Island Ecosystem and Vegetation Dynamics before and after the 2000-Year Eruption on Miyake-jima Island, Japan, with Implications for Conservation of the Island's Ecosystem

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Abstract

An active volcano, Mt. Oyama in Miyake-jima Island of the Izu Islands, Japan, erupted in 2000, and all the inhabitants were evacuated from the island. A new crater was formed, and since then, a large quantity of volcanic gas containing high concentrations of SO_2 and H_2S has been emitted. Indigenous plants and animals of the island have been heavily damaged by the volcanic deposits and gas. In this paper, we introduce the terrestrial ecosystem of Miyake-jima Island before the 2000 eruption, and then describe the damage to and recovery of vegetation after the eruption, with implications for restoration of the island's ecosystem. The damage to vegetation was extensive around the summit area, where some indigenous plant species may be extinct. The damage decreased at more distant sites from the crater. In 2001, damaged areas gradually extended toward the eastern leeward side, which was more frequently exposed to volcanic gas, while recovery of vegetation was observed on the northern side where volcanic ash was heavily deposited soon after the eruption of 2000 but was relatively less influenced by poisonous gas thereafter. The important process of vegetation recovery in damaged forests is stem sprouting shown by completely defoliated trees. On Miyake-jima Island, many engineering works (*e.g.*, check dam construction and revegetation work) have already been underway, on demand for improvement of island's security. Such construction, on the other hand, is likely to influence the island's ecosystem. We propose that restoration programs should be established considering utilization as well as conservation of the indigenous nature.

Key words: eruption, island ecosystem, restoration, vegetation recovery, volcano

1. Miyake-jima Island

Miyake-jima Island (55.14 km^2 in area) is situated on western rim of the Pacific Ocean (34°05'N, 139°31'E), about 180 km south of Tokyo (Fig. 1). Mt. Oyama in Miyake-jima Island is an active basaltic volcano. From July to September 2000, Miyake-jima erupted and ejected large amounts of volcanic ash, forming a large collapsed crater (more than 1 km in diameter and more than 400 m in depth) (Nakata *et al.*, 2001). All the people were evacuated from the Island in September 2000. Wind-borne material has covered extensive areas creating a new substrate. Since the formation of the new crater, a large quantity of volcanic gas containing high concentrations of SO_2 and H_2S has been emitted. The quantity of SO_2 gas reached 48,000 ton day^{-1} in the winter of 2000-2001 (Kazahaya *et al.*, 2001). Gas emission has still continued, which makes it difficult for people to resettle on the island. Plants and animals of the island have been severely damaged by the current volcanic activity.

Kamijo and co-researchers have investigated the vegetation of Miyake-jima Island from 1985 to the present. In this paper, we firstly introduce the terrestrial ecosystem of Miyake-jima Island before the 2000 eruption, and secondly describe the damage to and recovery of vegetation after the eruption.

1.1 Climate and Geology

Miyake-jima Island is located in a humid warm-temperate climate zone. The annual mean, minimum and maximum monthly temperatures are 17.4°C, 9.5°C and 26.1°C, respectively. The annual total, minimum and maximum monthly precipitations are 2,871.9 mm, 138.3 mm and 328.2 mm, respectively

