Colonization of Nishino-shima Island by Plants and Arthropods 31 Years after Eruption[1]

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Abstract: Although many researchers have studied colonization, the process has rarely been observed on newly emerged oceanic islands. To describe the colonization process of a remote oceanic island, I investigated the flora, vegetation, and pollinators of Nishino-shima Island 31 yr after a major eruption in 1973. Nishino-shima Island, which is 22 ha in size, is located 1,000 km south of mainland Japan. Vegetation cover had increased, especially on new lowland area, since a preliminary survey done 10 yr after the eruption, but plant species richness remained poor (only six species). Thus, the plant colonization rate (0.10 species/yr) was far slower than that of other volcanic islands such as Krakatau. Most plants (four species) had ocean-dispersed seeds, but two species were likely dispersed via attachment to seabirds. Despite colonization by only a few plant species, there were abundant flower visitors including ants, bugs, a butterfly, and a fly (but no bee species), and the average visitation rate per flower was 5.5 visits/12 hr in total observations. Most of the insects used multiple food sources, concurrently acting as scavengers or herbivores.

The process of colonizing remote oceanic islands has attracted many researchers because of the unique opportunity to study the pioneer organisms involved in the process. The central questions that investigators face include how organisms disperse to reach the islands, how species interact in the initial community, and what types of traits are advantageous in colonization of the island environment (Baker 1955, Carlquist 1974, Whittaker 1998).

Recently, molecular phylogenetic data have permitted more accurate speculation about the colonization and speciation history of oceanic islands (Armbruster and Baldwin 1998, Thorpe and Malhotra 1998, Ballard and Sytsma 2000, Emerson 2002, Percy and Cronk 2002, Price and Clague 2002, Kawakita and Kato 2004, Silvertown 2004). Colonization scenarios derived from limited indirect evidence, however, have been speculative because the invasion process has rarely been observed in real time on young oceanic islands. The most famous studies of colonization processes on a volcanic island have focused on Krakatau Island (Tagawa et al. 1985, Whittaker et al. 1989, 1997, 2000, Thornton 1997), Surtsey Island (Fridriksson 1989, Magnusson and Magnusson 2000, Frederiksen et al. 2001), and Long Island near Papua New Guinea (Edwards and Thornton 2001, Harrison et al. 2001, Thornton et al. 2001). However, each of those new islands lies within several dozen kilometers of the nearest mainland, so their conditions and the resulting challenges to colonizers differ greatly from those of true oceanic islands, which may be located several thousand kilometers from any source of land biota.

Nishino-shima Island (27° 14′ N, 140° 52′ E), which lies 130 km west of Chichi-jima Island (in the Ogasawara Islands) and about 1,000 km south of mainland Japan, erupted in 1973. The composition of its biota may be reset by another eruption in the near future. Thus, field observation of the initial

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biota on this young oceanic island provides a precious opportunity to describe the colonization process.

Two preliminary studies have investigated the biota of Nishino-shima Island. Before the 1973 eruption, the flora of the island consisted of three species in 1969 (Asami et al. 1970) (see Table 1). The crew aboard a fishing vessel observed smoke from an eruption in about 1950 (National Institute for Japanese Islands 2004), so it is likely that the vegetation of Nishino-shima Island had already declined as a result of ash deposition from intermittent volcanic activity before 1973. The flora of this island before the 1969 survey is unknown. In the subsequent visit to the island, Ohsawa and Kurata (1983) reported only four species in the flora 10 yr after the 1973 eruption. In this paper, I report the flora, vegetation, and arthropod fauna that had become established on Nishino-shima Island in 2004 (31 yr after the last eruption).

MATERIALS AND METHODS

Nishino-shima Island is in the Izu-Mariana Archipelago (Figure 1). Before the eruption of 1973, Nishino-shima Island was believed to have originated after the Quaternary geological period; this is far younger than other islands of the Ogasawara group, which originated in middle Eocene to Oligocene time (Umino 1985). Therefore, several species may have existed on the island before humans first visited, and humans have never historically inhabited the island. In 1973, an eruption occurred just east of the island, and the two islands were then united by tidal erosion and deposition. In this paper, the western plateau (25 m altitude) is referred to as the Old

