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ARTHROPODS OF ROSE ATOLL WITH SPECIAL REFERENCE TO ANTS AND PULVINARIA URBICOLA SCALES (HEMIPTERA: COCCIDAE) ON PISONIA GRANDIS TREES

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Table of Contents

List of Tables

List of Figures

ABSTRACT

Rose Atoll, at the eastern end of the Samoan Archipelago, is a small but important refuge for seabirds, shorebirds, and sea turtles. While the vertebrate community is relatively well-studied, the terrestrial arthropod fauna, and its role in ecosystem function, are poorly known. Arthropods may be influencing the decline of *Pisonia grandis*, an ecologically important tree that once dominated the 6.6 ha of land on Rose Atoll. Reasons for the decline are not fully understood but a facultative relationship between two invasive arthropods, the soft scale *Pulvinaria urbicola* and ants, likely has contributed to tree death. The primary objectives of this study were to systematically survey the terrestrial arthropod fauna and identify ant species that tend scales on *Pisonia*. Using an array of standard arthropod collecting techniques, at least 73 species from 20 orders were identified, including nine ant species. Of the ants collected, only *Tetramorium bicarinatum* and *T. simillimum* were observed tending scales on *Pisonia*. No known natural enemies of *Pulvinaria* scales were found, suggesting little predation on scale populations. Treatment of *Pisonia* with the systemic insecticide imidacloprid failed to eliminate *Pulvinaria* scales, although short-term suppression apparently occurred. The arthropod fauna of Rose Atoll is dominated by exotic species that likely have a significant impact on the structure and function of the island's ecosystem.

INTRODUCTION

Rose Atoll delineates the eastern end of the Samoan Archipelago and is one of the smallest atolls in the world. Islands of the atoll consist of Rose and Sand although only Rose Island is currently vegetated. Rose Atoll provides important nesting habitat for 12 federally protected seabird species and the threatened green sea turtle (*Chelonia mydas*), as well as resting and feeding grounds for seven shorebird species. To protect this important habitat, Rose Atoll was incorporated into the U.S. Fish and Wildlife Refuge system in 1973 as Rose Atoll National Wildlife Refuge (NWR). And in 2009, Rose Atoll NWR and surrounding water within 50 nautical miles (92.6 km) of the atoll were protected through designation as a Marine National Monument under the administration of the U.S. Fish and Wildlife Service (USFWS). Eradication of the Polynesian rat (*Rattus exulans*) from Rose Island during 1990–1991 further protected the terrestrial biota of the atoll (Morrell *et al.* 1991, Anon. 1994).

While the bird community of Rose Atoll is relatively well documented, the terrestrial arthropod community is poorly known. Early, incidental reports of arthropods on Rose Atoll were limited to "gnats, flies, crickets, ants, beetles, and sphinx moth caterpillars" (Mayor 1921, Sachet 1954). More recently, the list of terrestrial arthropods grew to 17 taxa from 10 orders, although they were not identified beyond the order level (Flint 1990). Clearly, identifying the arthropod community on Rose Atoll is needed to increase understanding of the island's ecosystem.

The vegetation structure of Rose Island has changed dramatically in the past 50 years. Prior to 1970, the island was dominated by *Pisonia grandis*, but following steady decline, *Pisonia* is now rare and the island is dominated by the tree heliotrope, *Heliotropium argentea.* Reasons for the decline of *Pisonia* on Rose Island are not fully understood and may include physical damage from storm events such as hurricanes Heta and Olaf in 2004 and 2005, respectively, drought (Batianoff *et al.* 2010), rising sea level resulting in an incursion of saltwater into the island's freshwater lens (Greenslade 2008), and an imbalance of bird guano-derived nutrients in the soil (Walker 1991, Greenslade 2008). However, physiological stress from feeding by the invasive soft scale, *Pulvinaria urbicola* (Hemiptera: Coccidae) also may have contributed to its decline.

Pulvinaria scales are sap-sucking insects that feed from phloem tissue through leaves and stems*.* When *Pulvinaria* abundances are high, the impact of herbivory can result in leaf distortion and loss, shoot dieback and tree death (Hill *et al.* 2003, Handler *et al.* 2007, Gaigher *et al.* 2011, Gaigher and Samways 2013). *Pulvinaria* abundances are generally thought to be enhanced by ants through a facultative relationship where ants benefit by obtaining carbohydrate-rich honeydew secreted by the scales, while scales in turn benefit from ants through removal of growth-inhibiting honeydew, assisted dispersal within and among trees, and protection from attack by natural enemies, such as predatory and parasitic insects (Delabie 2001, Gaigher *et al.* 2013). Overall, a small number of invasive ant species within the genera *Tetramorium*, *Pheidole* and *Anoplolepis* whose ranges overlap with *Pisonia* and *Pulvinaria* appear to be facilitating *Pulvinaria* scale population growth responsible for the problem (Hill *et al.* 2003, Freebairn 2007, Handler *et al.* 2007, Hoffmann and Kay 2009, Gaigher *et al.* 2011). *Pulvinaria* scales were first reported on *Pisonia* at Rose Atoll in 2002, and by 2006, only seven mature *Pisonia* trees remained (J. Burgett, USFWS, personal communication cited in Wegmann and Holzwarth 2006).

Managers of Rose Atoll NWR are keenly interested in identifying the fauna of the atoll and understanding factors that influence the health of its ecosystem. Our study was the first comprehensive survey of the terrestrial arthropod community found on the atoll. Specifically, our main objectives were: 1) to conduct a broad survey of the terrestrial arthropod community, including potential natural enemies of *Pulvinaria* scales, and 2) identify species of ants that tend *Pulvinaria* scales and determine their distribution across the landscape. In addition to the survey work, we also attempted to control *Pulvinaria* scales on *Pisonia* through the application of the systemic insecticide imidacloprid. The work took place over four trips between April 2012 and November 2013.

METHODS

Study Area

Rose Atoll National Wildlife Refuge is located approximately 280 km (150 nautical miles; 14^0 32' 49" S, 168^0 8' 38" W) east of Pago Pago, American Samoa and consists of two islands, Rose and Sand, approximately 6.6 and 1.3 ha, respectively (Figure 1). Rose Island, or Motu O Manu (island of seabirds) as it is known by people of the nearby Manu'a Islands, is a stable pinned islet built upon mid-Holocene limestone paleoreef flats and has only been exposed above sea level for 900 to 1,500 years (Dickenson 2009)*.* In contrast, Sand Island is an intermittently vegetated shifting sand bank that is currently devoid of vegetation. Rose Atoll has been closed to the public since designation as a National Wildlife Refuge in 1973. Perhaps due to a lack of fresh water, the atoll appears not to have been settled by Samoans*.*

The vegetation of Rose Island is dominated by *Heliotropium argentea* (Boraginaceae) but also includes *Boerhavia tetrandra* (Nyctaginaceae), *Cocos nucifera* (Arecaceae), *Cordia subcordata* (Boraginaceae), *Hibiscus tiliaceus* (Malvaceae), *Nephrolepis hirsutula* (Dryopteridaceae), *Pisonia grandis* (Nyctaginaceae), and *Portulaca lutea* (Portulacaceae). The vegetation has been categorized into six general types: open canopy; coconuts; *Heliotropium* scrub; young *Heliotropium* forest; mature *Heliotropium* forest; and mixed littoral forest (American Samoa Department of Marine and Wildlife Resources unpublished data; Figure 2). The open canopy vegetation type that falls within the forest matrix primarily consists of the ground cover *B.*