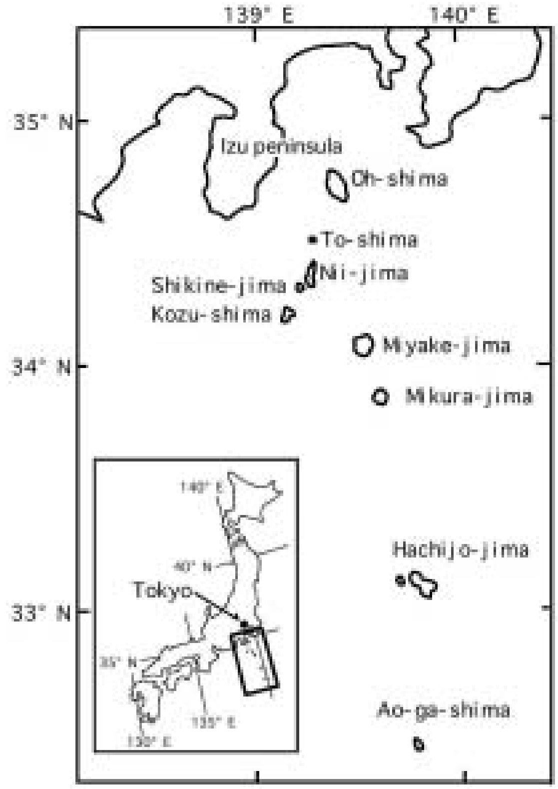

Fig. 1 A map of the Izu Islands.

(Meteorological Station at 36.2 m a.s.l. on the island). Since the island is small and isolated in the ocean, it is exposed to strong winds. The mean annual wind speed is 5.1 m s^{-1}, with the most frequent direction being SW (15% frequency from this direction). The wind speed becomes highest in January (monthly mean, 6.0 m s^{-1}), when the most frequent direction (22% of total time) becomes westerly.

The main stratovolcano was formed by Pleistocene volcanic activity (Isshiki, 1960; Miyazaki, 1984). Within recorded history, Miyake-jima Island erupted 15 times until 1999. The recent eruptions before 2000 (1874, 1940, 1962 and 1983) were characterized by the ejection of basaltic scoria and outflows of aa lava. In contrast, the volcanic activity of the 2000-2002 was characterized by formation of a large crater together with the ejection of large amounts of volcanic ash and gas. Such a type of eruption had not been recorded for 2,500 years prior to 2000 (Tsukui *et al.*, 2001).

1.2 Vegetation of Miyake-jima Island

The number of higher plants on Miyake-jima Island was about 500 species (Suzuki, 1956), includeing many taxa that are endemic to the Izu Islands (Fig. 2). Plants of the Izu Islands including Miyake-jima Island are morphologically different from those of the mainland, *e.g.*, larger leaf size (Fig. 2B), larger seed size (*e.g.*, *Castanopsis sieboldii*) (Kamijo, 2000), lack of prickles (Fig. 2C), larger flower size (*e.g.*, *Styrax japonica* var. *kotoensis*) or smaller flower size (Fig. 2D: *Campanula microdonta*). The island's populations of *C. microdonta* also have different mating systems from those of the mainland, *e.g.*, self-compatibility and smaller insect pollinators (Inoue, 1986, 1988). Inoue (1990) proposed that the smaller flower size and self-compatibility in the Izu Islands are explained by lower pollinator availability.

Fig. 2 Indigenous plants on Miyake-jima Island. (A) *Stachyurus praecox* var. *matsuzakii*. (B) Leaves of *Hydrangea involucrata* on Miyake-jima Island are much larger than those on the mainland. (C) *Aralia bipinnata*, lacking pirckles on stem. (D) Flowers of *Campanula microdonta.*

The natural vegetation of Miyake-jima is like a textbook of primary succession represented by chronosequences of volcanic substrata of different ages. A climax stage of the vegetation type is an evergreen broad-leaved forest composed of *Castanopsis sieboldii*, *Machilus thunbergii* and *Camellia japonica*. The vegetation on Miyake-jima Island has been disturbed by anthropogenic activities such as cultivation, clear-cutting for charcoal, and planting of *Cryptomeria japonica* for timber production. Most sites with moderate inclination on the old volcanic ejecta at lower altitudes are intensively cultivated, parallel with the practice of a traditional agroforestry technique using *Alnus sieboldiana*, an N-fixing tree. Deciduous broad-leaved forests and shrub composed of *A. sieboldiana*, *Prunus speciosa*, *Styrax japonica* var. *kotoensis* and *Weigela coraeensis* var. *fragrans* are distributed on younger substrata and on shifting cultivation fields. However, there remain untouched natural climax forests, which have been strictly preserved as sacred areas surrounding old shrines. On the summit and areas nearby, unique plant communities were distributed such as mossy *Irex crenata* scrub and natural grassland. Unfortunately, the 2000 year eruption was completely destroyed such communities.

