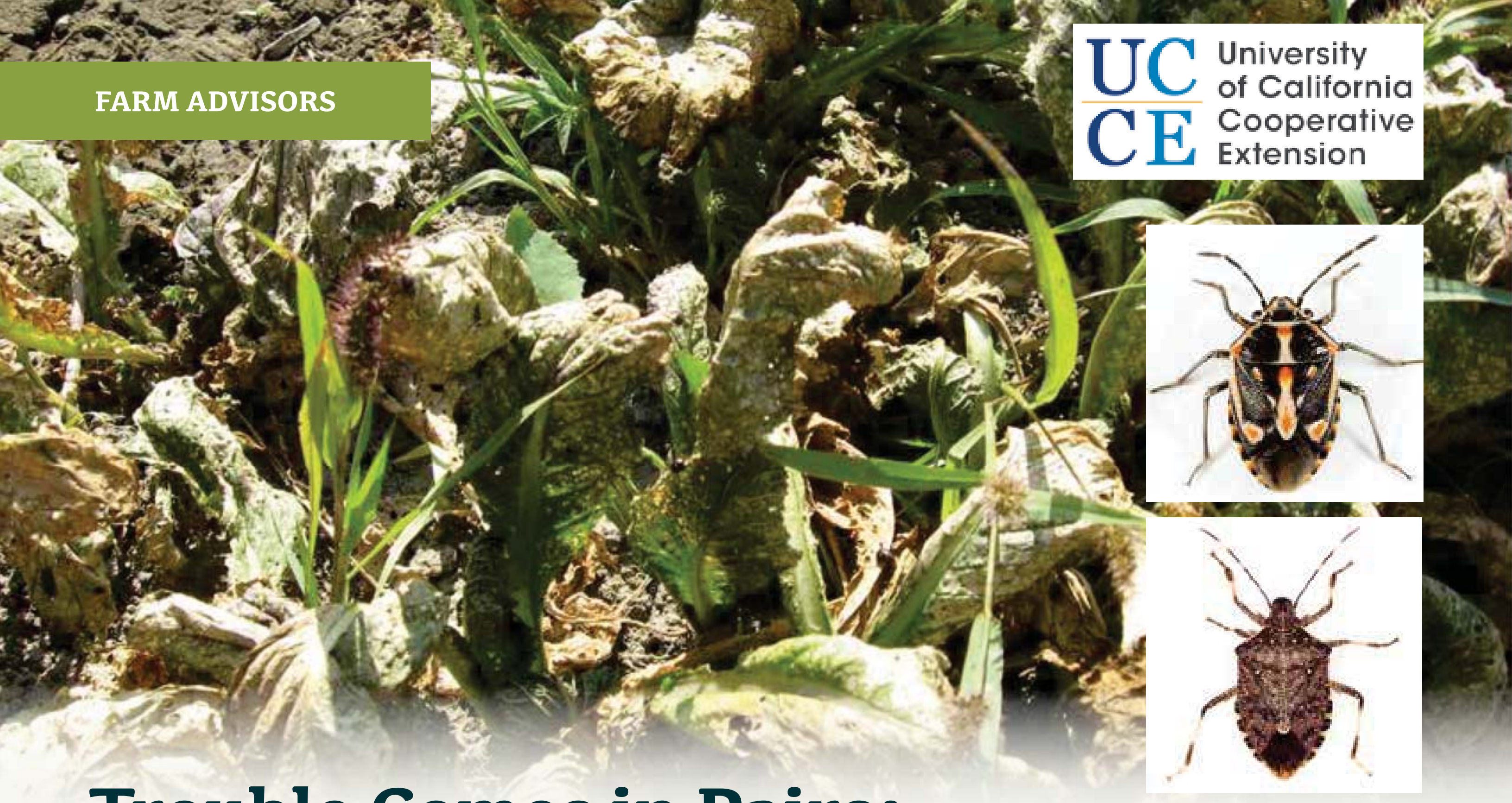

Trouble Comes in Pairs: Invasive stink bugs in California

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Worldwide, stink bugs are an economically important insect group that can be injurious to food crops. California (CA) has more than 70 stink bug species, a mixture of non-native and native species (Froeschner 1988; Lara et al. 2016). Among the non-natives are bagrada bug (BB; *Bagrada hilaris*) and brown marmorated stink bug (BMSB; *Halyomorpha halys*). Their invasion into CA poses a considerable threat to the state's specialty crop production and has triggered the development of pest management programs. Both stink bugs use their needle-like mouthparts to pierce and feed on plants and fruit, which may cause economic damage. With respect to BMSB and BB, there are notable differences and similarities in their invasion ecology which have influenced management programs in CA.