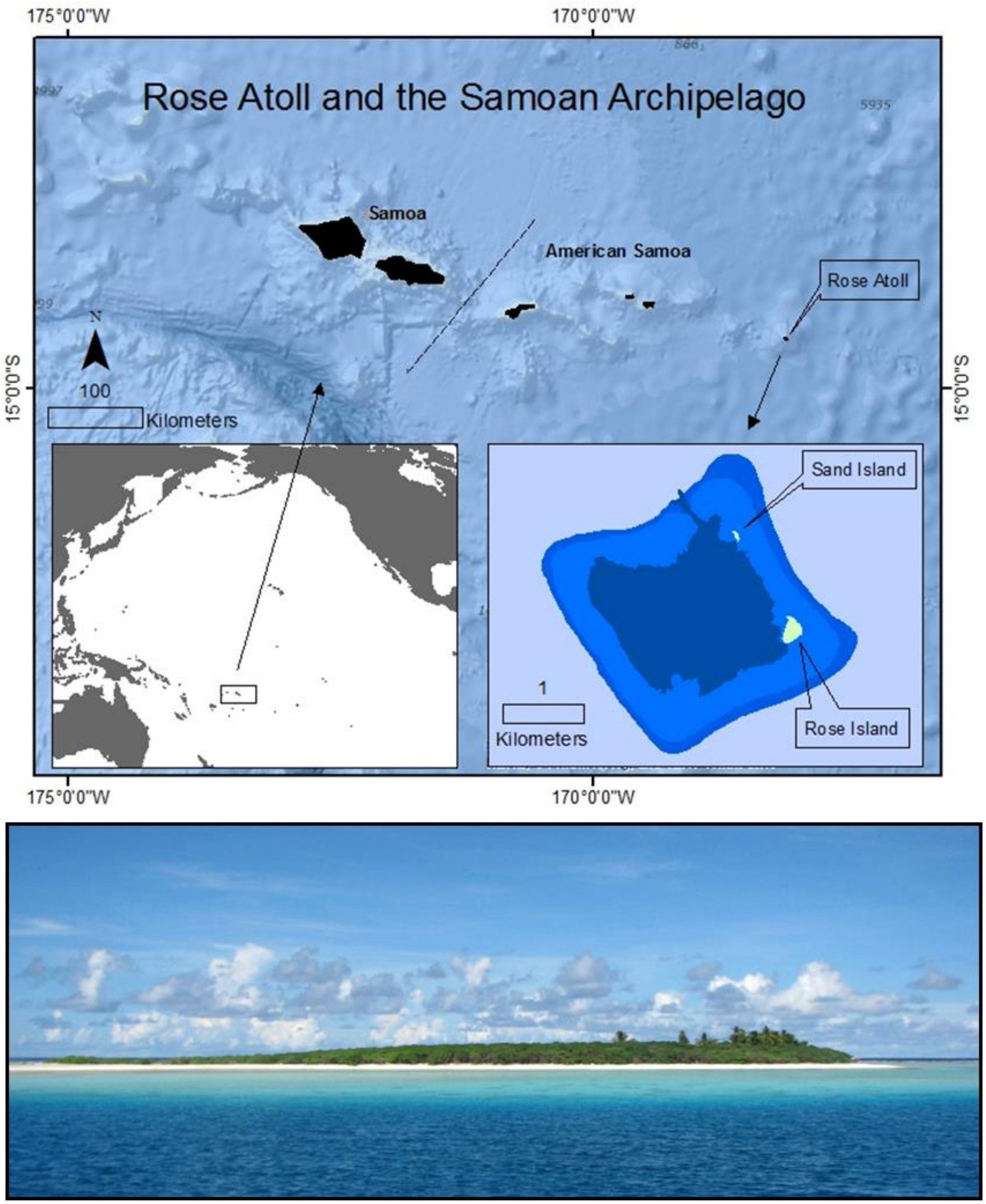


Figure 1. Location of Rose Atoll within the Samoan Archipelago (top). The photograph (bottom) shows the western side of Rose Island as seen from within the atoll lagoon. Trees on the right emerging from the low *Heliotropium* canopy include *Pisonia* and *Cocos nucifera*.

tetrandra. The coconut area is dominated by mature and subcanopy *C. nucifera* individuals, but trees were thinned drastically during 2012–2013 to control their spread. The three *Heliotropium* types are defined by plant size with scrub being the shortest. Mixed littoral forest contains *Heliotropium* but also contains much *C. subcordata* and *N. hirsutula*. Of the seven remaining *P. grandis* (Figure 2), five are found in the mixed littoral forest type and two stand within mature *Heliotropium*.