1.3 A study of primary succession on lava before 2000

Primary succession on lava flows on Miyake-jima was investigated in both 1998 and 1999 (Kamijo *et al.*, 2002). Three lava flows which are sequential in terms of ages of their establishment (1874, 1962 and 1983) and much older volcanic ejecta in the northwestern part of the island were selected (Fig. 3). The age of the lava was 16-, 37- and 125-years old, respectively, at the time of the field investigation. Species composition, forest structure and soil chemical properties were compared among these substrata of different ages.

The process of primary succession inferred from Kamijo *et al.* (2002) and from previous studies (Hiroki & Ichino, 1993; Kamijo & Okutomi, 1995; Kamijo, 1997) on Miyake-jima Island is summarized as follows; (1) successful colonization of deciduous *Alnus sieboldiana*, an N-fixing tree, on bare lava flows, (2) facilitation by N-fixation of *A. sieboldiana* and the colonization of seral deciduous species such as *Prunus speciosa* and climax evergreen spp. as *Machilus thunbergii*, (3) rapid above-ground biomass accumulation and formation of a mixed forest, (4) disappearance of *A. sieboldiana* and *P. speciosa* under

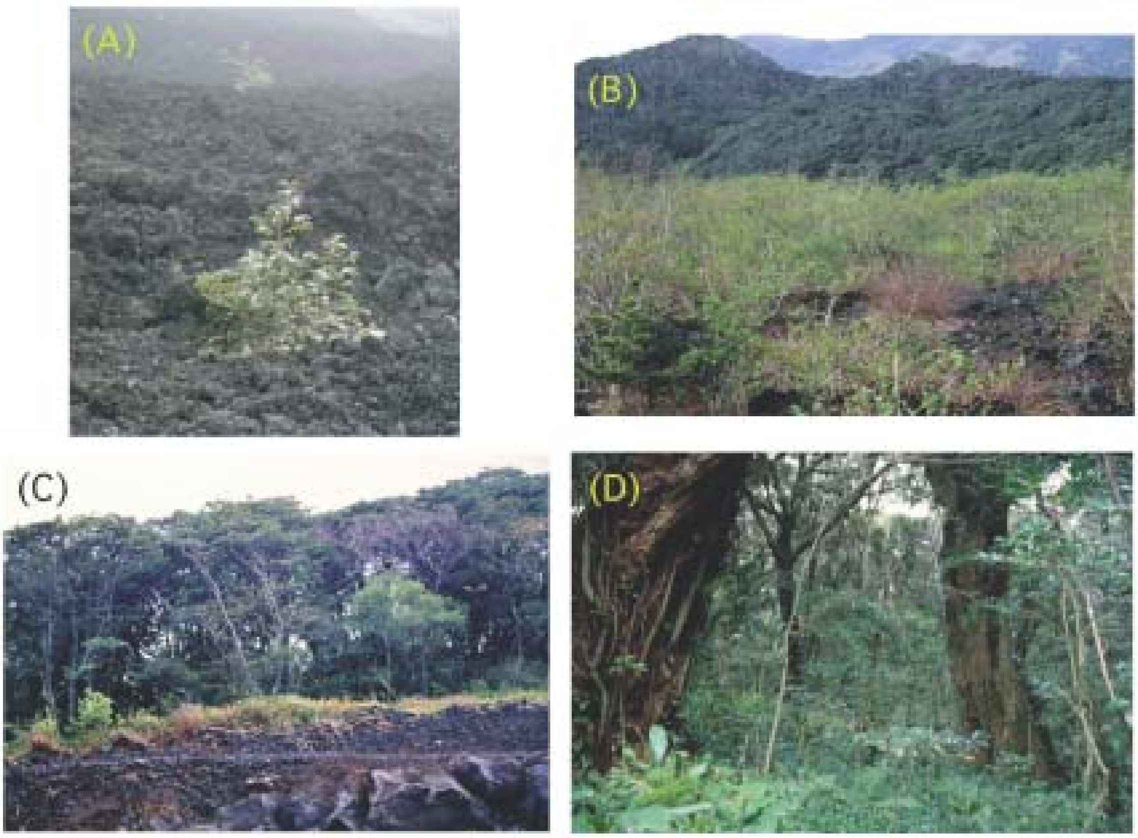

Fig. 3 An age sequence of three lava flows (1983, 1962 and 1874) and the old volcanic ejecta. These photographs were taken before the 2000 eruption. (A) a 1983 lava flow: plants are sparse, and trees of an N-fixing pioneer, *Alnus sieboldiana*, are found. (B) a shrub of *A. sieboldiana* on a 1962 lava flow. (C) a mixed forest of deciduous *Prunus speciosa* and evergreen *Machilus thunbergii*, on a 1874 lava flow. The Biomass and structure of the forests have developed, whereas the soil depth is extremely shallow and organic soil has accumulated in the interstices of lava. (D) a climax forest dominated by *Castanopsis sieboldii* strictly preserved by the old Mangan-ji shrine.

low light conditions, and (5) replacement of dominant evergreen tree species from *M. thunbergii* to *Castanopsis sieboldii*.

