et al. 2015; Roques et al 2015; Barham 2016; Popkin 2020; DiGirolomo et al. 2022). This proactive approach attempts to identify and forecast potential

invasion threats posed by herbivorous insects ahead of possible future incursions into at risk areas. For example, a group of 23 European nations have established plantings of native European trees in North America, Asia, and South Africa, possible source areas of invasive pests, to identify phytophagous insect species from different regions of the world that will attack these trees (Popkin 2020).

Data on insect identities can be a significant challenge for sentinel plant studies (Roques et al. 2015) and attack severity, when coupled together with pest and host plant phenological data, may collectively help identify future potential invasive pest species. In addition to identification of potential pest species, supplemental research would identify natural enemy species associated with key pests of concern, the life stages attacked, and quantification of impacts (Rathe et al. 2014). Having these types of data on natural enemy species in-hand prior to a pest invasion would have two advantages. First, it could significantly reduce the time needed to develop introduction biological control programs as natural enemy identities and possible levels of control would be known. Second, these data may identify natural enemy species that have potential for self-introductions into new areas should they accompany pestiferous hosts during the invasion process. Unintentional introductions in this manner exceed the number of natural enemy species deliberately introduced into areas in support of introduction biological control programs (Weber et al. 2021). Discovery of adventive natural enemy species has raised concerns over population-level impacts on non-target species, which has led to increased research activity on this phenomena (Weber et al. 2021) and proactive biological control research may ease concerns associated with potential non-target impacts by self-introduced natural enemy species.

Conducting horizon scans using online platforms, networks, professional meetings, and incursion monitoring programs

Online virtual tools that distribute information on new and emerging phytosanitary threats are an additional way to conduct "horizon scans" on a global level for potential invasive pests that may be suitable targets for proactive biological control research. PestLens (<https://pestlens.info/>), an early warning system, produces weekly email notifications that are

distributed automatically to subscribers. The information reported by PestLens that are relevant to proactive biological control research include descriptions and identification of new pest species, updates on pest distribution records (i.e., notification of invasion bridgeheads), new host records, notifications of significant pest outbreaks, and reports of new insect-vector relationships. Registered PestLens users can access a searchable archive of first records for pests of interest and contribute new information on pest threats to the site that may come from site visits and field work, collaborative projects with colleagues, or new information on known or emerging pest threats presented at professional meetings. The International Plant Sentinel Network (<https://www.bgci.org/our-work/networks/ipsn/>) is an early warning system for identifying emerging tree pests and aims to facilitate collaborative efforts amongst arboreta, botanical gardens, regional, national, and international plant protection organizations and research scientists (Barham 2016; Barham et al. 2016). Online community science platforms, like iNaturalist, may also be useful resources for alerts of new reports on “door knocker” species. International symposia are excellent sources for new information on emerging invasive threats that have not yet entered the peer-reviewed scientific literature.

Pest surveillance programs may be additional sources of information that result from near daily “horizon scanning” activities. Detections of pests, especially in monitoring traps deployed by regulatory agencies, would be indicative of incursions by live vagile adults that may result in establishment. For example, the California Department of Food and Agricultural (CDFA) runs statewide pest detection and emergency projects operations that are focused on early detection and rapid eradication of serious agricultural pests (i.e., insects and plant diseases) should incipient populations be detected (<https://www.cdafa.ca.gov/plant/pdep/>). Additionally, 16 border protection stations that monitor and inspect vehicles entering California along major highways in the north from Oregon and east of the state from Nevada and Arizona, USA. More than 20 million private vehicles and seven million commercial vehicles are inspected annually for plant material (i.e., fruit, vegetables, plants, and firewood) that are potentially infested with actionable pest species (<https://www.cdafa.ca.gov/plant/pe/ExteriorExclusion/borders.html>).

Frequent detections of species with known or suspected invasion potential by border protection programs may warrant consideration as potential targets for proactive biological control research.

What if proactive biological control research fails to identify host-specific natural enemies for a target pest?

A possible outcome resulting from proactive biological control research programs is the failure to identify natural enemy species that exhibit sufficient host specificity for future use in an introduction biological control project. This situation may be relevant for the proactive biological control program targeting *L. delicatula* in California with *A. orientalis* (Gomez-Marco et al. 2023). Host range testing indicated that *A. orientalis* is likely polyphagous and can successfully parasitize and develop in host species belonging to at least two different orders (Hemiptera and Lepidoptera) and seven families (Coreidae, Erebidae, Fulgoridae, Lasiocampidae, Pentatomidae, Saturniidae and Sphingidae). The previously unknown polyphagy of *A. orientalis* led to the conclusion that *A. orientalis* has a very broad host range and consideration of use in an introduction biological control program targeting *L. delicatula* should be viewed with extreme caution (Gomez-Marco et al. 2023). Despite this negative outcome, such findings allow research priorities for managing “door knocker” pests to be moved elsewhere. In California, proactive biological control research for *L. delicatula* is focusing on assessing possible levels of naturally occurring biotic resistance from resident (i.e., native and introduced) species of *Anastatus*. Additionally, it is likely that integrated pest management approaches that rely more heavily on control tactics other than biological control will be warranted and may need to be prioritized for *L. delicatula* management.