BB was first detected in the U.S. in CA (Los Angeles County) during 2008 and follow-up DNA analyses indicate CA populations originated from Pakistan (Reed et al. 2013; Sforza et al. 2017). In the U.S., BB has been recorded on 32 host plants from 8 families (Bundy et al. 2018). However, BB is mainly a pest threat to cultivated cole crops (Brassicaceae), including broccoli, cauliflower, cabbage, and kale. Feeding damage from BB causes stunted/malformed vegetative growth, wilting, and stippling (Fig 1). Severe damage symptoms from BB feeding, leading to plant death, are commonly observed with direct-seeded cole crops. BB's distribution in the U.S. is limited to southwestern states (CA, AZ, NV, NM, TX, and UT) and it thrives in warm climates, more so than BMSB. BB's current CA distribution ranges from Imperial Valley to parts of the Sacramento Valley, for a total of 22 invaded CA counties (Bundy et al. 2018). In CA, BB has peak activity occurring in spring and fall months, coinciding with the cole crop field season in agricultural areas in the state (Reed et al. 2013). It is estimated that during 2010-2014 BB generated >10% stand losses and plant injury to commercial broccoli crops in AZ and CA (Bundy et al. 2018).

When BMSB was first detected CA in 2002 (Riverside County) and breeding populations were confirmed in 2006 (Los Angeles County), it was already established on the East Coast where it arrived during the 1990s from Asia (Lara et al. 2016). Presently, BMSB has been recorded in 44 U.S. states on more than 100 host plant species from 56 families, including economically important vegetable, fruit, and nut specialty crops (NIC 2016). BMSB's feeding on fruit and nuts, for example, results in external peel discoloration and internal necrotic tissue (Fig 2). BMSB has

Fig 1. (A) Adult bagrada bugs on damaged sweet alyssum (Lobularia maritima, an ornamental brassica). (B) Feeding injury visible as wilting and lighter yellow-green blotches on kale. Photos used with permission from G. Arakelian.

a wider geographic distribution (establishment and detection) in CA than BB, ranging from Siskiyou County in the north to San Diego County in the south. Peak activity occurs during summer months. As of October 2018, BMSB is known to be established in 17 CA counties and it has been detected in 18 additional counties, where breeding populations have not been confirmed. BMSB appears to be gradually spreading from highly urbanized areas in the Sacramento Valley to the San Joaquin Valley where high market-value specialty crops like almonds and grapes are grown. BMSB feeding damage on commercial produce was recorded for the first time on peaches in 2016 and almonds in 2017 growing in Stanislaus County (Eddy 2018; Rijal and Gyawaly 2018). BB and BMSB are established in important agricultural regions like the San Joaquin Valley (BMSB and BB) and Imperial Valley (BB), where they represent a threat to a variety of commercial food crops. Incipient pest management programs for these two invasive pests continue to evolve in response to new infestations in CA.

The BB and BMSB IPM programs in the U.S. generally include population monitoring in combination with biological and chemical control options, with aspects of both still in development (see Bundy et al. 2018; Hamilton et al. 2018). For monitoring BB, pyramid traps baited with freshly crushed sweet alyssum exhibited some promise, but commercial plant-derived attractants are currently not available (UC IPM 2014a, Bundy et al. 2018). Interestingly, our BMSB monitoring studies in different parts of CA have demonstrated that the commercial BMSB pheromone is attractive to BB and using the pheromone is cost effective in detecting BMSB at low densities when combined with sticky panel traps (Fig 3). Having a functional low-cost monitoring system that can track several stink bugs of economic importance is a win-win situation for the implementation of IPM practices. The BMSB pheromone-panel trap combination is versatile and can be hung from tree branches or staked to the ground along the perimeter of orchard blocks (Fig 3). However, research is needed to determine action thresholds for triggering BMSB and BB treatments based on traps captures in CA.