Kamijo *et al.* (2002) indicated that the rate of above-ground biomass accumulation in the early primary succession of Miyake-jima Island is considerably faster (12 and 20 kg m^{-2} in 125 years) compared to that of a montane tropical evergreen forest of Hawaii on the same basaltic aa lava (1.9 kg m^{-2} on 137 year old aa lava flows at 914 m a.s.l. in Aplet and Vitousek, 1994). This is essentially due to the facilitation effects of *Alnus sieboldiana*, which symbiotically fixes N. The study of Miyake-jima Island in comparison with that of Hawaii suggests that the presence of N-fixing trees accelerates effects of early primary succession by adding N to the substrate (Kamijo *et al*., 2002).

Primary succession follows a different sere on different substrata (Miles, 1979). In the 2000-year eruption, wind-borne material composed mainly of volcanic ash covered extensive areas creating a new substrate for primary succession. As mentioned before, this type of eruption had not occurred for 2,500 years, making it distinct from previous eruptions accompanied by basaltic scoria and outflow of aa lava. The new sere on ash will differ from that studied by Kamijo *et al*. (2002), and a new study of primary succession through direct monitoring will be useful.

1.4 Birds and Reptiles

Miyake-jima is well-known as a "bird's island." . Higuchi (1973) reported 38 species breeding in terrestrial and freshwater habitats. There are many animals either endemic or semi-endemic to the Izu Islands: birds, such as *Trudus celaenops*, *Phylloscopus occipitalis* and *Parus varius owstoni* (Fig. 4), and lizards, such as *Eumeces okadae*. The densities of birds and lizards used to be very high, because predators such as snakes and carnivorous mammals were originally absent from the island until the introduction of weasels *Mustela itati itati*. *Parus varius owstoni* on Miyake-jima island has distinctive ecological features compared to its subspecies, *P. v. varius* on the mainland (Honshu), such as larger body size, smaller clutch size and larger egg size (Higuchi, 1975, 1976; Higuchi & Momose, 1981). Similar speciation is shown by *Eumeces okadae*, an endemic lizard species on Miyake-jima Island, whose clutch size is smaller and egg size is larger relative to those on the other islands where predators such as *Elaphe quadrivirgata* are distributed. In addition, female *E. okadae* noticeably reproduce biennially, which is rarely observed in lizards of other temperate regions (Hasegawa, 1984, 1994, 1997).

