NEW RECORDS AND ACCOUNTS

Ramie Moth, *Arcte coerula* (Lepidoptera: Noctuidae): A New Invasive Pest in Hawaii on Endemic Plants

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Abstract. In November 2018, the ramie moth, *Arcte coerula* (Guenée, 1852) (Lepidoptera: Noctuidae) was found defoliating māmaki trees, *Pipturus albidus* (Hook. & Arnott.) A. Gray (Urticaceae) on Maui. This was the first detection of the ramie moth in Hawaii and the United States. As of November 2020, this new pest has spread to Hawaii island. Māmaki has cultural importance to the islands as a medicinal plant in lāʻau lapaʻau, a traditional native Hawaiian healing methodology utilizing plants, ecological importance as an essential food source for endemic insects including the state insect, and economic importance as an emerging tea crop. Field and laboratory observations suggest that high populations of *A. coerula* could potentially devastate these trees. Here we review the literature regarding this insect and assess the threat *A. coerula* poses to Hawaii. The biology and life cycle of *A. coerula* feeding on māmaki in Hawaii is described.

Key words: Ramie moth, *Arcte coerula*, *Cocytodes coerulea*, māmaki, *Pipturus albidus*, exotic pest, new record, Hawaii

Hawaii is the most isolated landmass globally, which has resulted in an extensive diversification of endemic plants and animals on the islands. Sadly, Hawaii is also the "invasive species capital" of the world with about seventeen to twenty new adventive establishments yearly according to the Hawaii Department of Agriculture (Annual Report on the Biosecurity Program, 2020). Extensive human transportation worldwide has accelerated and facilitated the movement of species from their native geographical ranges to new regions like Hawaii. These invasive species can cause dramatic shifts in ecosystems, as many of these organisms become invasive and result in negative ecological and economic consequences.

In November 2018, the Hawaii Department of Land and Natural Resources, Division of Forestry and Wildlife (DLNR-DOFAW) staff discovered an unknown caterpillar defoliating *Pipturus albidus* (Hook. & Arnott.) A. Gray (Urticaceae) (māmaki) in the upper reaches of Olowalu Valley, in the West Maui Mountains. Within a week, they found the same caterpillars feeding on māmaki plants in the Olinda Rare Plant Facility in East Maui. Molecular sequencing by the University of Hawaii, Laboratory of Insect Systematics and Biodiversity (GenBank accession number: ON606018), and morphological examination by Paul Goldstein (United States Department of Agriculture, Systematic Entomology Laboratory) confirmed the identity as *Arcte coerula* (Guenée 1852) (Lepidoptera: Noctuidae), previously *Cocytodes coerulea* and commonly known as the ramie moth. *Arcte* *coerula* may pose a threat to native forests by its feeding on endemic plants such as māmaki, which has cultural, ecological, and agricultural importance. Additionally, *A. coerula* may impact the endemic state insect, the Kamehameha butterfly, *Vanessa tameamea* (Escholtz 1821) (Lepidoptera: Nymphalidae) populations by competing for the same native host plant resources, as well as other native species dependent on the plant. Here we describe the known distribution of *A. coerula* in Hawaii and depict its biology on māmaki. This is the first published report of *A. coerula* in Hawaii and the United States.

Materials and Methods

After initial detection, we conducted field surveys in native forests, māmaki farms, and residential areas on Maui and, later, on Hawaii island after *A. coerula* was reported in the Puna District by the public. We relied on public reports through the Hawaii Department of Agriculture (HDOA) and Hawaii Invasive Species Council (HISC) 643pest hotline for new detections of *A. coerula* and conducted surveys on populations of wild and cultivated māmaki. All specimens collected were brought back to laboratories on the respective islands and reared to adult on māmaki leaves and potted māmaki plants. Data on the biology and life cycle were obtained from specimens collected on Hawaii island and reared at the CTAHR Komohana Research and Extension Center in Hilo in cages kept outside at ambient conditions. Voucher specimens of *A. coerula* were deposited in the University of Hawaii Insect Museum and the Bishop Museum.