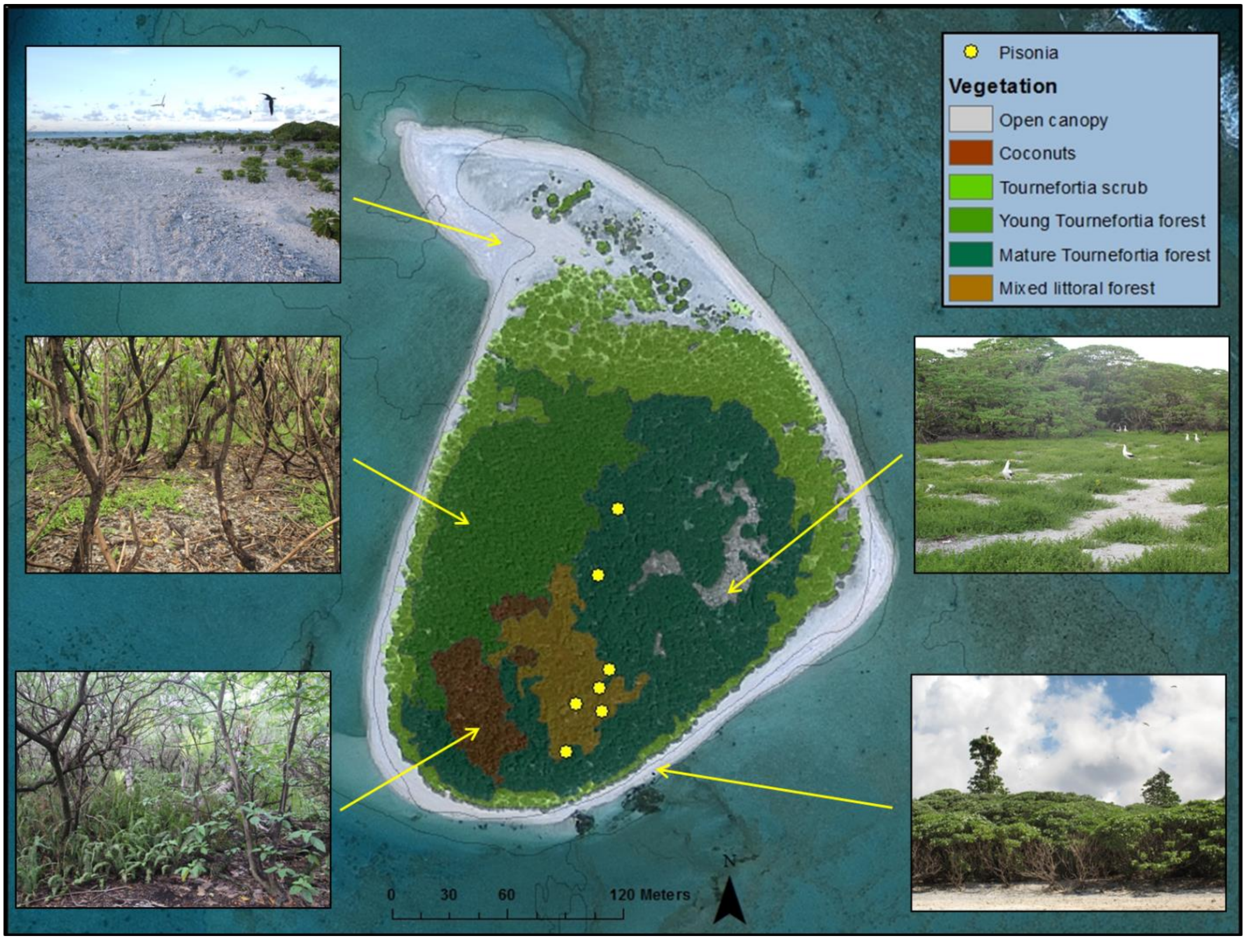


Figure 2. Generalized habitat map of Rose Island. The arrows point to the approximate location that each photograph was taken and the yellow dots indicate the locations of the remaining *Pisonia*. Two mature *Pisonia* can be seen emerging from the *Heliotropium* canopy in the photo at the lower right.

Comprehensive arthropod survey

A suite of standard sampling methods was used to inventory the arthropod fauna of Rose Atoll. Methods included pitfall traps, pan traps, malaise traps, baits, night lights, sifting of soil and litter, yellow sticky cards, and collecting by hand. Each method targeted a different part of the fauna, but overlap in the composition of arthropods was expected to occur. Ants were primarily targeted using baits and pitfall traps but hand collecting and litter sifting were used to target small, cryptic species that are often overlooked using baits and traps.

Arthropod sampling and navigation on the island were aided by a grid (30 x 30 m spacing) that had previously been established on the island by the USFWS. Pitfall traps, pan traps, and bait cards were placed at each point on the grid while the other techniques were implemented at various places on the island. Each collecting method is briefly described below. Additional information regarding the collecting methods used can be found in Zou *et al.* (2012).

Pitfall trapping: Pitfall traps primarily collect arthropods as they walk along the ground, and they are particularly effective at capturing spiders, Collembola, Isopods, and other flightless taxa (Figure 3). Traps consisted of 120 ml plastic specimen cups (5.7 cm diameter x 7.2 cm deep) placed into the ground so the top lip was even with the surface. Approximately 40 ml of an ethylene glycol mixture (antifreeze; a 50% solution with water) was poured into each cup as a preservative. A 27-cm diameter plastic picnic plate was suspended about 15 cm above each trap using rocks and sticks to prevent flooding during rain.

Pan trapping: Yellow colored pan traps are designed to mimic flowers and are generally attractive to flying insects such as Diptera and Hymenoptera but also collect arthropods attracted to water or that haphazardly fall into the traps (Figure 3). Traps were 15-cm diameter plastic picnic bowls and contained approximately 100 ml of water into which a drop of unscented liquid detergent was added to reduce surface tension and facilitate capture of arthropods.

Malaise trapping: Malaise traps are mesh tent-like structures that primarily intercept insects as they fly along the forest floor, but they also collect ground-dwelling arthropods that travel onto vegetation (Figure 3). At two locations within the interior of the island, one bi-directional, Townes-style malaise trap (Townes 1972) fitted with a polyethylene collecting jar (BioQuip Products, Gardena, CA) was erected. Ethylene glycol was used as a preservative in the collecting jars.

Baiting: Bait was used to attract and collect ants (Figure 3). Each bait consisted of approximately 5 g of canned tuna mixed in its packaged oil placed on a 5 x 7 cm paper card in an open plastic petri dish nestled within the leaf litter or coral rubble on the ground. After approximately 60 minutes, the petri dish containing ants and remaining bait was capped with the lid and sealed with a rubber band.

Night lighting: Lights run at night are highly attractive to many adult Lepidoptera, Diptera, and Coleoptera. For about two hours on two nights, a battery-powered light (Coleman camp lantern) was suspended from a tree to illuminate an adjacent hanging white cotton bed sheet. Insects landing on the sheet were collected by hand.

Litter and soil sifting: Litter and soil supports a variety of small, cryptic arthropods that are generally not collected using other methods. Approximately six samples consisting of about 4 l of litter and soil (0–5 cm deep) were excavated using a trowel and placed into plastic zip lock bags and returned to camp where they were immediately searched for arthropods. Arthropods were extracted from the substrate by placing about 250 ml subsamples into white plastic dish-washing bins and sorted by hand. Collecting efforts focused on the southern section of the island where the organic horizon was best developed.

Yellow sticky cards: Yellow sticky cards are similar to pan traps in that they are designed to capture flying insects that are attracted to bright colors, and they are particularly effective at collecting parasitoid wasps when placed in close proximity to potential hosts. A clear sticky substance applied to the surface of the card captures insects upon contact. Yellow sticky cards (Seabright Laboratories, Emeryville, CA) were placed on lower branches of *Pisonia* trees to collect parasitoid wasps possibly attacking *Pulvinaria* scales. In total, five cards were hung from three *Pisonia* trees infested with scales.

Hand searching: Hand searching generally consisted of shaking vegetation to dislodge arthropods onto a 70 x 70 cm nylon sheet supported by a wooden frame, overturning rocks and downed coarse wood debris, and excavating dead wood. Hand searching took place opportunistically throughout the island.

The survey primarily took place during 15–19 April 2012 when all collecting techniques were used. However, additional hand collecting took place during 17–21 March 2013 and 18–21 November 2013. Sand Island was briefly searched for arthropods by hand once during 15–19 April 2012 and 18–21 November 2013.

Arthropod identifications were made using taxonomic keys by RP or by experts specializing on individual taxa (see acknowledgements). In some cases, determinations could not be made to the species level due to the inaccessibility of reference material, a lack of appropriate taxonomic keys, specimens not being in the adult stage, or specimens being damaged. In a few cases, determinations by taxonomists included "nr" (meaning near) or "cf" (meaning to compare to known specimens) in the species name. In these cases, species-level determinations could not be made without examination of additional specimens or voucher material but are similar to the species listed. Voucher material from this study will be deposited within entomology collections at the B. P. Bishop Museum, Honolulu, Hawai'i, and American Samoa Community College (ASCC), American Samoa. The residency status (i.e., native or exotic) of species was determined from the literature or expert opinion, but residency status was impossible to ascertain in many cases because of inadequate knowledge of native distributions. The long history of arthropod invasion into the Pacific Basin facilitated by humans has further reduced our ability to determine the natural ranges of some species. As a result, the status of several identified species is qualified or unknown.