Proactive biological control research should be funded as insurance programs

Funding and development of proactive biological control research programs is analogous to buying insurance. The owners of insurance policies hope not to need them but benefit from being holders when catastrophe strikes. Federal and state agencies responsible for developing biological control programs for

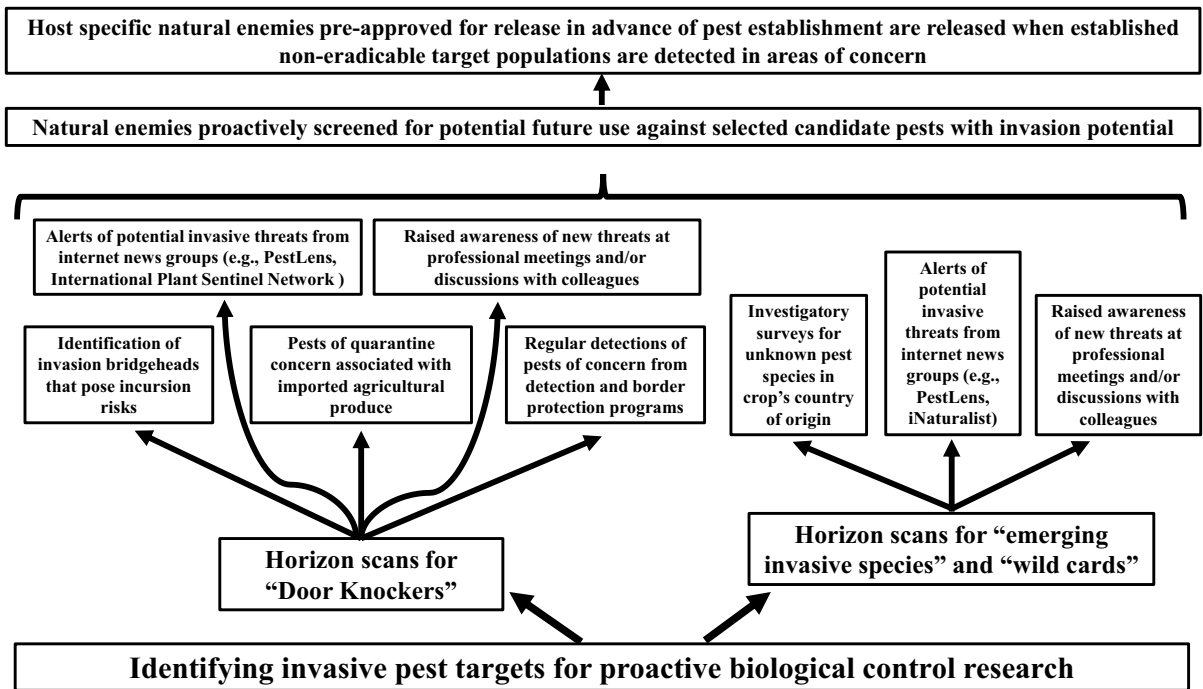


Fig. 2 Possible steps and outcomes when selecting invasive pest targets for proactive biological control research programs

managing invasive pests could enact funding programs as “insurance” against future pest threats to support proactive biological control research efforts. The CDFA Office of Pesticide Consultation and Analysis runs a proactive IPM (Integrated Pest Management) solutions program, of which proactive biological control research is a component eligible for competitive funding via a grant application and review process. The goal of the program is to identify, anticipate, and prepare in advance for the arrival into California of invasive pests and to have management strategies in place that can be rapidly implemented should established pest populations be detected (<https://www.cdfa.ca.gov/oefi/opca/proactive-ipm.html>). Since its inception in 2019, this program has sponsored research on *L. delicatula*, *H. lauri*, swede midge, *Contarina nasturtii* (Keiffer) (Diptera: Cecidomyiidae), South American tomato pinworm, *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae), emerald ash borer, *Agrilus planipennis* Fairmarie (Coleoptera: Buprestidae), and cotton seed bug, *Oxycarenus hyalinipennis* (Costa) (Hemiptera: Lygaeidae).

Conclusions

Development of introduction biological control research programs to manage invasions are reactive and can take years to develop. To reduce development and implementation times, proactive biological control research programs aim to identify potential invasive pests that may be good targets for introduction biological control prior to pest establishment in at risk areas. Natural enemies are identified, screened for safety, and approved for release prior to detection of established non-eradicable target pest populations (Fig. 2). In some instances, host-specific natural enemies may not be identified, and, in these cases, resources may need to be redirected to the development of management programs that rely more heavily on alternative pest control options. Investment in proactive biological control research can be viewed as being analogous to an insurance policy, excellent to have, but something policy holders hope will not be needed. Proactive biological control research is a new twist on a classic approach to managing invasive pests.

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Declarations

Conflict of interest The author declares that there are no conflicts of interest.

Informed consent No informed consent was needed for the writing of this article.

Research involving human and animal participants This article does not contain any studies with humans or vertebrate animal subjects.

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