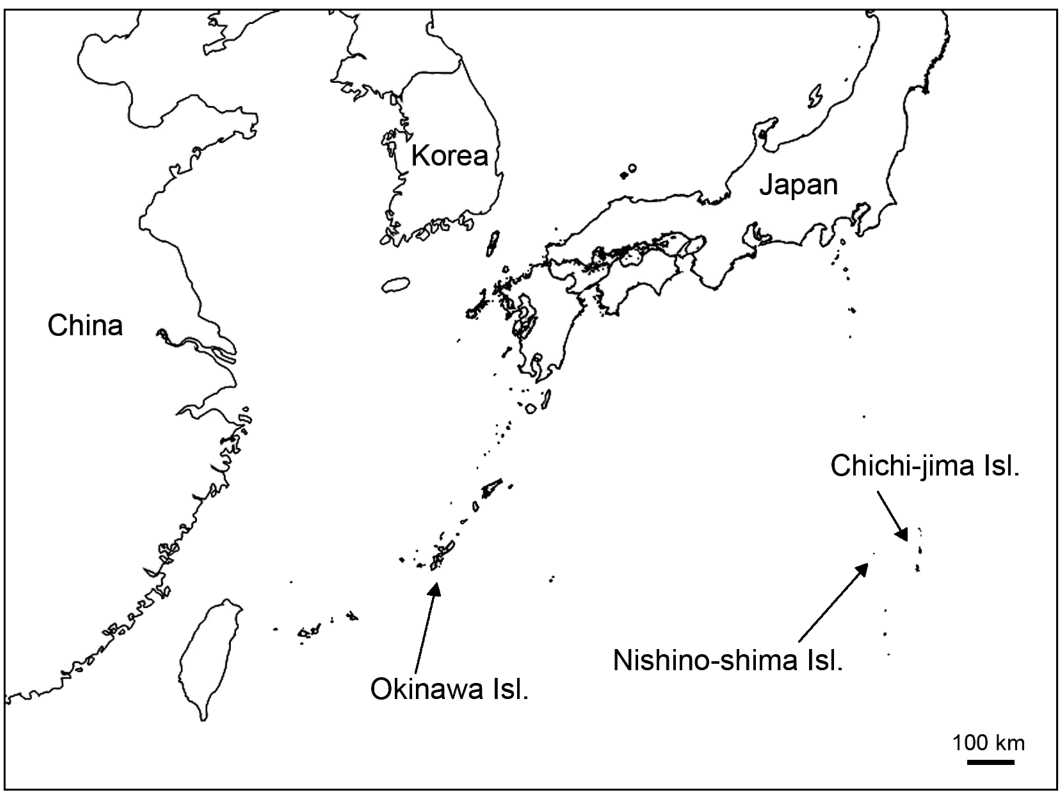

Figure 1. Location of Nishino-shima Island.

Plateau, and the eastern plateau and middle lowland are referred to as the New Plateau and New Lowland, respectively, reflecting the origins of these parts of the island (see Figure 2).

The Old Plateau consists of andesitic rock and is surrounded by a coastal cliff. Its surface is a dry, immature soil about 30 cm deep, containing little organic matter and much rock. The New Plateau consists of lava without any soil, and the New Lowland substrate is primarily lava-derived gravel. Salty Nakano-ike pond is located in the southeastern part of the island. No data are available concerning climate conditions on Nishino-shima Island, but there is likely to be less precipitation than on Chichi-jima Island (which receives about 1,200 mm annually) because of its low elevation. Dry conditions have probably combined with the immature soil to slow colonization.

The field survey was conducted in July 2004. I drew a vegetation map and investigated the flora by walking around the island and recording the phytosociological aspects of the established vegetation using 4-m^2 quadrats ($n = 15$). Flower visitors were observed on three species of flowering plants (*Portulaca oleracea*, *Vitex rotundifolia*, and *Ipomoea pes-caprae*) for a total of 450 min by direct observation and by recording visits with a digital video camera. I collected by sweep net any insects that visited the flowers. I also captured other arthropod species gathering on seabird corpses and moving on the soil surface by hand during my traverse of the island. Arthropods were identified to species level by consulting with taxonomic specialists.

RESULTS

The flora of Nishino-shima Island consisted only of six angiosperms in 2004: *V. rotundifolia*, *Eleusine indica*, *P. oleracea*, *Echinochloa crus-galli* var. *caudata*, *I. pes-caprae*, and *Tetragonia tetragonoides* (Table 1). This represents very poor species diversity compared with that of other volcanic islands (Table 2). Among the 2004 flora, *E. indica*, *P. oleracea*, and *E. crus-galli* var. *caudata* were recorded on the Old Plateau in 1969 and likely survived the 1973 eruption. In contrast, *I. pes-caprae* invaded within 5 yr after the eruption (Ohsawa and Kurata 1983), and *V. rotundifolia* and *T. tetragonoides* invaded between 6 and 31 yr after the eruption. Thus, the migration rate in Nishino-shima Island was 0.10 plant species/yr during the first 31 yr. All species except *T. tetragonoides* exhibited reproductive structures such as flower buds, flowers, or seeds during my survey. Four species exhibit ocean dispersal, and the remaining two species exhibit dispersal via attachment to birds. All plant species had hermaphroditic flowers, and five of the six species were short-lived herbs (Table 1).