Additionally, we searched for evidence of parasitoid attack of *Pulvinaria* scales. Parasitoid wasps emerge from the bodies of scales, leaving a characteristic exit hole. During 17–21 March 2013, we collected six large *Pisonia* leaves that were heavily infested with scales (> 100 scales/leaf). The leaves were collected into plastic zip lock bags, placed into a cooler with ice, and returned to the lab at ASCC for microscopic evaluation of parasitism. Following examination, all leaves and scales were destroyed by freezing for 24 hours.

Evaluation and measurement of *Pisonia* and treatment with imidacloprid

During April 2012, six canopy-emergent *Pisonia* were identified on Rose Island, but an additional individual was located during November 2013, bringing the total number of trees to seven. During November 2013, the size of all seven *Pisonia* and the extent to which leaves were infested by scales were determined. Several trees supported multiple vertical stems of significant size, therefore each stem > 5 cm diameter at breast height (dbh) was measured separately. Measurements of stem size included dbh (cm), total height (m) and crown diameter (m). DBH and crown diameter were measured using a diameter tape and stem height was estimated using an extendable pole. The general health of each stem was estimated based upon the percentage of the existing canopy that was alive (without regard to the level of scale

Figure 3. Methods used to survey arthropods included pitfall traps (rain cover not shown; A), malaise traps (B), yellow pan traps (C) and tuna bait (D). Additional methods (not photographed) included night lighting, sifting of litter and soil, deploying yellow sticky cards, and searching by hand.

infestation), as follows: > 90% alive, 76–90% alive, 51–75% alive, 25–50% alive, and < 25% alive. The extent to which stems and leaves were infested with scales was estimated as: 1) the percentage of all leaves that contained one or more mature female scales (as determined by the presence of white egg sacs), and 2) the number of mature female scales on infested leaves (< 5/leaf, 5–50/leaf, > 50/leaf). Scales were primarily restricted to the underside of leaves. In general, estimates of scale abundance were made using binoculars to search leaves within the canopy. In addition to these measurements, the species of ants found on each stem, when present, was recorded.

During 15–19 April 2012, all *Pisonia* trees on Rose Island were heavily infested with *Pulvinaria* scales. Following that discovery, USFWS decided that the four largest trees would be treated with the systemic insecticide, imidacloprid, in an attempt to control the scales. Imidacloprid is a neonicotinoid neurotoxin that acts by interfering with stimuli in the insect nervous system. During 22–28 November 2012 and again during 17–21 March 2013, each of these *Pisonia* was treated with the commercially available Ima-Jet (5% imidacloprid) by direct injection into the tree's vascular system using a QUIK-jet™ applicator guided by Arborplugs™ (all products were supplied by Arborjet Inc., Woburn, MA). Root drenching has been used to incorporate imidacloprid into tree foliage to control scale insects (Howard and Steinberg 2005, Grafton-Cardwell *et al.* 2008), but we used direct injection following recommendations outlined on the Ima-Jet label. Imidacloprid was injected into xylem tissue around the perimeter of *Pisonia* generally at 0.5–1.0 m above the ground. The dosage and number of injections into each tree was based upon stem diameters and label recommendations. In general, all stems about 20-cm diameter or larger were treated. The inaccessibility of most of the leaves high within the canopy and limited time on the island prevented a quantitative evaluation of the effect of imidacloprid on scale abundances. By March 2013, one of the four mature trees had fallen, but it was still alive and was also treated.

RESULTS

Comprehensive arthropod survey

Overall, at least 73 arthropod species from four classes, 20 orders and at 51 families were identified (Table 1). Insecta was the most diverse class (50 species from 11 orders), followed by Arachnida (16 species) and Malacostraca (7 species). Among insects, Diptera (flies) were most diverse (11 species), followed by Hymenoptera (ants and a wasp; 10 species) and Coleoptera (beetles; 7 species). Araneae (spiders) were also relatively diverse with eight species collected. Decapoda (hermit crabs) were not systematically collected so the three species identified may be an underestimate of the fauna.

The residency status of many species collected could not be determined, but for those with known distributions, 14 species are considered native or possibly native, while 28 species are considered exotic, or likely exotic (Table 1). No identified species are thought to be endemic to the atoll.

- No terrestrial arthropods were found on Sand Island, although small hermit crabs may exist there.
- No parasitoid wasps were collected on the yellow sticky cards. In addition, microscopic examination the six *Pisonia* leaves that were heavily infested with scales did not identify any parasitoid exit holes on scale bodies.

Diversity and distribution of ants

Nine ant species were collected during the survey (Table 1, Figure 4). Ant abundances were not quantified, but observations indicate that *Pheidole oceanica*, *Tetramorium bicarinatum* and *T. simillimum* were the most abundant and widespread species on Rose island. *Tetramorium simillimum* was found on 37 stations, followed by *T. bicarinatum* and *P. oceanica* at 31 and 30 stations, respectively. Distributions of these three species largely overlapped, and no clear island-wide pattern was observed (Figure 5). The two *Tetramorium* species were observed tending *Pulvinaria* scales on *Pisonia*. Only *P. oceanica* is considered native to the Samoan Archipelago and therefore possibly native to Rose Atoll. The eight exotic species collected are generally widespread in the Pacific Basin.

Table 1. Arthropods collected from Rose Atoll between April 2012 and November 2013.

Taxon	Genus & species	Previously reported from Samoa?[1]	Residence status in Samoa
Arachnida			
Acari			
undetermined	undetermined sp. 1	-[2]	-[2]
Oribatida	undetermined sp. 1	-	-
Oribatida	undetermined sp. 2	-	-
Oribatida	undetermined sp. 3	-	-
Araneae			
Araneidae	*Neoscona theisi* (Walckenaer)	yes	probably exotic
Clubionidae	*Clubiona* sp. nr. *upoluensis*	-	-
Lycosidae	*Hogna crispipes* (Koch)	no	probably exotic
Salticidae	*Thorelliola ensifera* (Thorell)	yes	possibly native
Scytodidae	*Scytodes* sp. maybe *fusca* Walckenaer	-	-
Theridiidae	*Coleosoma* sp.	-	-
Theridiidae	undetermined sp. 1	-	-
Theridiidae	undetermined sp. 2	-	-
Pseudoscorpionida			
Chthoniidae	undetermined sp.	no	probably exotic
Schizomida			
Hubbardiidae	Hubbardiinae, undetermined sp. 1	yes	probably exotic
Chilopoda			
Scolopendromorpha			
Scolopendridae	*Otostigmus* sp.	-	-
Geophilomorpha			
Mecistocephalida	*Mecistocephalus* cf. '*maxillaris*' (Gervais)	-	-
Insecta			
Blattodea			
Blaberidae	*Pycnoscelis indicus (Fabricius)*	yes	exotic
Blattidae	*Periplaneta australasiae (Fabricius)*	yes	exotic
Collembola			
Entomobryidae	undetermined sp.	-	-
Hypogastruridae	undetermined sp.	-	-
Sminthuridae	undetermined sp.	-	-
Coleoptera			
Anthribidae	Anthribidae G. sp.	-	-
Cerambycidae	*Sybra alternans* Wiedemann	no	exotic
Curculionidae	*Pentarthrum* cf. *obscurum* Sharp	no	exotic