The unique ecosystem on Miyake-jima Island has been regrettably influenced by introduction of weasels (Fig. 5) in both 1975-1976 and 1982 (Moyer *et al.*,

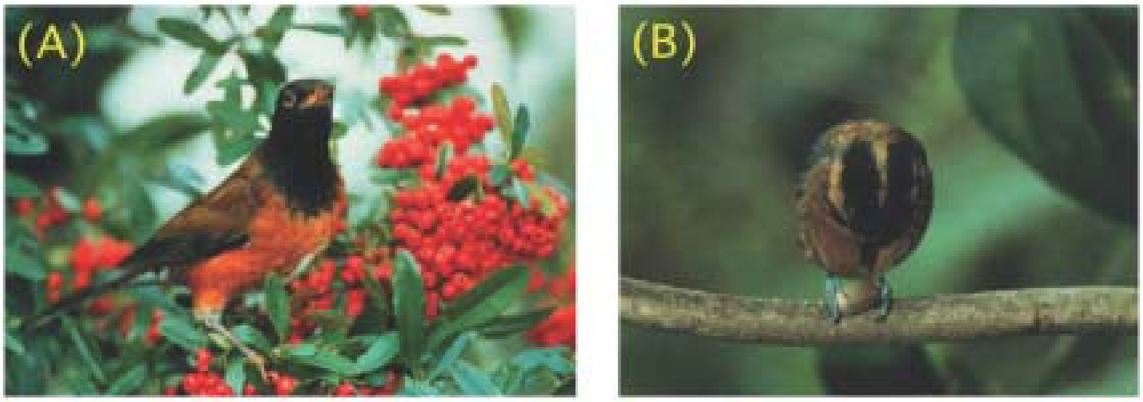

Fig. 4 Indigenous birds on Miyake-jima Island. (A) *Turdus celaenops*, most famous species on Miyake-jima Island. (B) *Parus varius owstoni* eating a nut of *Castanopsis sieboldii.* (Photoes by H. Tsumura)

Fig. 5 An introduced weasel *Mustela itati itati* on Miyake-jima Island. (Photo by H. Tsumura)

1985; Takagi & Higuchi, 1992; Hasegawa, 1999). The densities of *Trudus celaenops* and *Eumeces okadae* dramatically decreased after the introduction of this carnivorous mammal in 1982 (Takagi & Higuchi, 1992; Hasegawa, 1999).

These birds and lizards have also been influenced by the 2000-yr eruption and volcanic gas. Monitoring studies of birds have been continued after the eruption (Yamamoto, 2001; Higuchi, 2001).

2. The Damage to and Recovery of Vegetation after the Eruption of the Year 2000

Mt. Oyama in Miyake-jima Island erupted in July 2000, and ejected large amounts of volcanic ash and gas. Direct effects of the eruption on the ecosystem occur from deposition of ash and exposure to volcanic gas, while indirect influences are attributed to mudflows triggered by rainfall (Yamakoshi *et al.*, 2002), acidification of ash by SO_2 gas (Kato *et al.*, 2002) and many engineering works by humankind.

2.1 The vegetation damage from the 2000 eruption

The summit and adjacent area of the volcano (Mt. Oyama) were most severely damaged by the 2000 eruption (Fig. 6), where a small population of some indigenous plant species, such as *Tsusiophyllum tanakae* and *Parnassia palustris* var. *multiseta* used to established. Since the distribution of such species was restricted to this relatively small area (summit), they may be extinct on Miyake-jima (Kamijo, 2001).