Portulaca oleracea dominated the vegetation of Nishino-shima Island (Figure 2, Table 3). The vegetation of the Old Plateau was dominated by *P. oleracea* and *E. crus-galli* var. *caudata* and included several widely separated individuals of *E. indica* and *T. tetragonoides*. *Portulaca oleracea* also dominated the New Lowland, and *V. rotundifolia* and *I. pes-caprae* appeared only in the New Lowland. In contrast, the New Plateau consists of a lava substrate that has not yet developed any soil, and it still had no plants 31 years after the eruption (Figure 2). Only the northern area of the New Plateau, where relatively more weathering has progressed than elsewhere, seems likely to support the establishment of vegetation by means of seed recruitment in the near future. In addition, *V. rotundifolia* was spreading along the boundary between the New Plateau and the New Lowland and may eventually extend its distribution upward into the New Plateau. In 2004 there was approximately 50% vegetation coverage in the Old Plateau, 20% in the New Lowland, and 0% in the New Plateau (Figure 2). Two patches of *I. pes-caprae* were found in the New Lowland, but they seemed to have decreased in extent from 20 yr before when *I. pes-caprae* had expanded into a patch approximately 10 m in diameter (Ono and Okutomi 1985). Each plant community consisted of one to three species and typically covered 20–40% (range, 5 to 100%) of each 4-m^2 quadrat (Table 2).

In total, I recorded 33 visits to flowers during 450 minutes of observation of three plant

TABLE 1

Change in the Flora of Nishino-shima Island between 1969 (Asami et al. 1970) and 1983 (Ohsawa and Kurata 1983) and between 1983 and 2004 (This Study)

Species (Family)	1969	1983[a]	2004	Life Form	Sex[b]	Dispersal	Clonal Growth	Distribution
Eleusine indica (Gramineae)	OP	OP	OP, NL	Annual	H	Epizoochorous		Worldwide
Portulaca oleracea (Portulacaceae)	OP	OP	OP, NL	Annual	H	Ocean		Worldwide
Echinochloa crus-galli var. *caudata* (Gramineae)	OP	OP	OP, NL	Annual	H	Epizoochorous		Worldwide
Ipomoea pes-caprae (Convolvulaceae)	—	NL (30)	NL	Perennial	H	Ocean	Yes	Tropical
Vitex rotundifolia (Verbenaceae)	—	—	NL	Shrub	H	Ocean	Yes	East Asia and Oceania
Tetragonia tetragonoides (Aizoaceae)	—	— (1)	OP, NL	Perennial	H	Ocean	Yes	Pacific coast
Calophyllum inophyllum (Guttiferae)	—	— (1)	—	Tree	H	Ocean		Tropical Asia and Africa
Terminalia catappa (Combretaceae)	—	— (1)	—	Tree	Gm	Ocean		Tropical Asia and Africa
Barringtonia asiatica (Lecythidaceae)	—	— (2)	—	Tree	H	Ocean		East Asia, Oceania
Palm sp.	—	— (2)	—	Tree	?	Ocean		
Entada phaseoloides (Leguminosae)	—	— (1)	—	Woody vine	H	Ocean	Yes	Tropical Asia and Africa

Note: OP, Old Plateau; NL, New Lowland.
[a] Number of ocean-dispersed seeds observed by Ohsawa and Kurata (1983) in parentheses.
[b] H, hermaphrodite; Gm, gynomonoecy.

TABLE 2

Floristic Diversity of Some Volcanic Islands after Eruption

Parameter	Krakatau Island[a]	Surtsey Island[b]	Long Island[c]	Nishino-shima Island
Country	Indonesia	Iceland	Papua New Guinea	Japan
Latitude	6.1° S	63.4° N	5.2° S	27.1° N
Eruption date	1883	1963	1645	1973
Area (km^2)	17	2.8	330	0.2
Altitude (m)	813	150	1,280	25
Distance from nearest mainland	31 km (Sumatra Island)	33 km (Iceland)	55 km (Papua New Guinea)	1,000 km (Japan)
Eruption (E) + years (number of plant species)	E + 3 (35) E + 25 (120) E + 51 (290)	E + 5 (4) E + 10 (13) E + 25 (18)	E + 354 (305)	E + 10 (4) E + 31 (6)

[a] Species richness is of Rakata Island (Whittaker et al. 1992).
[b] Fridriksson (1989).
[c] Harrison et al. (2001).