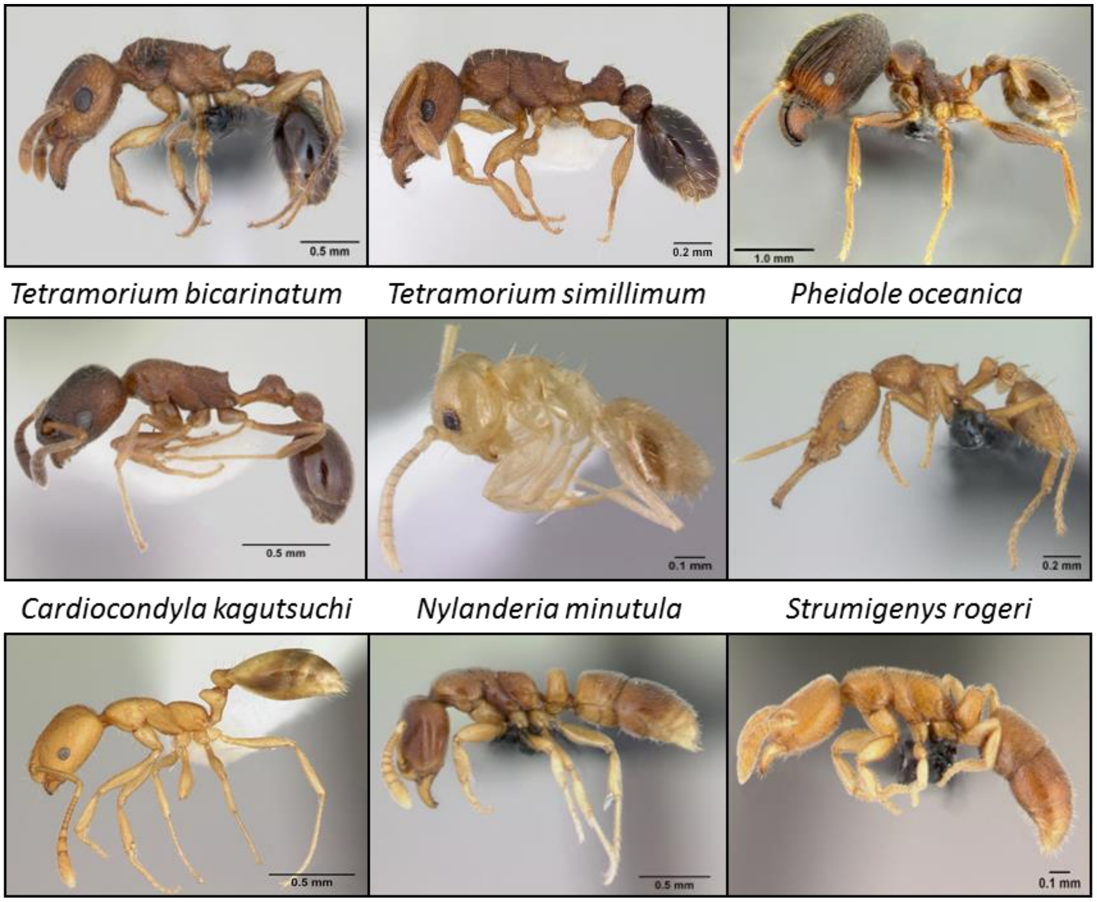
Taxon	Genus & species	Previously reported from Samoa?[1]	Residence status in Samoa
Dermestidae	*Dermestes ater* DeGeer	no	exotic
Elateridae	*Meristhus oceanicus* van Zwaluwenburg	yes	native
Elateridae	*Propsephus tongaensis* (Candeze)	yes	possibly native
Tenebrionidae	Tenebrionidae G. sp.	-	-
Dermaptera			
Anisolabididae	*Euboriella annulipes* Lucas	yes	exotic
Diptera			
Chironomidae	Chironomidae G. sp.	-	-
Chloropidae	*Cadrema pallida* Loew	yes	exotic
Ephydridae	*Hecamede granifera* Thompson	no	exotic
Hippoboscidae	*Olfersia* sp.	-	native
Milichiidae	*Milichiela* sp.	-	-
Phoridae	*Dohrniphora cornuta* (Bigot)	yes	exotic
Phoridae	*Megaselia* sp. 1	-	-
Phoridae	*Megaselia* sp. 2	-	-
Sarcophagidae	*Sarcophaga misera* Walker	yes	exotic
Syrphidae	*Simosyrphus grandicornis* (Macquart)	yes	exotic
Tachinidae	*Peribaea* sp.	-	-
Hemiptera (Auchenorrhyncha)			
Cicadellidae	undetermined sp. 1	-	-
Hemiptera (Heteroptera)			
Miridae	undetermined sp. 1	-	-
Pentatomidae	*Oechalia consocialis* (Boisduval)	no	possibly native
Hemiptera (Sternorrhyncha)			
Aphididae	undetermined sp. 1	-	-
Coccidae	*Pulvinaria urbicola* Cockerell	yes	exotic
Hymenoptera			
Formicidae	*Cardiocondyla kagutsuchi* Terayama	yes	exotic
Formicidae	*Hypoponera punctatissima* (Roger)	yes	exotic
Formicidae	*Ponera swezeyi* (Wheeler)	yes	exotic
Formicidae	*Monomorium pharaonis* (Linnaeus)	yes	exotic
Formicidae	*Nylandaria minutula* (Forel)	yes	exotic
Formicidae	*Pheidole oceanica* Mayr	yes	native
Formicidae	*Strumigenys rogeri* Emery	yes	exotic
Formicidae	*Tetramorium bicarinatum* Nylander	yes	exotic
Formicidae	*Tetramorium simillimum* (F. Smith)	yes	exotic
Eucoilidae	undetermined sp. 1	-	-
Lepidoptera			
Arctiidae	*Utetheisa pulchelloides* Hampson	yes	native
Noctuidae	*Achaea janata* (Linnaeus)	yes	native

Taxon	Genus & species	Previously reported from Samoa?[1]	Residence status in Samoa
Noctuidae	*Spodoptera litura* (Fabricius)	yes	native
Undetermined	undetermined sp. 1	-	-
Undetermined	undetermined sp. 2	-	-
Undetermined	undetermined sp. 3	-	-
Neuroptera			
Chrysopidae	undetermined sp.	-	probably exotic
Orthoptera			
Mogoplistidae	*Ornebius* sp.	-	probably exotic
Myrmecophilidae	*Myrmecophilus* cf. *quadrispina* (Perkins)	yes	exotic
Psocoptera			
Lepidopsocidae	undetermined sp.	-	-
Psocidae	undetermined sp.	-	-
Malacostraca			
Amphipoda			
Talitridae	undetermined sp.	-	-
Decapoda			
Coenobitidae	*Birgus latro* (Linnaeus)	yes	native
Coenobitidae	*Coenobita brevimanus* Dana	yes	native
Coenobitidae	*Coenobita perlatus* Milne-Edwards	yes	native
Isopoda			
Porcellionidae	*Porcellio* cf. *laevis*	no	exotic
Scyphacidae	Alloniscus cf. *oahuensis*	yes	probably native
Ligiidae	possibly *Ligia* sp.	-	probably native