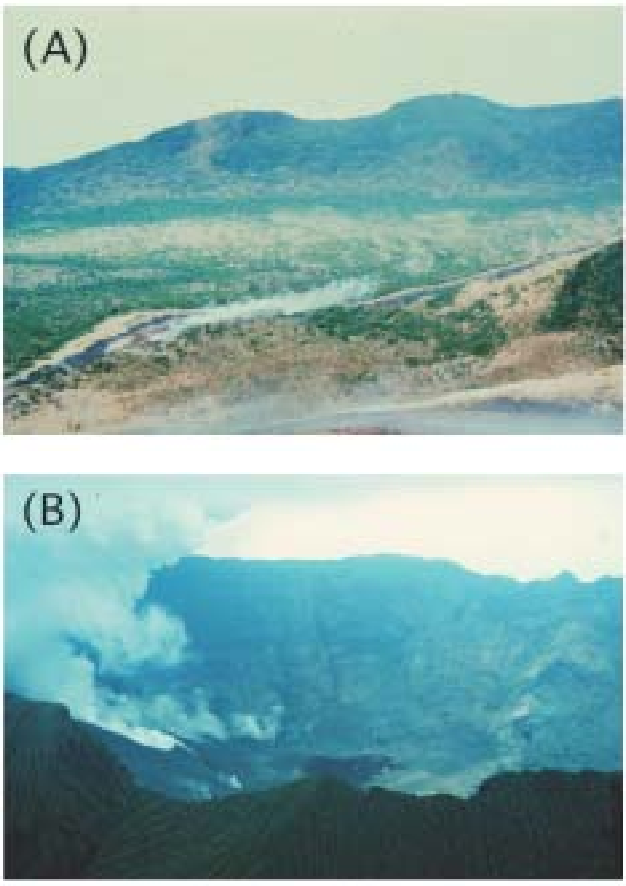

Fig. 6 The caldera of Mt. Oyama, Miyake-jima Island (A) before and (B) after the 2000-year eruption.

After the eruption in July 2000, vegetation on Miyake-jima was initially influenced by heavy deposition of volcanic ash. The vegetation damage was extensive around the summit area (Figs. 7 & 8), but except for the pathways of mudflows which ran from the summit area to the foot of the island (Fig. 9), the damage decreased at sites more distant from the crater (Kamijo, 2001). The degree of damage showed gradation from the summit area (most severe) to the foot of volcano (seemingly no damage) in the following order: (1) new crater, (2) bare land, (3) all trees buried or felled (Fig. 7A), (4) defoliation of all trees (Fig. 7B), (5) mixture of defoliated trees and normal trees (Fig. 7C), (6) normal vegetation (Fig. 7D).

Heavy volcanic gas, the most important feature of this eruption, is another major factor of damage to the island's vegetation. Poisonous gas composed of SO_2 and H_2S has been continuously emitted since the eruption of September 2000, causing widespread defoliation particularly on the leeward side of the volcano. A photograph taken in July 2001 (Fig. 10) shows a completely defoliated forest on the eastern leeward side of Miyake-jima (Miike district) in spite of a relatively thin accumulation of volcanic ash (3-5 cm). This implies that the main cause of the defoliation is volcanic gas, not ash.

As Figure 11 shows, the area damaged in terms of vegetation has changed shape. From March to September 2001, the damaged area extended toward the eastern leeward side, while recovery of vegetation was observed on the in northern side where volcanic ash was heavily deposited soon after the eruption of July and August 2000 (Kamijo *et al.*, 2002).

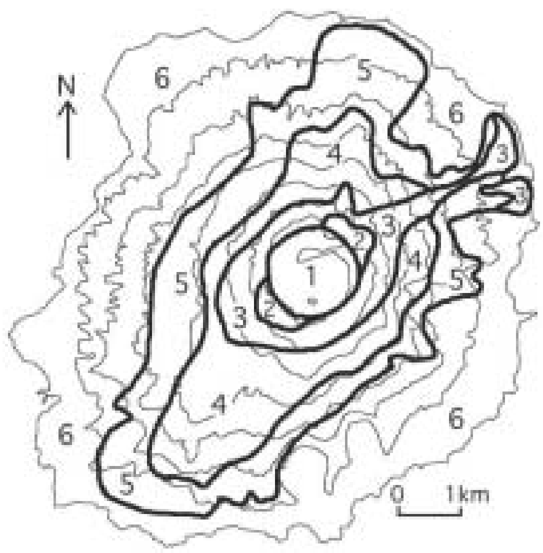

Fig. 7 A map of vegetation damaged by the 2000 eruption (Kamijo, 2001). 1: new crater, 2: bare land, 3: all trees buried or felled, 4: defoliation of all trees, 5: mixture of defoliated and normal trees, 6: normal vegetation.

