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Post release evaluation of *Rodolia cardinalis* (Coleoptera: Coccinellidae) for control of *Icerya purchasi* (Hemiptera: Monophlebidae) in the Galápagos Islands

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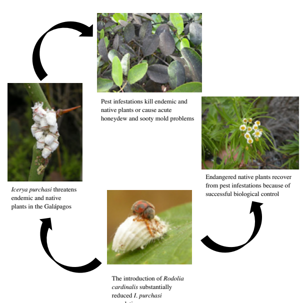
HIGHLIGHTS

- *Rodolia cardinalis* is a specific predator of *Icerya purchasi*.
- This predator was released on the Galápagos Islands for biological control of *I. purchasi*.
- Pest populations have been reduced substantially by *R. cardinalis*.
- Non-target impacts were not observed.
- It is concluded that the first biological control program in the Galápagos was successful.

GRAPHICAL ABSTRACT



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ABSTRACT

Post-release field evaluations (2009–2011) of the impacts of *Rodolia cardinalis* (Mulsant) (Coleoptera: Coccinellidae) released in the Galápagos Islands in 2002 for the classical biological control of *Icerya purchasi* Maskell (Hemiptera: Monophlebidae) indicated that substantial (~60–98% reduction in *I. purchasi* densities) and persistent suppression of this pest has occurred. Most endemic and native plants surveyed appear to no longer have heavy *I. purchasi* infestations nor disfiguring honeydew contamination. However, pest suppression by *R. cardinalis* was less successful on some plant species, such as the native sand dune-inhabiting *Scaevola plumieri* (L.) Vahl. on which substantial, but fluctuating *I. purchasi* densities remain. In urban areas, invasive ant species tending *I. purchasi* colonies likely interfered with biological control. In 22 h of field cage observations of *R. cardinalis* foraging on native plants infested with various combinations of five non-target arthropod species and *I. purchasi*, no attacks on non-target prey occurred. In field cages, all observed attacks and feeding activity were on *I. purchasi*. Captures of *R. cardinalis* were significantly higher on yellow sticky traps placed in plants infested with *I. purchasi* compared to plants that were not hosts of *I. purchasi*. We conclude that the first biological control project in the Galápagos Islands with *R. cardinalis* against *I. purchasi* has been very successful and *R. cardinalis* is highly unlikely to affect non-target species following its establishment and spread in the archipelago.

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1. Introduction

The Galápagos archipelago (Ecuador) is famous for the evolutionary and ecological insights that scientists have gained studying the unique flora and fauna of these islands. Regrettably, this biota is under threat, and invasive species, either intentionally or accidentally introduced by humans, are the principal stress responsible for the decline of habitat quality and endemic species populations. Every year, cargo boats and commercial flights transport humans, freight, and luggage sufficient to support >170,000 visitors and a resident population of >30,000 people (Gardener and Grenier, 2011). Introductions of exotic insects have increased exponentially as a direct result of tourism and population growth (human settlement growing at ~6% per year). At least 23% of the known Galápagos insect fauna are introduced (Causton et al., 2006). Among the most damaging of these invasive insects is the cottony cushion scale, *Icerya purchasi* Maskell (Hemiptera: Monophlebidae: Iceryini) (Causton et al., 2006). This hemipteran was first recorded in the Galápagos Islands in 1982, and by 1996 had spread to 15 of the 18 largest islands in this archipelago (Calderón-Alvarez et al., 2012).

I. purchasi is a cosmopolitan plant pest native to Australia and possibly New Zealand that feeds on >200 plant species (Caltagirone and Doutt, 1989; Causton, 2001). Dense scale populations damage plant health, and honey dew excreted by *I. purchasi* stimulates growth of sooty mold on leaves and stems, disfiguring plants. Because honey dew is a rich carbohydrate source, it is highly attractive to invasive ant species (e.g., *Camponotus conspicuus zonatus* Emery, *Solenopsis geminata* (Fabricius), and *Monomorium floricola* (Jerdon) (all Hymenoptera: Formicidae) in the Galápagos, which tend *I. purchasi* colonies to harvest the sugar (Hoddle, 2011). In the Galápagos Islands, *I. purchasi* infests 80 native or endemic plants, 19 of which are on the IUCN Red List of Threatened Species, of which ten are classified as Endangered or Critically Endangered (Calderón-Alvarez et al., 2012). Furthermore, the debilitating effects of *I. purchasi* on some rare plants indirectly harms populations of native vertebrates and invertebrates that depend on those plants for food or shelter (Roque-Albelo, 2003; Causton et al., 2006). In 1996, the Charles Darwin Foundation and the Galápagos National Park Service formed a Technical Advisory Committee to address the *I. purchasi* invasion, and classical biological control with a predatory coccinellid, *Rodolia cardinalis* (Mulsant), was proposed as one potential control option (Causton et al., 2004).