Pesticide bioassays have identified active ingredients that could be used for BMSB and BB control (Palumbo et al. 2015; Kuhar and Kamminga 2017). Some of the efficacious products identified from experiments are registered for control of other insect pests in CA. Products with bifenthrin, for example, are registered for control of native stink bugs like Uhler's (*Chlorochroa uhleri*) and red-shouldered (*Thyanta pallidovirens*) on crops like pistachios and almonds (UC IPM 2014b). While useful, some insecticides may negatively impact communities of beneficial insects, such as egg parasitoids and generalist predators, and may have limited residual activity against repeated stink bug infestations thereby necessitating repeat applications throughout the growing season (Hamilton et al. 2018). Consequently, pesticide applications should be properly timed to optimize control benefits and regular

Fig 2. BMSB adult with extended needle-like mouthpart (red arrow) on a pistachio nut (inset). BMSB feeding causes internal necrotic feeding damage to developing kernel (black arrows). Photos used with permission from J. Lara and M. Lewis.

monitoring of pest populations can help with this. To reduce overreliance on chemical control, consideration should be given to other pest management options, like biological control, which can target stink bug pests at vulnerable stages of their life cycle.

Under laboratory conditions, a single mated BB and BMSB female can lay an average of 95 and 240 eggs, respectively, (Halpert and Eger 2008; Lee et al. 2013) which suggests these pests have high potential for rapid population growth, especially BB which is capable of multiple generations in warmer areas of the U.S. (Bundy et al. 2018). In the field, eggs hatch into highly mobile nymphs which eventually grow into an even bigger triple threat: hungry, flight-capable, reproductive adults. One sustainable approach for suppressing stink bug populations in CA would be to target the egg stage with natural enemies. At the onset of BB and BMSB infestations in CA, effective resident natural enemies closely associated with these pests were lacking. Their initial absence may, in part, explain the spread and buildup of BMSB and BB populations over time in the state, but this situation is changing. A cost-effective solution for BMSB and BB control in CA could be classical biological control. This is a science-based strategy that aims to reunite pests in invaded regions with their co-evolved natural enemies sourced from the pest's native range.

The concept of classical biological control is simple: introduce and establish species of specialized parasitoids from the home range of the target pests that attack stink bug eggs. Establishment of an effective natural enemy could dampen the potential for rapid population growth of invasive stink bugs in invaded areas. Ideally, parasitoid species with strong specificity for target stink bugs should be used in biological control programs. Strong specificity for the pest helps ensure that non-target stink bug species (some of which are beneficial because they are predatory) are not put at unnecessary risk of attack from the introduced natural enemy.

On the classical biocontrol front, a collaborative partnership between the U.S. Dept. of Agriculture, the CA Dept. of Food and Agriculture, the University of CA Riverside, and affected stakeholders, are leading efforts in evaluating the safety (in a secure quarantine facility) of egg parasitoid species that were sourced from the respective home ranges of each pest (Lara et al. 2016; Sforza et al. 2017). These natural enemies are *Trissolcus hyalinipennis* (sourced from Pakistan) and *Trissolcus japonicus* (sourced from China) for BB and BMSB control, respectively (Fig 4). Surprisingly, self-introduced populations of both parasitoid species have been detected in the U.S. *Trissolcus hyalinipennis*, the BB egg parasitoid, was detected in Riverside and Los Angeles Counties in 2017 (Ganjisaffar et al. 2018; BioSCAN Project). *Trissolcus japonicus*, the