[1] Primarily from Kami and Miller (1998)
[2] Unknown due to taxonomic uncertainty

Evaluation and measurement of *Pisonia* and treatment with imidacloprid

Pulvinaria scale abundance on the leaves of treated *Pisonia* was very low during March 2013 compared to April 2012, suggesting that imidacloprid had a significant impact on scales. The tree that had fallen between April and November 2012 (*Pisonia* 4, Table 2) was still alive and supporting many new shoots, most of which appeared to be free of scales in March 2013 (Figure 6). On standing trees, numerous new shoots grew from the main stems and branches, and we observed new growth at branch tips. Infested leaves were uncommon and patchily distributed within trees, and scale density per infested leaf was low. However, by November



Monomorium pharaonis *Hypoponera punctatissima* *Ponera swezyi*

Figure 4. Ant species collected from Rose Atoll. *Tetramorium bicarinatum* and *T. simillimum* were observed tending *Pulvinaria* scales on *Pisonia*. Although *Pheidole oceanica* was not observed tending scales at Rose, it has been observed tending *Pulvinaria* scales on *Pisonia* at Swains Atoll. Photo credits are as follows: www.AntWeb.org; April Nobile (*T. bicarinatum*, *T. simillimum*, *C. kagutsuchi*, *S. rogeri*, *M. pharaonis*, *H. punctatissima*); Eli Sarnat (*P. oceanica*); Erin Prado (*N. minutula*, *P. swezyi*).

2013 all four treated trees had become reinfested with light to moderate levels of scales (Table 2). In contrast, scale abundance was heavy on the three untreated trees during all three observation periods (April 2012, March and November 2013).

During November 2013, 23 stems from seven *Pisonia* were measured and evaluated for overall health and level of scale infestation (Table 2). On no trees were more than 75% of all branches alive. The percentage of live branches on individual stems ranged from 76–90% (1 stem) to < 5% (2 stems). The percentage of leaves infested with scales and the abundance of scales on leaves were generally positively related. Observed levels of infestation were generally low; on 18 stems the percent of leaves with scales was ≤ 20%, while scales were not found or were uncommon on 15 stems. Ants were seen on all trees but not all stems: *Tetramorium bicarinatum* was found on 17 stems and *T. simillimum* was detected on one stem.

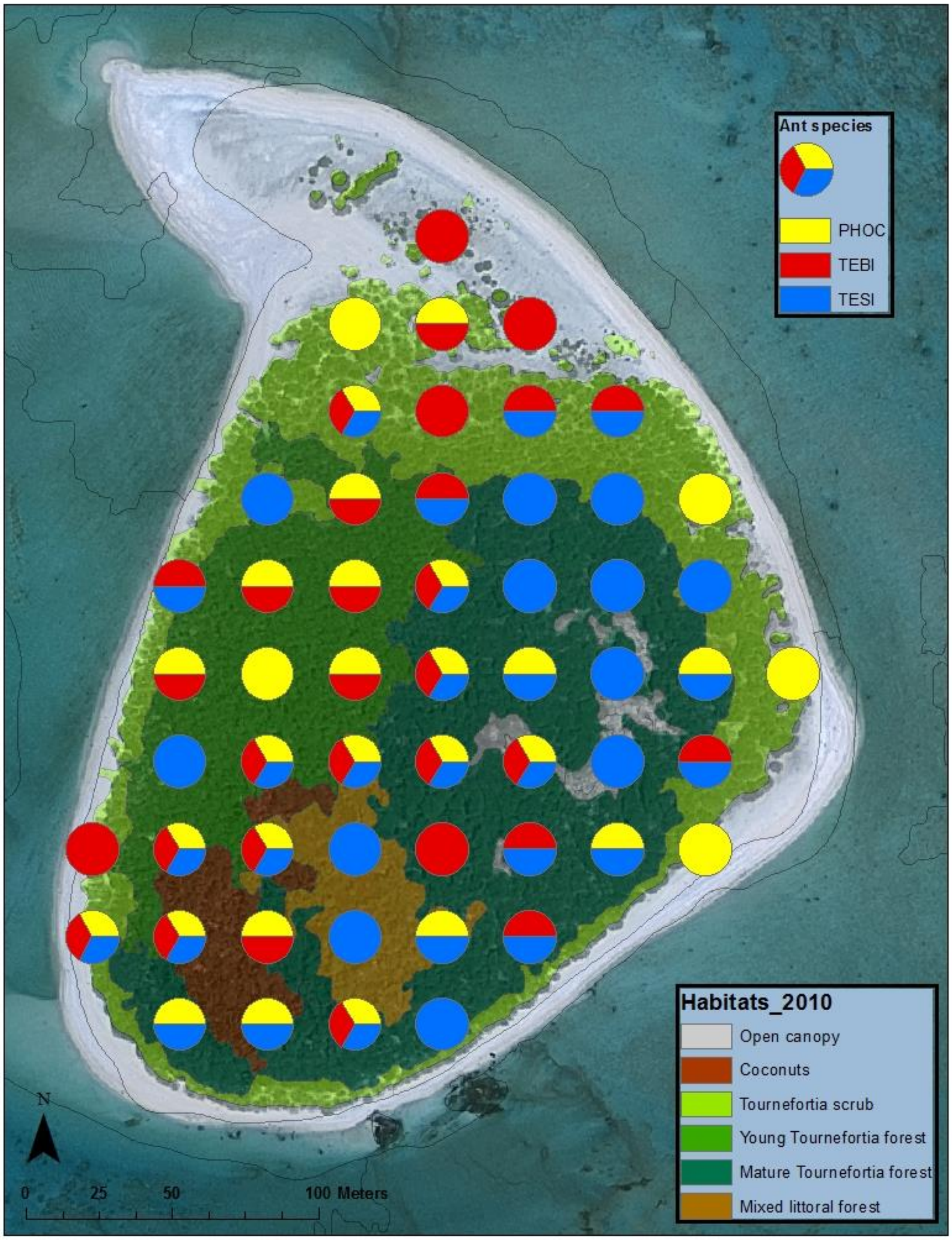


Figure 5. Distribution of *Pheidole oceanica* (PHOC), *Tetramorium bicarinatum* (TEBI) and *Tetramorium simillimum* (TESI) on Rose Island based on detections at bait cards and pitfall traps along a 30 m grid. Colored pie slices show the presence of each species at each site but are not indicative of abundance.

Table 2. Size and health of *Pisonia*, extent of scale infestation and ant species present during 18–21 November 2013. *Pisonia* 1–4 were treated with imidacloprid during April 2012 and March 2013.