Results

Origin and distribution. *Arcte coerula* is native to Southeast Asia. It has since spread into other parts of Asia including Japan, India, and Sri Lanka as well as Oceania including Australia, Fiji, and Papua New Guinea (Jackson and Mua 2016). In Hawaii, *A. coerula* has been recorded feeding in both wild and cultivated populations of māmaki on Maui and Hawaii island. The known distribution on Maui is scattered across the island in a range of habitats (Fig. 1a). In November of 2019, *A. coerula* was detected in the Puna District of Hawaii island. As of January 2022, this pest has been detected from the Kaʻū District and up north to the Hilo and Hāmākua Districts. (Fig. 1b). Larvae have been recorded in residential areas, māmaki farms, and native forests.

Host range. Larvae are known to feed and reproduce on a range of host plants in the nettle family (Urticaceae). In its native range of Southeast Asia, *A. coerula* larvae are found on various ramie species (*Boehmeria* spp.), which are commonly used as a natural fiber crop (Ide 2006). However, it has also been reported feeding on other Urticaceae genera including *Cypholophus* Weddell, *Debregeasia* Gaudich, *Girardinia* Gaudich, and *Pipturus* Weddell (Jackson and Mua 2016). Other authors have noted larvae feeding on *Vitis* sp. Linnaeus (Vitaceae) and *Trema tomentosa* (Roxburgh) H. Hara (Cannabaceae) (Robinson et al. 2010). Adults will sometimes feed on tree sap and decaying or overripe fruit such as bananas (Jackson and Mua 2016).

Biology and description. ***Eggs.*** Eggs are clear-white, circular, about 1 mm in diameter, and usually laid singly on the underside of leaves (Fig. 2a). In some instances, multiple eggs may be laid on a single leaf. In general, females will lay an average of five to ten eggs per plant. However, we have found up to 75 eggs on a single tree, indicating that the females may egg dump during the end of their life cycle. There have been several observed occurrences of a female laying an egg mass with as many as 220 eggs on the