Over the last 120 years, *R. cardinalis* has successfully suppressed *I. purchasi* populations in many countries (Caltagirone and Doutt, 1989). *R. cardinalis* is a specialist predator with a very restricted prey range that is probably limited to the family Monophlebidae, and possibly to the tribe Iceryini (Caltagirone and Doutt, 1989). Strong prey fidelity by *R. cardinalis* has two major consequences: (1) high safety because non-target species are unsuitable to the predators as food sources and (2) high target suppression because all feeding and reproduction occur on the target pest (Hoddle, 2004). Another reason for the success of *R. cardinalis*, is that coccidophagous cocinellids have developmental rates that are equal to or greater than those of their prey (Dixon et al., 1997). This allows coccidophages such as *R. cardinalis* to successfully reduce prey abundance (Dixon et al., 1997).

Following a review period, the Technical Advisory Committee concluded that control of *I. purchasi* in the Galápagos Islands with pesticides was not feasible, and that biological control with *R. cardinalis* offered the best prospect for permanent and widespread suppression of *I. purchasi* across all affected habitats. In 1999, *R. cardinalis* was imported from Australia into quarantine at the Charles Darwin Research Station, Puerto Ayora, Santa Cruz, to undergo safety testing to evaluate the threat, if any, this natural enemy might pose to non-target species, especially native or endemic insects (Causton et al., 2004) and native finches that might prey on this natural enemy (Lincango et al., 2011). Analysis of quarantine host specificity trials and bird feeding studies, coupled with published studies on the use of *R. cardinalis* for *I. purchasi* control in other countries, supported the conclusion that this natural enemy would not present a significant threat to non-target species and that the first biological control program in the Galápagos should be initiated (Causton et al., 2004; Lincango et al., 2011). Between 2002 and 2005, 2206 adult *R. cardinalis* were released on 10 different islands. Populations readily established and dispersed unassisted to additional islands. All habitats infested with *I. purchasi* were infiltrated (e.g., natural, urban, and agricultural zones), and rapid suppression of high density *I. purchasi* populations was observed, sometimes within ~3 months of the arrival of *R. cardinalis* (Calderón-Alvarez et al., 2012).

In October 2009, the *Icerya–Rodolia* biological control project in the Galápagos was considered sufficiently mature for a comprehensive post-release review, and a two year evaluation project was initiated. The project had two major objectives: (1) to monitor the population phenology of *I. purchasi* and retrospectively assess the impact of *R. cardinalis* on *I. purchasi* in natural and urban areas on two different islands (Santa Cruz and San Cristóbal), and (2) to investigate under field-like conditions the hypothesis derived from host specificity studies in quarantine that in the Galápagos *R. cardinalis* has a prey range restricted to *I. purchasi*. The results of these studies are reported here.

2. Materials and methods

2.1. Population phenology of I. purchasi and R. cardinalis 2009–2011

I. purchasi and *R. cardinalis* counts were taken on two islands for a two (Santa Cruz) or one (San Cristóbal) year period during 2009–2011. Timed counts were made monthly at study sites on a variety of native or introduced host plants.

2.1.1. Surveys on Santa Cruz

On Santa Cruz, populations of *I. purchasi* and *R. cardinalis* were sampled monthly at four relatively undisturbed wilderness sites for 26 months, from October 2009 to November 2011. All plant species sampled were excellent hosts for *I. purchasi* and had supported dense pest populations before the release of *R. cardinalis* (Causton, 2001; Calderón-Alvarez et al., 2012). Two study sites, Tortuga Bay and Playa Estación, were located in the salt tolerant littoral zone (Peck, 2001). At both sites, we sampled one host plant: *Scaevola plumieri* (Goodenaceae) (Tortuga Bay) and *Laguncularia racemosa* (L.) C.F. Gaertn (Combretaceae) (Playa Estación), with one-minute timed counts being made on each of 40 randomly selected plants each month. Plants at these two sites existed as near monocultures.

The other two sites were in the lowland arid zone (Peck, 2001): El Barranco close to the Charles Darwin Research Station (CDRS) campus and the Tortuga Bay pathway. At the El Barranco site, three tree species – *Acacia insulae-iacobi* Riley (Mimosaceae) ($n = 10$), *Acacia macracantha* Humb. & Bonpl. ex Willd (Mimosaceae) ($n = 18$), and *Parkinsonia aculeata* L. (Caesalpiniaceae) ($n = 18$) – were located, tagged, and examined for one minute periods repeatedly at monthly intervals. These tagged trees were the same as those used for previous *I. purchasi* surveys prior to the release of *R. cardinalis* (Causton, pers comm.). At the Tortuga Bay pathway site, a cobbled walking path 2490 m in length was used as a transect, and plants immediately adjacent to the path were randomly