Pisonia	stem	stem dbh (cm)	stem height (m)	crown radius (m)	tree health (%)[1]	scale distribution (%)[2]	scale abundance (no./leaf)[3]	ant species[4]
Pisonia 1	1	52.0	9.5	2.0	51−75	0−10	none	TEBI
	2	12.6	6.5	0.7	26−50	0−10	none	TEBI
	3	12.2	5.6	0.7	51−75	0−10	none	none
	4	8.0	3.0	0.5	26−50	11−20	<5	TEBI
	5	5.8	2.5	0.7	26−50	21−30	<5	TEBI
	6	10.1	5.3	0.5	26−50	0−10	none	none
	7	5.5	4.5	0.3	26−50	0−10	none	none
	8	9.3	3.8	0.3	26−50	0−10	none	TEBI
Pisonia 2	1	59.1	11.5	3.7	51−75	11−20	5−50	TEBI
	2	14.8	7.0	1.0	51−75	31−40	5−50	TEBI
Pisonia 3	1	48.2	9.3	4.2	51−75	0−10	5−50	TEBI
	2	36.3	7.0	2.5	51−75	0−10	5−50	TEBI
	3	14.1	7.5	1.0	51−75	0−10	none	none
	4	5.7	4.3	0.5	26−50	0−10	<5	TEBI
	5	14.2	5.5	0.7	26−50	0−10	none	TEBI
Pisonia 4	1	13.3	4.0	2.0	51−75	0−10	<5	none
	2	6.1	3.0	1.7	51−75	0−10	none	TEBI
	3	5.9	3.6	0.8	76−90	11−20	<5	TEBI
	4	6.4	2.5	1.3	26−50	0−10	none	TEBI
Pisonia 5	1	12.0	5.7	1.0	26−50	11−20	>50	TEBI
	2	6.0	3.0	0.2	<25	75−100	>50	TEBI
Pisonia 6	1	33.3	7.4	1.3	26−50	75−100	>50	TEBI
Pisonia 7	1	10.2	6.5	0.4	<25	75−100	>50	TESI

[1]Based on the percentage of the stems that were alive
[2]Percentage of leaves that contained one or more adult female scales
[3]The abundance of adult female scales on infested leaves
[4]Ant species present: none = no ants; TEBI = *Tetramorium bicarinatum*; TESI = *Tetramorium simillimum*

Figure 6. *Pulvinaria* scales on *Pisonia* leaves and healthy flush of new foliage following treatment with imidacloprid. *Pulvinaria* scales are evident on the mid-rib and lateral veins of *Pisonia* leaves (A and B). The elongated white structures are egg sacs produced by mature female scales. Note the numerous small, paler immature scales scattered throughout the leaf (examples indicated by arrows, B). Ants can be seen tending scales of all sizes (A and B). The background photograph (C) shows numerous new, largely scale-free, *Pisonia* shoots growing from a mature tree that had fallen sometime between April and November 2012. The photograph was taken March 2013, approximately four months following treatment with imidacloprid. By November 2013, it again was infested with scales.

DISCUSSION

The Rose Atoll terrestrial arthropod community

Our study represents the first systematic survey of the terrestrial arthropod community of Rose Atoll. Documentation of at least 73 species from 20 orders indicates that this diminutive but ecologically important atoll supports a relatively rich assemblage of arthropods. Comparative data are scant for uninhabited oceanic islands of similar size and degree of isolation, but the islands of Palmyra Atoll, totaling about 235 ha, were recently found to support at least 116 arthropod species (Handler *et al.* 2007). On larger Midway Atoll (621 ha), nearly 550 species have been collected over the past 100 years (Nishida and Beardsley 2002). On both Palmyra and Midway, non-native species dominate the fauna, presumably reflecting their long history of significant and frequent human impact.

Prior to our study, 17 arthropod taxa had recently been reported from Rose Atoll, including three flies (Diptera) and spiders (Araneae), two moths (Lepidoptera) and beetles (Coleoptera) and one cricket (Orthoptera), scale (Homoptera), wasp (Hymenoptera), ant (Hymenoptera), earwig (Dermaptera), cockroach (Blattodea) and spider mite (Acari) (Flint 1990). Although these arthropods generally were not identified beyond the order level, most were likely to have been collected during our survey. Notably absent from our survey, however, was a large, orange paper-nest wasp. This wasp was most likely a vespid within the subfamily Polistinae. These eusocial wasps build characteristic "paper" nests in shrubs and trees and are generalist predators of other arthropods, particularly caterpillars (Evans and West Eberhard 1970, Kasper et al 2004). Neither did we collect the larvae of the Celerio sphinx moth (likely *Hippotion celerio*) that was observed feeding on *Portulaca* in 1920 (Mayor 1921). *Portulaca* appears to have been relatively uncommon in 1920, as it is today, so the sphinx moth population may have been small at that time. Both of these species are large and relatively conspicuous, so it is likely that they no longer exist on the atoll.

Determining the status of arthropod species on oceanic islands is difficult due to generally poor knowledge of natural distributions of many species coupled with the long history of human-mediated introductions on islands. For many taxa, those within the same biogeographic province, such as an archipelago, are likely to share similar colonization histories, although some differences can be expected due to island size and degree of isolation (MacArthur and Wilson 1967, Simberloff 1974). The extent to which arthropods on Rose Atoll are also naturally found on the high islands of the Samoan Archipelago is unknown, but if a species is native to the archipelago then it is probably native to Rose Atoll as well. Therefore, we consider at least 13 species to be native, or probably native, to Rose Atoll. In contrast, all taxa identified to the species level are also found elsewhere; thus, none are endemic to Rose Atoll. Species endemic to Rose Atoll are unlikely because atolls of the south and central Pacific Ocean emerged above sea level only about 900–1500 years ago (Dickinson 2009), a period generally considered too brief for species to evolve.

Six species collected during our survey were not previously reported from the Samoan Archipelago, including three Coleoptera, one Pseudoscorpionida, one Diptera, one Hemiptera and one Isopoda (Kami and Miller 1998). Although the Samoan arthropod fauna is relatively well known, particularly for ants (Wetterer and Vargo 2003) and spiders (Berland 1942), these six species from Rose Atoll may have been missed during earlier surveys of the main islands. Alternatively, they may represent relatively recent introductions that have not yet been collected in the main islands. One taxon of particular interest is the pseudoscorpion within the family Chthoniidae, which represents the first record of that family in the Samoan Archipelago. All other species not previously reported are represented in the archipelago by other members of their families.

The small size and relative isolation of Rose Atoll did not prevent the colonization of arthropods with extremely specialized habitat requirements. For example, the myrmecophilic (ant-loving) cricket *Myrmecophilus* cf. *quadrispina* was collected within dead wood. This flightless cricket is an obligate commensal within ant nests where it scavenges for food and is protected from most natural enemies. These crickets are attacked by ants if detected, but they appear to avoid conflict by displaying ant-like behavior and through tactile mimicry (they generally "feel" like an ant; Holldobler and Wilson 1990). If noticed by ants, they also can escape through evasive behavior (Desutter-Grandcolas 1997). Because myrmecophilic crickets depend upon ant nests for survival, it is likely that an intact ant nest, rather than simply a queen ant, colonized Rose Atoll. The ant species from which this cricket was found is not known, but *M. quadrispina* has been found in *Pheidole* nests in Hawai'i (Desutter-Grandcolas 1997).