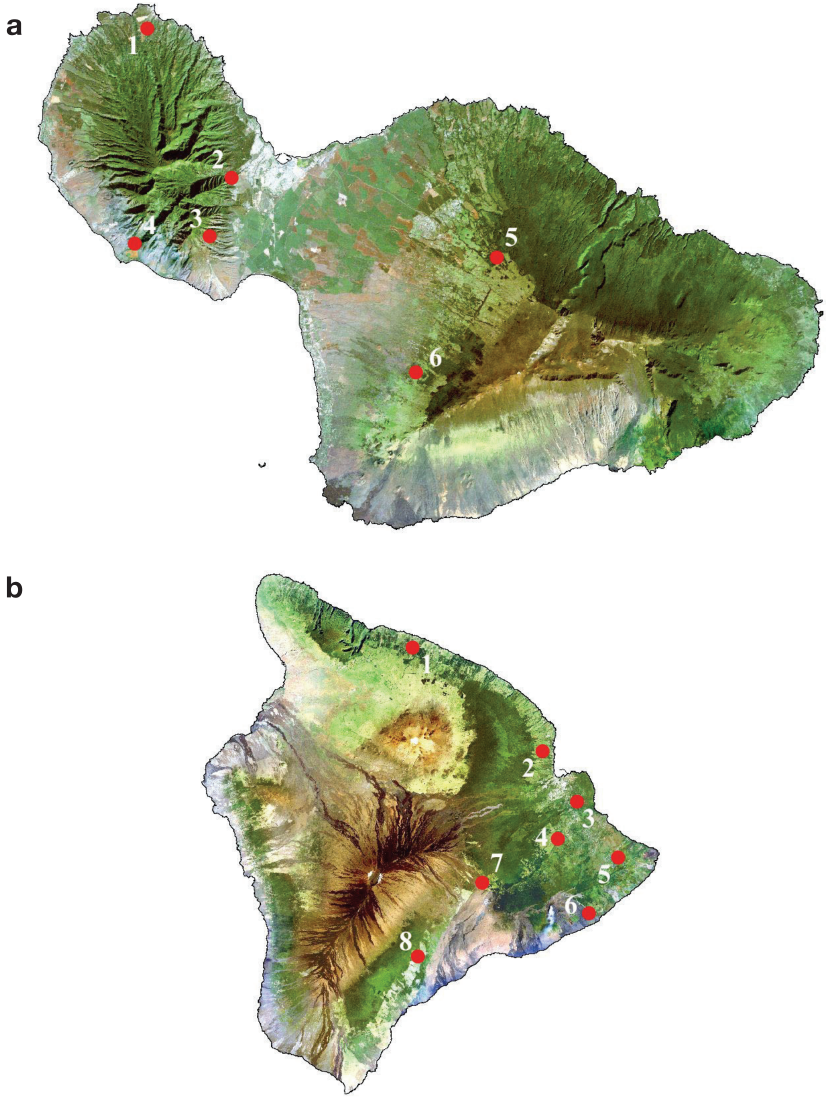

Figure 1. a. Distribution (red dots) of *Arcte coerula* on the island of Maui: 1 Kahakuloa, 2 ʻĪao Valley, 3 Waikapū, 4 Olowalu, 5 Olinda, 6 Kēōkea; **b.** Distribution (red dots) of *A. coerula* on the island of Hawaii: 1 Honokaʻa, 2 Pāpaʻikou, 3 Hilo, 4 Mountain View, 5 Pāhoa, 6 Kalapana, 7 Volcano, 8 Pāhala.

underside of a leaf (Fig. 2b). It takes less than a week for eggs to hatch.

Larvae. Early instar larvae are green and white (Fig. 3) and may be mistaken for the native Kamehameha butterfly, *Vanessa tameamea* (Escholtz 1821) (Fig. 4a) or the endemic moth *Udea stellata* (Butler 1883) (Lepidoptera: Crambidae) (Fig. 5a) which also use māmaki as a host plant. We have also found tomato

Figure 2. a. Unhatched *Arcte coerula* egg (arrow), 1 mm in diameter. Laid on the underside of host plant leaves; **b.** *Arcte coerula* egg mass with 150 hatched eggs.

looper, *Chrysodeixis chalcites* (Esper 1789) (Lepidoptera: Noctuidae) (Fig. 6) feeding on māmaki. However, *Arcte coerula* can be distinguished from these other Lepidopterans by the presence of black dotted markings on the side of its body, thin white setae or hairs, and its defensive behaviors described in the biology and behavior section below. As they develop, *A. coerula* larvae become more distinctive, with vibrant yellow and black patterning and bright orange-red spots on

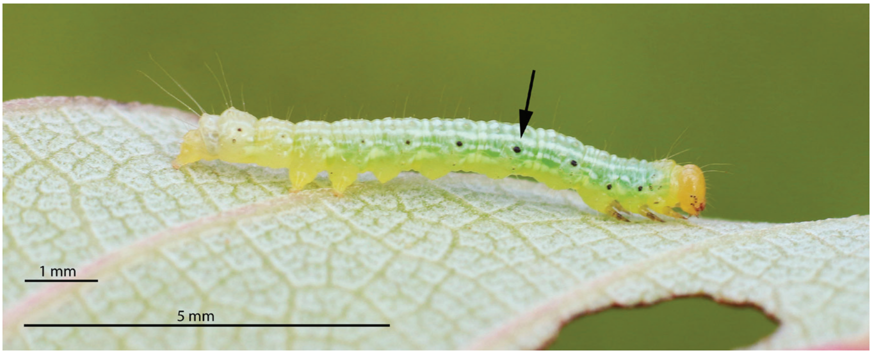

Figure 3. First instar larva of *Arcte coerula*. Black markings (arrow) on its side distinguish these larvae from other Lepidoptera that also use māmaki as a food source.

