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Diversity, endemism and origins of scale insects on a tropical oceanic island: Implications for management of an invasive ant

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ABSTRACT

Detailed assessment of scale insect (Hemiptera: Coccoidea) faunas on islands may help predict impacts of invasive ants (Hymenoptera: Formicidae) and inform options for their management, including biological control. Mutualism between scale insects and the invasive ant *Anoplolepis gracilipes* on Christmas Island, Indian Ocean, threatens the conservation of the island's endemic land crab fauna, alters rainforest structure and composition, and disrupts ecosystem processes. Diversity and endemism of the scale insect fauna were assessed through broad survey across rainforest, targeted search on endemic plant species, and inspection of ornamental and horticultural plants in settled areas. Emphasis was placed on honeydew-producing species that sustain ant supercolonies and detection of endemic scale insects that could be non-target species in a biological control programme for honeydew-producing scale insects. Origins of the fauna were inferred using scale insect databases and interception records at Ports-of-Entry for the United States and Korea. Twenty-eight scale insect species in seven families are identified for the island. Four honeydew-producing species, the lac scale *Tachardina aurantiaca* (Kerriidae) and three soft scale species (Coccidae), are abundant in rainforest and tended by ants. No endemic species were found. Compositionally, the scale insect fauna resembles that of many other tropical islands: almost all species are biogeographically widespread, host-plant generalists, and routinely intercepted in human-mediated dispersal pathways. The likely source bioregion is Sundaland where 27 of the 28 species on the island have been recorded and which has been the major pathway for movement of plant material to the island for over a century.

Introduction

Scale insects (Coccoidea) are a diverse group of sap-sucking insects (c. 8000 species) distributed throughout the world (Ben-Dov et al., 2015). Disproportionately common among invasive insects (Miller et al., 2005), they are important plant parasites with large conservation impacts upon natural areas, most notably on islands (Challinor and Wingate, 1971; Causton et al., 2004; Fowler, 2004; Hamilton, 2007; Marler and Lawrence, 2012; Ryan et al., 2014). Invasive honeydew-producing scale insects can be especially damaging; they are almost universally tended by other insects, mainly ants, which benefit the scale insects through the removal of honeydew, protection from natural enemies, and sometimes dispersal of crawlers (Way, 1963; Gullan, 1997). Conversely, most of the world's worst invasive ant species use the simple carbohydrates in honeydew to build and sustain their populations, which amplifies their impacts (Wilder et al., 2011; Helms, 2013; Wills et al., 2015).

The conservation implications of these scale insect–ant associations are vividly illustrated in rainforest on Christmas Island, Indian Ocean. Here, mutualism between scale insects and the invasive yellow crazy ant *Anoplolepis gracilipes* Fr. Smith (Hymenoptera: Formicidae; YCA hereafter) provides the foundation for 'invasional meltdown' (Simberloff and von Holle, 1999; O'Dowd et al., 2003). The YCA has formed high-density (>1000 ants m^{-2}), expansive (10–100 ha, ~25 km^2) supercolonies (Abbott, 2005; Green and O'Dowd, 2009) where they invariably co-occur with high densities of honeydew-producing scale insects (O'Dowd et al., 2003; Abbott, 2004). High scale densities lead to forest dieback and associated YCA abundance results in the local extirpation of an endemic keystone arthropod, the red land crab *Gecarcoidea natalis* (Pocock 1888) (Gecarcinidae). This alters forest structure and composition, deregulates seedling recruitment and litter breakdown, and facilitates rainforest invasion by the giant African land snail *Achatina* (*Lissachatina*) *fulica* (Bowdich 1822) (Achatinidae) (O'Dowd et al., 2003; Green et al., 2011). Furthermore, YCA supercolonies directly threaten a variety of

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endemic arthropods, reptiles, birds and mammals (Davis et al., 2008, 2010; Beeton et al., 2010).

Invasion by the YCA and its association with scale insects are key conservation threats on this oceanic island (Australian Department of the Environment, 2005; Beeton et al., 2010). Sustainable and safe mitigation of this threat presents formidable challenges in such a remote, isolated location (Green and O'Dowd, 2009). Both field experiments and laboratory dietary studies indicate that the simple carbohydrates supplied in honeydew are critical to YCA colony growth, worker foraging tempo and aggression, and supercolony persistence (Green et al., 2013), indicating that suppression of scale insect abundance could limit YCA abundance and impact.

Information on diversity and endemism of the scale insect fauna on the island is critical to development of a biological control programme for the YCA based on its reliance on honeydew-producing scale insects. Chalcidoid parasitoids will be used against the species of honeydew-producing Coccoidea most abundant in YCA supercolonies to reduce carbohydrate supply to the YCA. Introduction of the wasp *Tachardiaephagus somervillei* (Mahdihassan 1923) (Chalcidoidea: Encyrtidae), a known parasitoid of the lac scale *Tachardina aurantiaca* (Kerriidae) in its native distribution in Malaysia (Hayat et al., 2010), is planned, so it is essential to determine if there are any endemic Coccoidea on Christmas Island that could be potential non-target species.