The composition of the arthropod fauna of Rose Atoll is likely fluid over time, fluctuating as new species colonize and established species are extirpated. The frequency at which new species arrive is unknown but is surely facilitated by human contact with the island. An example of a possible new introduction is that of the green lacewing (Neuroptera) that was collected during November 2013. This large, relatively conspicuous insect may have been missed during the intensive survey of March 2012, but it also may have colonized the island subsequent to that survey. Extirpations of established species also undoubtedly occur. Arthropods with strict host-dependencies, such as many herbivores and specialized predators, are vulnerable to localized extinction if their host disappears. Several plant species have been reported in the past on Rose Atoll but were not observed on the island during our surveys, including *Barringtonia asiatica*, *Calophyllum inophyllum*, *Cenchrus echinatus* (invasive grass eradicated in 1994), *Ipomea macrantha*, *I. pes-caprae*, *Suriana maratima* and *Terminalia* sp. (Wegmann and Holzwarth 2006). Arthropods associated with those plants may have disappeared as well. In contrast, Fox (1973) noted how well-established populations of the heliotrope moth (*Utetheisa pulchelloides*) occasionally die off in New Zealand despite an abundance of their food plant, indicating the unpredictability of extirpation. Causes of extirpation are numerous, but insufficient food, predation, disease, or severe weather events all may play a role in the process on oceanic islands.

Ants and *Pulvinaria* scales

Eight of the nine ant species collected on Rose Atoll are exotic species that are widespread in the Pacific Basin (Wetterer and Vargo 2003). Only *Pheidole oceanica*, a species that is distributed throughout Polynesia and the Western Pacific region, is considered native to the Samoan Archipelago, and therefore may have colonized the atoll naturally. All nine species are also known from Ta'u (U.S. Geological Survey unpublished data), the nearest landmass to Rose Atoll. It is possible that additional ant species will be discovered, particularly small, cryptic species that live within soil and litter. We did not quantify ant abundance, but it was apparent that the ant fauna is dominated both numerically and spatially by *P. oceanica*, *Tetramorium bicarinatum* and *T. simillimum*. Foraging ranges of these three ant species essentially occupy the entire island. Their foraging ranges clearly overlap to some degree as one or more of these species was sometimes detected in the same pitfall trap or on the same bait card. Even the northern tip of the island, where vegetation cover is sparse, supports ants. Here, entrances to *T. bicarinatum* nests were commonly found at the base of *Heliotropium*. The shade and leaf litter afforded by these compact shrubs presumably provide suitable habitat in this hot environment.

Only *T. bicarinatum* and *T. simillimum* were observed tending *Pulvinaria* scales on *Pisonia* on Rose Island. The degree to which each ant species tends the scales seemed to fluctuate over time: *T. simillimum* was most common during April 2012 and March 2013 and *T. bicarinatum* was dominant during November 2013. Mechanisms driving this difference are unclear. While *P.*

oceanica was not observed tending scales on Rose Atoll, it was found tending *Pulvinaria* scales on *Pisonia* on Swains Atoll (Mark Schmaedick unpublished data). On Rose Atoll, it is possible that *Tetramorium* are excluding *P. oceanica* from the scales, and in their absence, *P. oceanica* would assume that behavior.

No known natural enemies of *Pulvinaria* scales were collected on Rose Atoll. Parasitoid wasps and coccinelid beetle larvae are significant enemies of *Pulvinaria* scales and have been used effectively in biocontrol efforts (Smith *et al.* 2004). The only parasitoid we collected was an undetermined species of Eucoilidae (Cynipoidea). Its host on the island is not known, but eucoilids are considered to be internal parasitoids of the larval and pupal stages of Diptera (Quinlan 1978). We also did not detect any signs of parasitism over several hundred scales examined microscopically, further suggesting the absence of parasitoids associated with the scale. Many green lacewings are predators of honeydew-producing insects, and the species collected during November 2013 may convey some predation pressure on *Pulvinaria* scales. Green lacewings are commonly used to control pest aphids, but to our knowledge, are not considered an effective predator against *Pulvinaria* scales.

Pulvinaria scales were found to utilize host plants other than *Pisonia* on Rose Atoll. Scales were detected in relatively low numbers on *Cordia* leaves, primarily on trees adjacent to infested *Pisonia*, although *Cordia* is apparently not a preferred host (Batianoff *et al.* 2010). We also found scales on the root crown, stem and basal leaves of *Boerhavia* in open habitat as well as under the *Heliotropium* canopy. It is likely that *Boerhavia* infested with scales are found throughout Rose Island. *A T. bicarinatum* nest was discovered within the roots of a scale-infested *Boerhavia* plant on the northern end of the island, suggesting that scales on *Boerhavia* may help support these ants even in sparsely-vegetated areas.

Treatment of *Pisonia* with imidacloprid

Treatment of *Pisonia* with the systemic insecticide, imidacloprid, to control *Pulvinaria* scales yielded mixed results. Approximately four months following the initial treatment, scales were largely absent from *Pisonia* leaves, indicating a strong insecticidal effect of the treatment. Furthermore, vigorous growth of new shoots on the treated trees (including the tree that had fallen) suggested that *Pisonia* may recover if scales can be suppressed to very low levels. But by November 2013, eight months after the second application of imidacloprid, infestation levels on leaves increased to light or moderate levels on treated trees, indicating some recovery of the scale population. It is unclear why the scales increased after the second application, but it may have been due to the attenuation of imidacloprid concentrations within the leaves over the preceding eight months. Imidacloprid can persist in a tree for a year or more, although its overall availability to herbivorous insects depends upon the life of individual leaves (Sean Facey, ArborJet, Inc., personal communication). Alternatively, the second treatment may have preceded a flush of new, palatable foliage such that much of the imidacloprid was incorporated into older leaves that subsequently abscised or had become less favorable for the scales. Regardless, imidacloprid seemed effective to some extent eight months after the second treatment because scale populations were smaller on treated trees compared to untreated trees. The long-term efficacy of imidacloprid treatment on these trees is unknown, but imidacloprid treatment of *Pisonia* on Palmyra Atoll during 2004–2007 did not result in significant long-term suppression of scale abundances (Nonner 2007, USFWS unpublished data).

Summary

Rose Atoll supports a diverse assemblage of arthropods, most of which appear not to be native to the atoll. How these species influence the ecosystem is not fully understood, but intensive herbivory by the invasive *Pulvinaria* scale has likely contributed to the dramatic decline of the ecologically important *Pisonia* on Rose Island. Two ant species displayed the facultative relationship with *Pulvinaria* scales observed elsewhere in the Pacific and Indian Oceans, but their role in facilitating the outbreak of the scales on Rose Island remains to be determined. In general, ants are thought to benefit scales primarily through protection from natural enemies, but no natural enemies were identified during our survey, obscuring the value of the ants to the scales. Injection of *Pisonia* trees with the systemic insecticide, imidacloprid, failed to eliminate *Pulvinaria* scales from their leaves, although short-term suppression apparently occurred. A longer-term study would be necessary to determine whether scale abundances would fully rebound, as had been observed earlier on Rose and Palmyra atolls.

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