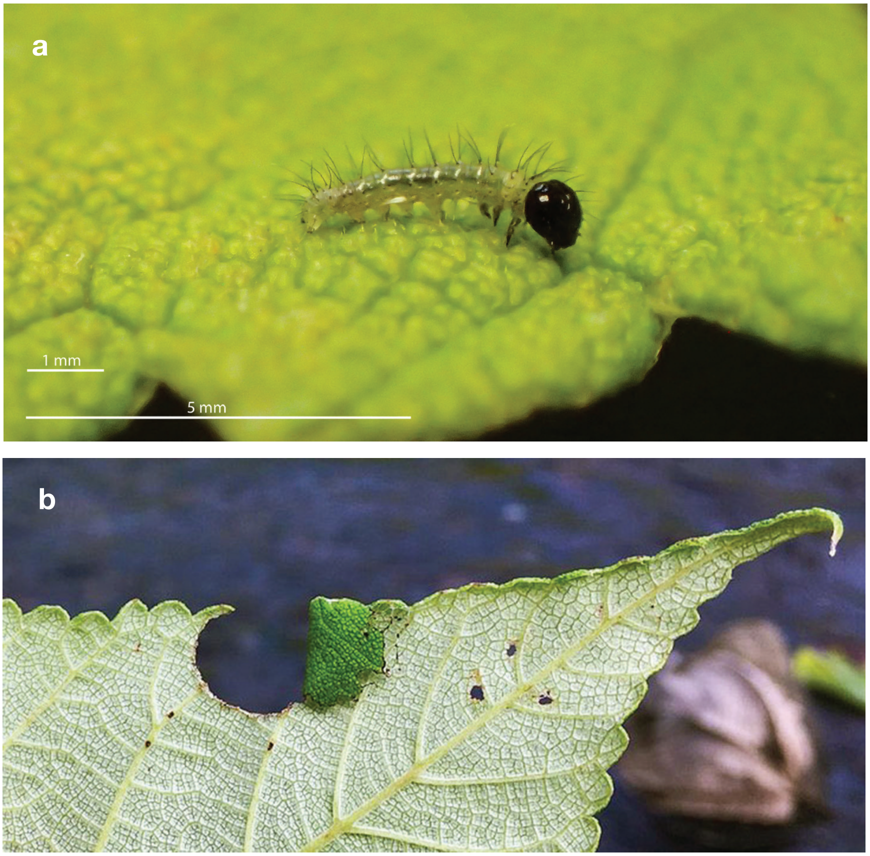

Figure 4. a. First instar larva of *Vanessa tameamea*; **b.** Larvae typically found in a tent-like protective structure at the edge of a leaf. Photo courtesy of DLNR-DOFAW.