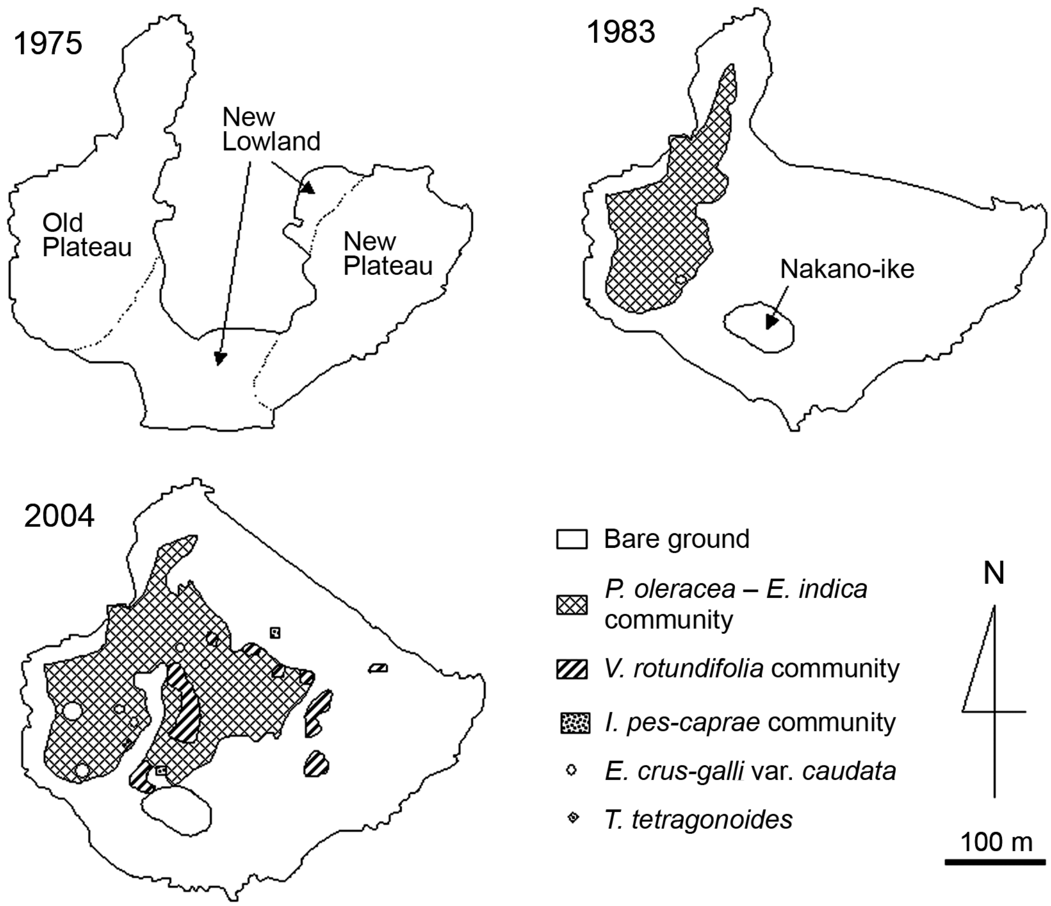

FIGURE 2. Shape of the three regions of Nishino-shima Island, and vegetation change from shortly after the island's eruption in 1973 until 2004.

species. From this, visitation frequency was calculated as 5.5 visits/flower/12 hr. Although observation time was limited, this frequency is not low compared with that on other islands of the Ogasawara group such as Muko-jima, Yome-jima, and Nakoudo-jima (2.4), and Chichi-jima and Haha-jima (5.1) (unpubl. data). Ants accounted for 26 visits (79% of the total), followed by bugs (five visits; 15% [Figure 3]), and one visit each by a butterfly and a fly (Table 4). However, there were no bee species, and the visitation frequency excluding ants was 0.6 visits/flower/12 hr, which is lower than on other Ogasawara islands. Thus, although insect visitors were present, their diversity was limited. In addition, I also observed a woolly bear caterpillar (*Dermestes ater*), earwigs, and spiders among the arthropod fauna (Table 5). All of the identified plant (Table 1) and arthropod (Table 5) species are widely distributed around the world.