In this study, we conducted surveys in natural and settled areas on Christmas Island to determine (i) the scale insect fauna of the island and its likely origins, (ii) those honeydew-producing scale insects that potentially support YCA supercolonies, and (iii) the presence of any endemic scale insects that could be significant non-target species in a biological control programme.

Methods

Christmas Island (105°40′E, 10°30′S) is a small, high (134 km^2, 364 m elevation) oceanic island lying 360 km south of Java and 1500 km to the northwest of Western Australia in the northeastern Indian Ocean. Most (74%) of the original rainforest vegetation remains intact. The climate is tropical, with c. 2000 mm annual rainfall and distinct wet and dry seasons.

The search for scale insects was structured in four ways (Fig. 1). First, a subset of 150 waypoints was selected from an island-wide grid of c. 1000 waypoints used for biodiversity monitoring, at 364 m spacing (Green and O'Dowd, 2009; Boland et al., 2011). Timed search (30 min) of above-ground parts of plants within a 50-m radius of each waypoint was done at each location in the dry season (June–November) in each of 2010, 2011, and 2012. These waypoints were chosen because they are accessible from nearby roads or tracks, encompass the three major forest types on the island (Plateau, Scree, and Terrace), and are located in all four quadrants of the island.

Second, a total of 21 km along five walking tracks—Northwest Point Track (4.7 km), Boulder Track (6 km), Blowholes Road (3.4 km), Martin Point Lookout to the boundary of the national park (1.9 km), and Dolly Beach Boardwalk (1.8 km)—was searched during the dry season in both 2011 and 2012. Together, the searches at waypoints and along walking tracks totaled 405 h of actual search time.

Third, endemic plants were examined under the assumption that they would be more likely to harbour endemic scale insects (Neumann et al., 2007; Lincango et al., 2010). Of the 18 species of endemic plants known on Christmas Island, 14 species were located and examined in each of 2010, 2011 and 2012 (Table 1). Nine of these 14 species are considered rare. A total of 125 locations with rare endemic plants were searched (Fig. 1). For each common endemic plant species, 30 haphazardly selected individuals were examined in each of the three years of search.

Fourth, since residential areas on the northeast corner of the island represent the most likely direct source for scale insects in natural areas, we inspected a variety of ornamental and horticultural plants in home gardens, public parks, and along roadsides over three years.

The origins of the scale insect fauna of Christmas Island were inferred by determining each species' geographical distribution, likely native bioregion, and host plant range (Ben-Dov et al., 2015). To determine which of these scale insect species are likely to have been introduced following human settlement of the island, we examined interception records in association with plant material at Ports-of-Entry (POEs) in the United States (Miller et al., 2014; USDA, APHIS, lists of intercepted plant pests, 1930–1940, 1971–1981) and the Republic of Korea (Suh et al., 2013). We supplemented interceptions records by determining those scale insect species that are considered major

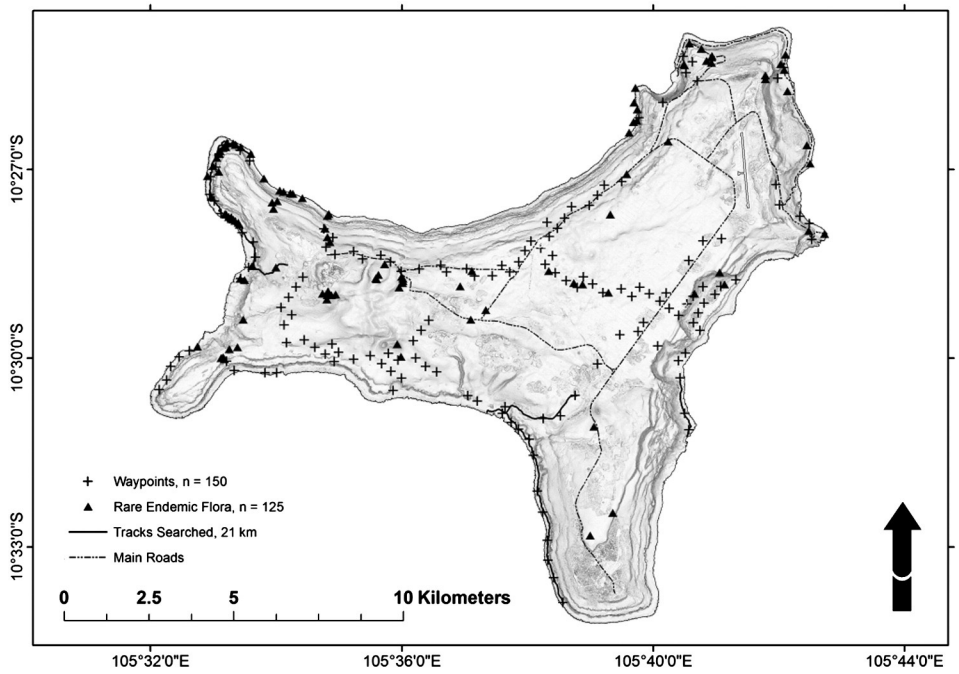

Fig. 1. Structured search for scale insects on Christmas Island centred on selected waypoints from the island-wide survey, search along walking tracks, and targeted search of endemic flora (see Table 1).