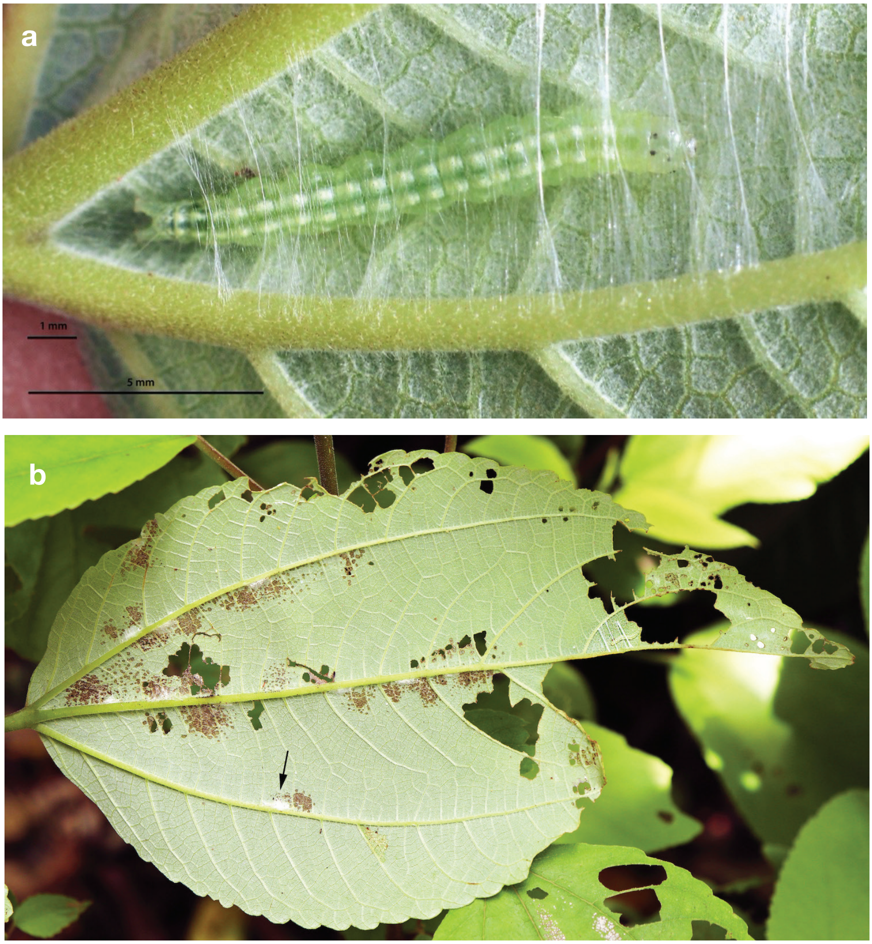

Figure 5. a. Sixth instar larva of *Udea stellata*; **b.** Larvae typically found in a silken protective structure (arrow) on the underside of leaves with brown speckling from feeding damage.

their sides. There are two color morphs of *A. coerula* that develop in response to varying population densities which impact the production of a juvenile hormone (JH) analogue (Ikemoto 1984). The black bands on the larva's body are narrow under solitary conditions, creating a yellow morph larva (Fig. 7a), and conspicuously widen under crowded conditions, creating a black morph (Fig. 7b) (Ikemoto 1984). Most larvae collected in Hawaii are the black morph indicating gregarious larval behavior.

First instar *A. coerula* larvae emerge at about 2 mm in length and grow rapidly through five instars, up to 100 mm before pupating. Although previous studies have indicated six larval instars (Ikemoto 1984, Ide 2006), specimens collected in Hawaii typically had only five instars, with occasional larvae going through six or seven molts. Head capsule size was measured

Figure 6. Late instar larvae of tomato looper, *Chrysodeixis chalcites*. Although this caterpillar also has black markings on its side like *A. coerula*, their head capsule is green rather than tan or black and has a black line across the side (arrow).

after each molt using a microscope micrometer from captive larvae reared from eggs, reported here as mean head capsule width and range: 1st instar: $\overline{x}$ = 0.65 mm, 0.45–1.10 mm, (n = 25); 2nd instar: $\overline{x}$ = 1.26 mm, 0.75–2.00 mm, (n = 19); 3rd instar: $\overline{x}$ = 2.00 mm, 1.30–2.80 mm, (n = 17); 4th instar: $\overline{x}$ = 3.12 mm, 2.25–3.85 mm, (n = 15); 5th instar: $\overline{x}$ = 5.3 6 mm, 5.00–6.00 mm, (n = 9). Larval duration averaged about a month from egg emergence to pupation, but duration was variable.

Pupa. Larvae pupate in the soil or at the base of the plant in leaf litter. Pupae are an average of 28 mm, 25–39 mm, (n = 20) in length (Fig. 8) and take about 13 to 25 days to emerge. Variation in emergence time is likely due to seasonal temperature changes.

Adults. Adults are large moths with a forewing length (FWL) ranging from 22 mm to 36 mm ($\overline{x}$ = 30 mm; n = 20). They have a dark brown head and dark brown forewings with black markings, speckles of silvery-blue, and scalloped termen or wing edges (Fig. 9). Hindwings have distinctive bright silvery-bluish markings which distinguish them from the similarly large black witch moth *Ascalapha odorata* (Linnaeus 1758) (Lepidoptera: Erebidae) that is also found in Hawaii. Adults reared in captivity had a short lifespan, living no more than a week and sometimes feeding on decaying fruit and sugar water in the cages. There was approximately a 1:1 male to female ratio. Sex was determined during the pupal stage based on the genital opening on the ventral side of the abdominal segments (Lin et al. 2020).