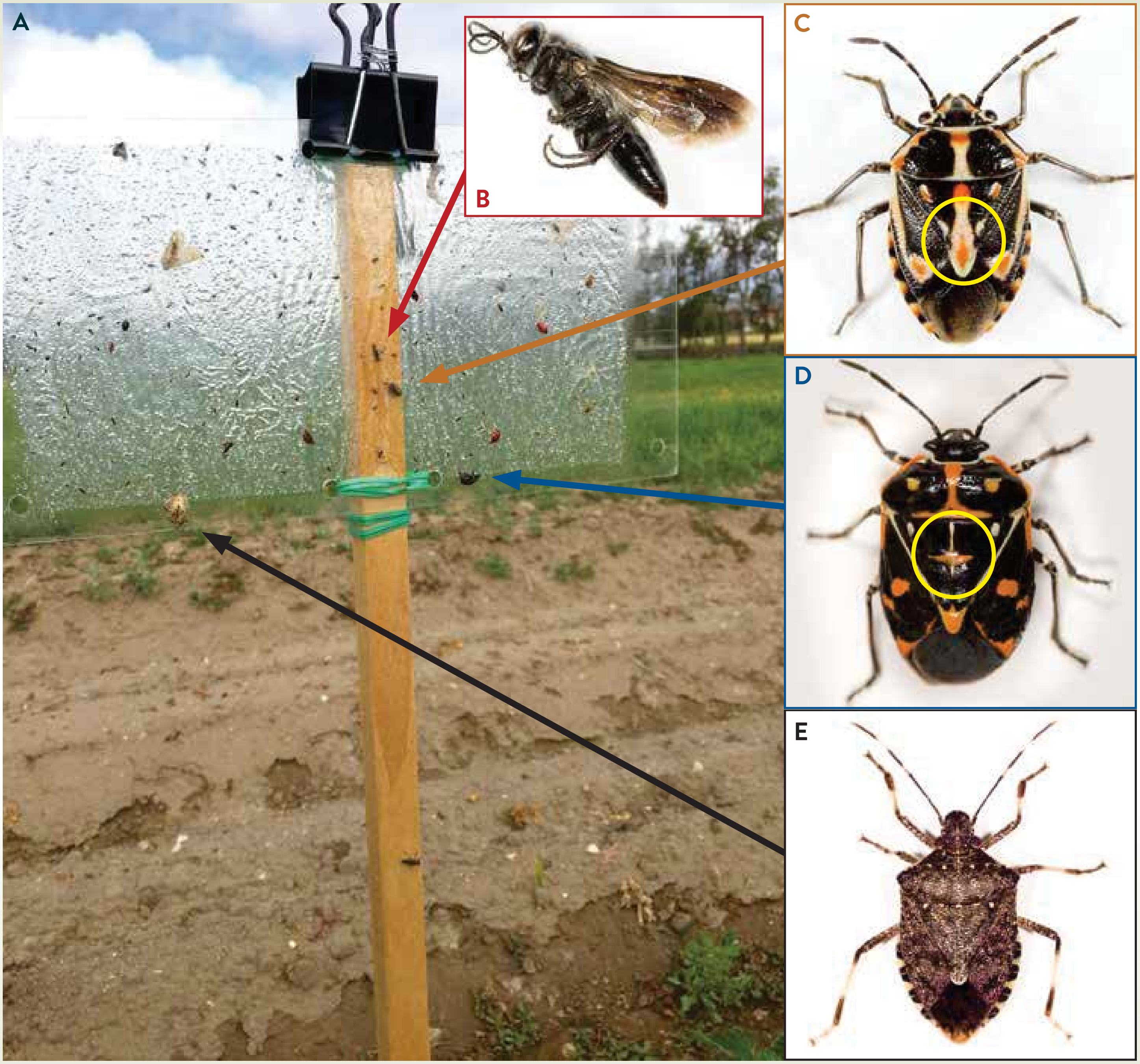

Fig 3. (A) Sticky panel trap baited with BMSB pheromone staked to the ground (on a 5 ft. wooden stake) in a tomato field in Orange County. Several stink bug species of interest and associated natural enemies have been captured on this trap: (B) red arrow = *Astata* sp., (a predatory wasp that attacks stink bugs), (C) orange arrow = *Bagrada hilaris* (BB in main text), (D) blue arrow = *Murgantia histrionica*, (E) black arrow = brown marmorated stink bug (BMSB in main text). Yellow circle positioned over scuttelum of the relatively larger *M. histrionica* (generally 8.0 – 11 mm in length) and smaller *B. hilaris* (5 – 7 mm) further highlights morphological differences between these two similar looking stink bugs. In *M. histronica*, two orange stripes meet to form a cross-like pattern. In *B. hilaris*, the transverse strip is absent. Photos used with permission from J. Lara and M. Lewis.

BMSB egg parasitoid, self-established in Mid-Atlantic states (first detected in MD in 2014) and the Pacific Northwest (first detected in WA in 2015), but has not been detected in CA (Lara et al. 2016; Hedstrom et al. 2017). These developments have expanded research efforts to detect (in the case of *T. japonicus*) or monitor the spread (in the case of *T. hyalipennis*) of these egg parasitoid species in CA. With respect to detecting *T. japonicus* in CA, collaborations with managers of community and botanical gardens, and commercial orchards, have provided access to sites infested with BMSB, including areas near major ports in Los Angeles County. The objective of these survey efforts is to determine whether or not *T. japonicus* is attacking BMSB eggs in CA.

As the biocontrol research unfolds, you can assist as a community scientist with BMSB and BB monitoring in CA. If you suspect you have found one of these pests in any part of CA, please take a

Fig 4. (A) A group of Trissolcus japonicus females parasitizing a BMSB egg mass in the UC Riverside Insectary & Quarantine Facility. (B) A few weeks later, individual adult parasitoids will emerge from each parasitized egg.

picture and share your observation(s) on iNaturalist (https://www.inaturalist.org/). The iNaturaist app is available for free download and is compatible with most major smartphone platforms. Furthermore, if you suspect you found one of these pests in a new, previously un-infested part of CA, please contact your local Ag. Commissioner's Office or the authors of this publication. ■

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