DISCUSSION

Diversity of the flora and fauna of Nishino-shima Island is still very poor compared with that of other volcanic islands, but vegetation is gradually spreading. The plant migration rate was far slower than that observed on

TABLE 3

Results of Phytosociological Survey of Old Plateau and New Lowland on Nishino-shima Island on 10 July 2004

Parameter/Species[a]	Old Plateau									New Lowland						Freq.
Quadrat no.	4	5	6	7	8	9	10	11	12	1	3	13	15	2	14	
Elevation (m)	10	10	10	15	15	25	20	20	15	5	5	5	5	5	5	
Slope (°)	5	0	0	0	0	0	0	0	3	0	0	0	0	0	0	
Exposure	S 60° E	—	—	—	—	—	—	—	N 30° W	—	—	—	—	—	—	
Area (m^2)	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	
Height (cm)	5	30	25	25	5	20	5	5	50	20	20	30	20	30	30	
Cover (%)	40	50	20	30	20	5	100	100	80	30	30	40	40	40	80	
No. of species	1	2	3	3	1	3	1	1	1	2	2	2	1	2	1	
Portulaca oleracea	3	1	1	1	2	+	5	5		3	2	2	3	2		13
Eleusine indica		3	2	2		1			5	1	2	3				8
Echinochloa crus-galli var. *caudata*				1												1
Tetragonia tetragonoides						+										1
Ipomoea pes-caprae															5	1
Vitex rotundifolia														3		1
Community no.[b]	1	1	1	1	1	1	1	1	1	1	1	1	1	2	3	

[a] Numbers for species refer to cover estimates as follows: +, <1%; 1, 1–10%; 2, 10–25%; 3, 25–50%; 4, 50–75%; 5, 75–100%.
[b] 1, *O. oleracea–E. indica* community; 2, *V. rotundifolia* community; 3, *I. pes-caprae* community.

FIGURE 3. Two bugs (*Nysius* sp.) visiting a *Portulaca oleracea* flower.

Krakatau Island at the first colonization phase (2.78 species/yr [Whittaker 1998]). Of the flora observed in 2004, *V. rotundifolia*, *T. tetragonoides*, *I. pes-caprae*, and several species in the genus *Portulaca* are common along coastlines of Pacific islands (Whistler 1992), so they likely arrived by ocean dispersal. A high proportion of ocean-dispersed species has also been reported for the early phases of succession in the flora on other newly emerged islands (Thornton 1996, 1997). Although Ohsawa and Kurata (1983) recorded several ocean-dispersed seeds (*I. pes-caprae*, *T. tetragonoides*, *Terminalia catappa*, *Calophyllum inophyllum*, *Barringtonia asiatica*, *Entada* sp., and coconuts) along the coast of Nishino-shima Island, only two of these species (*I. pes-caprae* and *T. tetragonoides*) established successfully after the 1973 eruption. Thus, plant colonization of some new islands seems to be difficult even after propagules arrive at the island.

TABLE 4

Flower Visitors and Number of Visits on Nishino-shima Island

Flowers	Time (min)	Visitors: Fly	Butterfly	Bugs	Ants
Portulaca oleracea	90			5	1
Vitex rotundifolia	280	1	1		16
Ipomoea pes-caprae	80				9

All the plant species on Nishino-shima Island, including *E. indica* and *E. crus-galli* var. *caudata*, whose seeds are dispersed by attachment to birds (epizoochory), are cosmopolitan, with a worldwide or wide distribution, and there are no species endemic to the Ogasawara Islands, Japan, or Taiwan. The presence of cosmopolitan arthropod fauna agreed with the pattern of occurrence of fauna on other volcanic islands (New and Thornton 1988, Thornton et al. 1988, Edwards and Thornton 2001). Birds observed on the island were eight colonizers (*Sula leucogaster*, *S. dactylatra*, *Anous stolidus*, *Sterna fuscata*, *Thalasseus bergii*, *Bulweria bulwerii*, *Puffinus pacificus*, and *Oceanodroma tristrami*) and three noncolonizers (*Egretta garzetta*, *Pluvialis fulva*, and *Arenaria interpres*) (Kawakami et al. 2005). In particular, *S. leucogaster* nested at high density in vegetated patches on the Old Plateau and New Lowland (Figure 4). Nests of these seabirds may represent an important disturbance factor in terms of plant recruitment, and the deposition of guano by the birds is likely to accelerate the development of soils suitable for vegetation development.