Biology and behavior. In Southern Japan where ramie plants (*Boehmeria nipononivea* Koidzumi) are grown, *A. coerula* is multivoltine with populations appearing in the spring and fall with densities peaking in August and September (Ide 2005). Field surveys on Maui and Hawaii island have also shown *A. coerula* to be multivoltine; however, populations peaked in the spring, from March to May, and decreased dramatically in the summer. Low-density populations of *A. coerula* can be found throughout the year

Figure 7. a. Fifth instar yellow morph *Arcte coerula* larva; **b.** Fifth instar black morph *A. coerula* larva.

in Hawaii. *Arcte coerula* larvae can be distinguished from endemic species on māmaki by their active movements and aggressive defensive behavior. Early instar larvae were observed defensively dropping from leaves when disturbed and moving quickly between leaves on the plant. *Arcte coerula* does not produce any protective structures, unlike the leaf folding behavior seen in *Vanessa tameamea* (Fig. 4b) and silk coverings made by *Udea stellata* (Fig. 5b). In later instars, *Arcte coerula* displays a distinctive, aggressive, defensive behavior when disturbed or threatened. The larva rears up its head and legs, thrashes around, and regurgitates a green liquid to defend itself. Similar behavior was also reported by Jackson and Mua (2016).

Damage. *Arcte coerula* larvae will feed on both young and mature leaves of host plants. Early instars create small holes on the leaves as they feed (Fig. 10a). In later larval stages, *A. coerula* larvae create sizable areas of feeding damage and

Figure 8. *Arcte coerula* pupa.

Figure 9. *Arcte coerula* adult. The hindwing markings are distinctive of this species.

completely strip leaves, leaving only the major veins (Fig. 10b). We conducted a simple laboratory experiment using 1-gallon potted māmaki to quantify the extent of damage *A. coerula* inflicts. Plants were infested with one or two newly hatched *A. coerula* larvae. Within two weeks, we observed 100% defoliation and the eventual death of the potted māmaki plants infested with *A. coerula* larvae by the second or

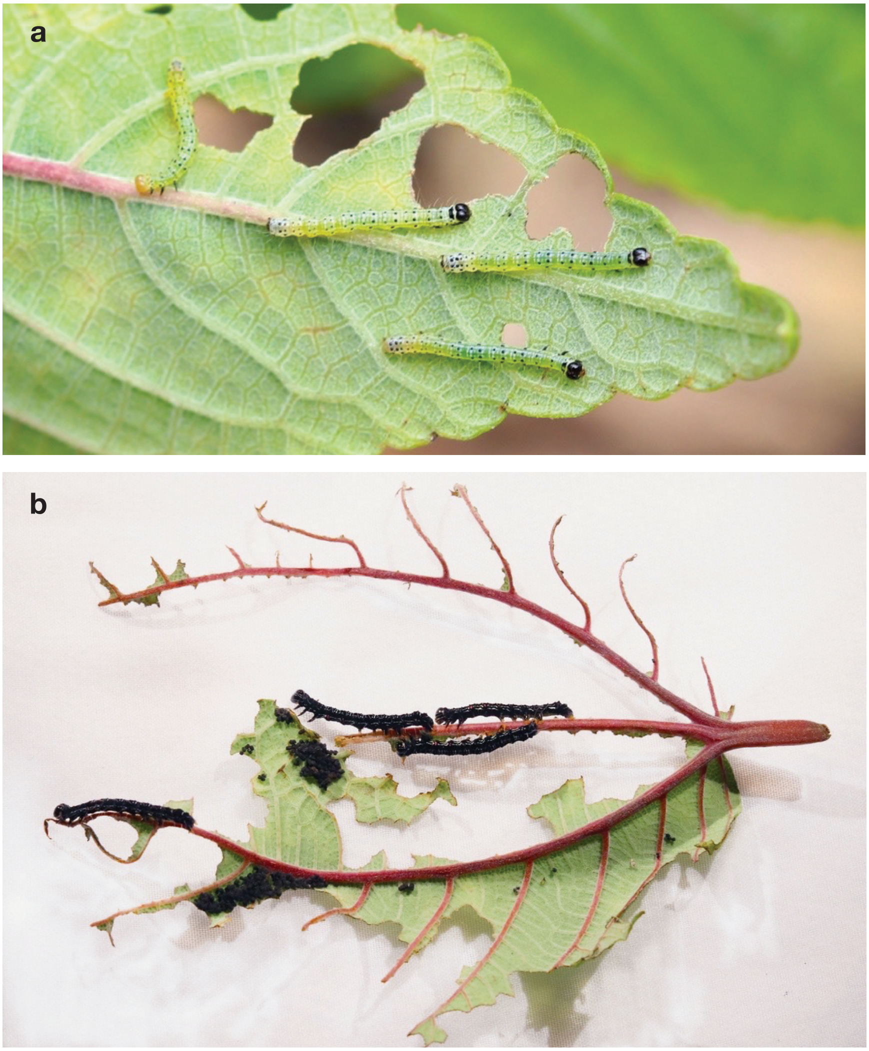

Figure 10. a. Feeding damage by 1st instar *Arcte coerula* larvae; **b.** Feeding damage by 3rd instar larvae.

third instar. Adults do not cause any feeding damage to the host plants.

Management. There is very little information available on how to manage this pest. In Australia, botanical insecticides (such as neem, derris powder, pyrethrum), insecticidal soaps, and microbial products such as spinosad and *Bacillus thuringiensis kurstaki* have been used (Jackson and Mua 2016). However, these products are not labeled for use in Hawaii on māmaki plants and are not recommended in Hawaii as they will also impact the endemic Lepidoptera populations that feed on māmaki and other endemic Urticaceae. Classical biological control is potentially the best

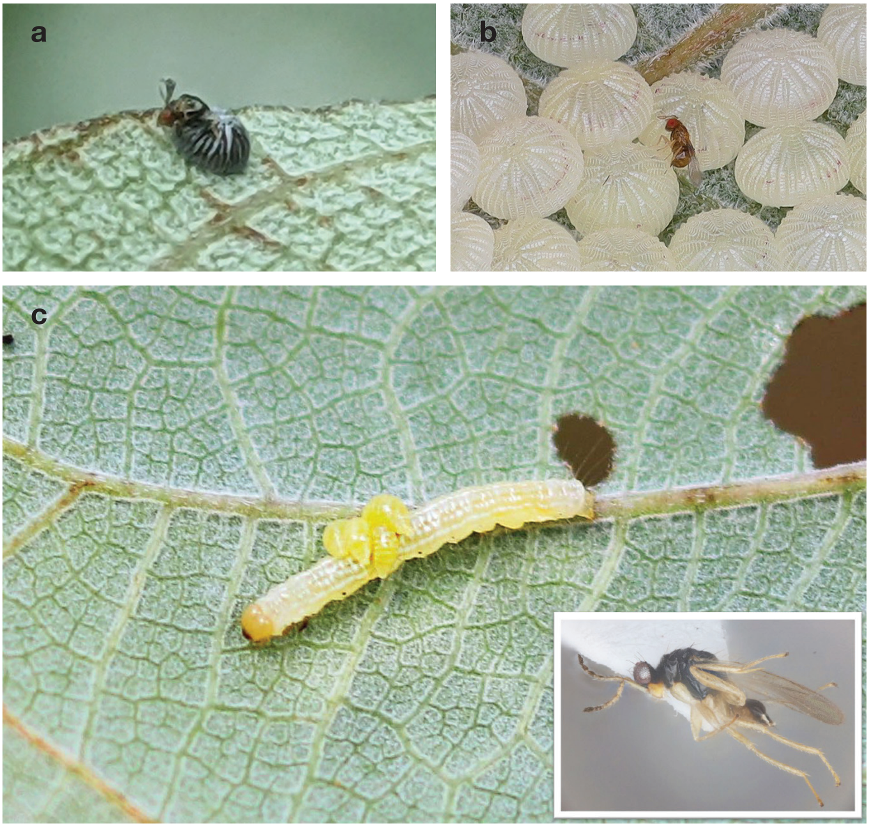

Figure 11. a. Egg parasitoid of *Arcte coerula* emerging; **b.** *Trichogramma* sp. parasitizing the egg of *Arcte coerula*; **c.** Gregarious larval Eulophidae ectoparasitoid of *Arcte coerula*.

management strategy for *A. coerula*.