On Rakata Island (in the Krakatau Islands), 120 plant species were present only 25 yr after the 1883 eruption (Whittaker et al. 1992) (Table 2). Because Rakata Island is at least 85

TABLE 5

Arthropod Fauna Observed on Nishino-shima Island

Species	1983[a]	2004[b]	Food Items	Dispersal	Distribution
Spider	—	OP, NL	Anthropod	Air	
Ant (*Tetramorium bicarinatum*)	—	OP, NL	Nectar, pollen, corpse	Debris rafting	Tropical
Ant (*Pheidole nodus* var. *praevexata*)	Yes	—	Nectar, pollen, corpse	Debris rafting	Asia
Butterfly (*Vanessa indica*)	—	OP, NL	Nectar	Flight	Worldwide
Woolly bear (*Dermestes ater*)	Yes	NL	Corpse	Debris rafting	Worldwide
Earwig (Anisolabididae)	—	NL	Corpse	Debris rafting	
Bug (*Nysius* sp.)	—	OP, NL	Nectar, plant body	Debris rafting	
Moth (*Spoladea recurvalis*)	—	NL	Nectar	Flight	Worldwide
Fly (Muscidae)	—	OP, NL	Nectar, pollen, corpse	Debris rafting	
Dragonfly (*Pantala flavescens*)	Yes	—	Arthropod	Flight	Worldwide

[a] Records for 1983 from Ohsawa and Kurata (1983).
[b] OP, Old Plateau; NL, New Lowland.

Figure 4. Nesting seabirds (*Sula leucogaster*).

times the size of Nishino-shima and is close (within 40 km) to large neighboring islands (Java and Sumatra), the low barrier to dispersal makes the colonization process faster than on oceanic islands located farther from other sources of biota. The floral richness on Rakata in 1989 had reached 410 species (Thornton 1996), a level that is already larger than the diversity of native plants in the Ogasawara Islands (327 species). This means that the time scale for colonization of remote oceanic islands is considerably longer than has been indicated by previous studies of volcanic islands nearer to other land.

On Krakatau Island, six endozoochorous plant species had already been recorded only 13 yr after the eruption (Thornton 1997), and 124 bird- or bat-dispersed plant species had migrated to the island within 109 yr (Whittaker and Jones 1994). However, there were no endozoochorous plant species on Nishino-shima 31 yr after the 1973 eruption. Frugivorous land birds may not settle on a new island until after the vegetation has developed and produced a food source for the birds. In contrast, ocean dispersal for long-distance dispersal has occurred with higher frequency than previously considered (Higgins et al. 2003, de Queiroz 2005). Several patches of *V. rotundifolia* became established after 1983 in the New Lowland areas of Nishino-shima. Because the distance among patches was more than 100 m, multiple colonizations probably occurred successfully during the last 20 yr. Endozoochory is unlikely to offer an advantage in terms of immigration to a remote island early on compared with ocean dispersal. Although the island flora is dominated by species dispersed by means of seeds in fleshy fruit (Ono and Sugawara

1981, Lloyd 1985, Webb and Kelly 1993), the dominance of endozoochory in island flora is likely to result from other reasons, such as a larger species pool in the flora of nearby land, rather than solely from a higher migration rate per species (Porter 1984).

In spite of the poor diversity of the island's flora, flies, butterflies, bugs, and ants visited the flowers on Nishino-shima Island. Among the visitors, the butterfly *Vanessa indica* was observed only once, so this insect probably arrived by chance from somewhere distant. Other flower visitors had multiple sources of food, concurrently acting as scavengers or herbivores. Some studies have reported that a wide range of arthropod taxa can invade the unvegetated habitat that exists after an eruption, and predators and scavengers usually dominate this community (Ball and Glucksman 1975, Howarth 1979, New and Thornton 1988, Thornton et al. 1988, Edwards and Thornton 2001). Such types of insects also act as pollinators of pioneer plants during the early stages of plant colonization. I found no bee species on Nishino-shima Island. Insects that depend only on flowers for their food may have difficulty surviving due to the limited floral availability and diversity. The colonization of flower visitors was also slower than on Krakatau, where bees from genera such as *Apis* and *Xylocora* visited flowers as early as 37 yr after the eruption (Thornton 1997).

The Nishino-shima flora is still in its initial stages of colonization even 31 yr after the 1973 eruption. Thus, continuing study of Nishino-shima as colonization progresses will provide new insights into island colonization theory.

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