Natural enemies. Field surveys detected egg parasitism on both Maui and Hawaii island (Fig. 11a). Several egg parasitoids have been found including a *Trichogramma* sp. (Fig. 11b). A gregarious, larval Eulophidae ectoparasitoid was also found on Hawaii island (Fig. 11c). Further work is needed to identify the parasitoids using morphological and molecular methods.

Surveying the same plants on successive trips showed more eggs than larvae present on the trees, indicating that larval predation may occur. We have not determined the species responsible but hypothesize that ants might predate on *A. coerula*, as they are often present on the māmaki plants surveyed. Little fire ant, *Wasmannia auropunctata* (Roger 1863) (Hymenoptera: Formicidae), was observed feeding on collected *A. coerula* eggs. The number of early instar larvae collected during surveys was much greater than the number of later instar larvae collected despite larger instars being more conspicuous, again suggesting that larval mortality by predation may be substantial. We frequently observed the aforementioned characteristic feeding damage on leaves during our surveys despite no larvae being found on the plant. We have also observed that the larvae are palatable to birds such as chickens (*Gallus gallus domesticus* (Linnaeus 1758)) despite their bright, putatively aposematic, coloration. At least seven species of oligophagous parasitoid wasps are known to parasitize *Udea stellata* on māmaki (Kaufman and Wright 2010) and twelve species of parasitoids have been recorded on *Vanessa tameamea* (Leeper 2014). Further research will be undertaken to determine whether any of these resident species of wasps might provide biotic resistance to this new invasive species. If resident natural enemies do not exert significant population control on *A. coerula*, classical biocontrol agents may need to be sought for importation to Hawaii.

Discussion

The surveys to date have revealed expanding populations of *A. coerula* on Hawaii island, with significant populations in some locations judging from numbers of eggs and larvae observed. The expanding populations on Hawaii island are cause for concern in cultivated and wild māmaki stands. Additionally, *A. coerula*'s broad host range may be problematic in Hawaii's native forests, which include other Urticaceae such as endemic ʻakolea (*Boehmeria grandis* (Hook. & Arnott.) A. Heller), olonā (*Touchardia latifolia* Gaudich), and ōpuhe (*Urera glabra* (Hook. & Arnott.) Weddell). These plants have importance to Native Hawaiians who traditionally use these species for medical and cultural practices. Feeding on these species by *A. coerula* has yet to be observed, possibly due to their rarity in the wild, and māmaki is currently the only known host in Hawaii. The spread of *A. coerula* through Hawaii's forests could be detrimental to native ecosystems and conservation efforts, as māmaki is a substantial understory component to many native forests. Māmaki is the host plant to a wide range of endemic and introduced insects (Swezey 1912, 1922; Swezey and Williams 1931), where some of these species especially Lepidopterans can also serve as a valuable food source for native birds (Banko 1978). Competition with *A. coerula* for the same resources will threaten these important endemic insects and further disrupt native ecosystems. If populations of *A. coerula* can burgeon under some circumstances, their impacts have the potential to be severe, judging from observed defoliation on potted māmaki plants.

The perceived health benefits of māmaki tea have led to an increase in its commercial production, primarily on Maui and Hawaii island. *Arcte coerula* has the potential to devastate the agricultural production of māmaki if populations continue to increase. Additionally, māmaki is a common ornamental plant throughout the state. The impacts on tea farmers and the ornamental industry using māmaki are potentially substantial.

Another significant concern is the spread of *A. coerula* to the other Hawaiian Islands. Currently it is only detected on Maui and Hawaii island, and the Hawaii Department of Agriculture has taken measures to limit its spread. Egg parasitism and larval mortality seem to be high in many invaded areas, albeit variable depending on location, suggesting that resident natural enemies may have significant impacts on the moth populations. It remains to be seen if resident larval parasitoids that attack other Lepidoptera on māmaki are effective and can exert control on *A. coerula* populations, or if they are deterred by the defensive behaviors of *A. coerula* or are unable to use it as a host. We will continue to delineate the extent of new infestations of *A. coerula*, damage to plants in wild and cultivated settings, the ability of resident natural enemies to exert population control, and the potential need for exploration for classical biological control agents.

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