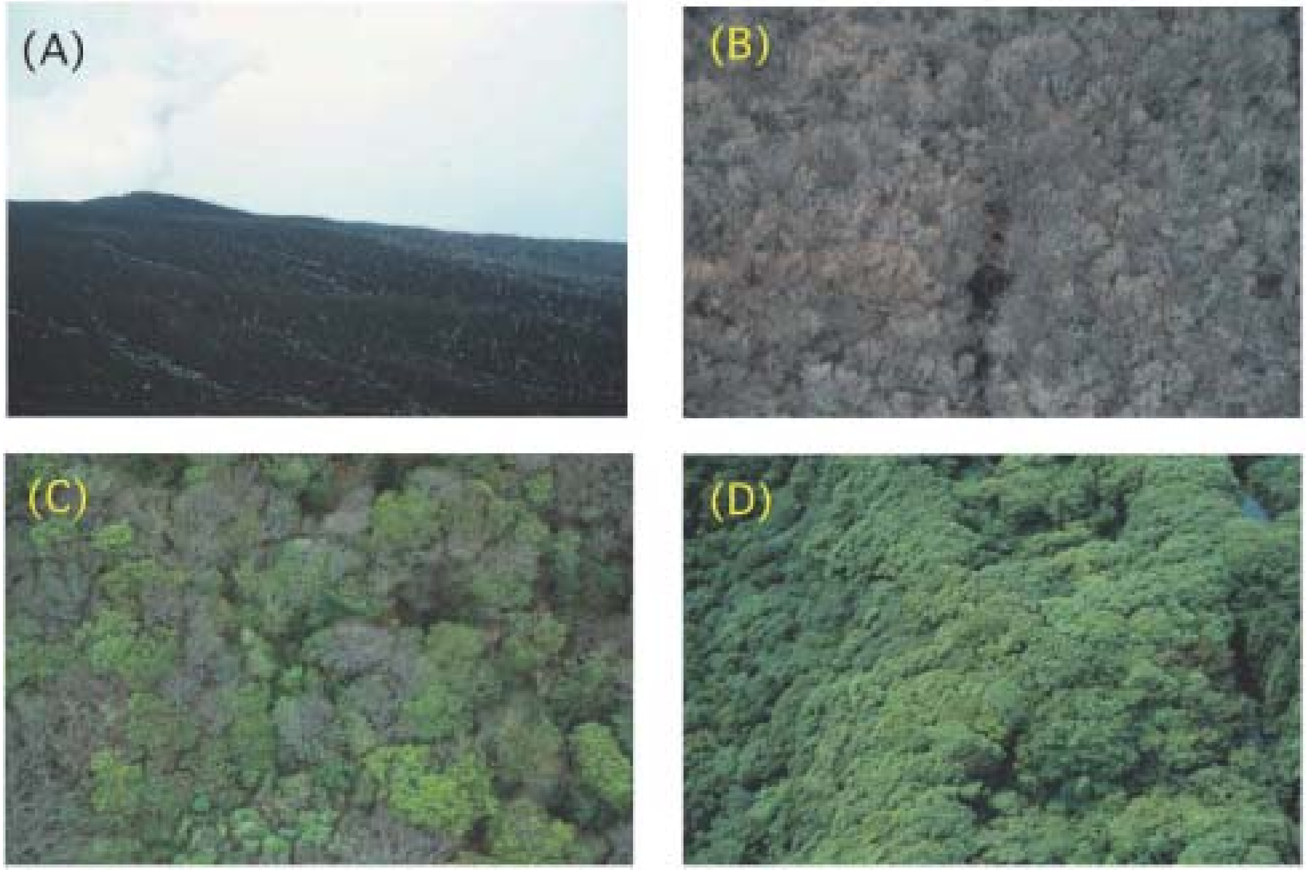

Fig. 8 Photographs of damaged vegetation. (A) all trees buried or felled. (B) defoliation of all trees. (C) mixture of defoliated trees and normal trees. (D) normal vegetation.

Fig. 9 A photograph of a mud flow taken in July 2000.

Fig. 10 A photograph of a *Machilus thunbergii* forest taken in July 2001 on the eastern leeward side of Miyake-jima. In spite of the thin accumulation of ash (3-5 cm), the forest is completely defoliated. This indicates that the main cause of the defoliation was volcanic gas, not ash.

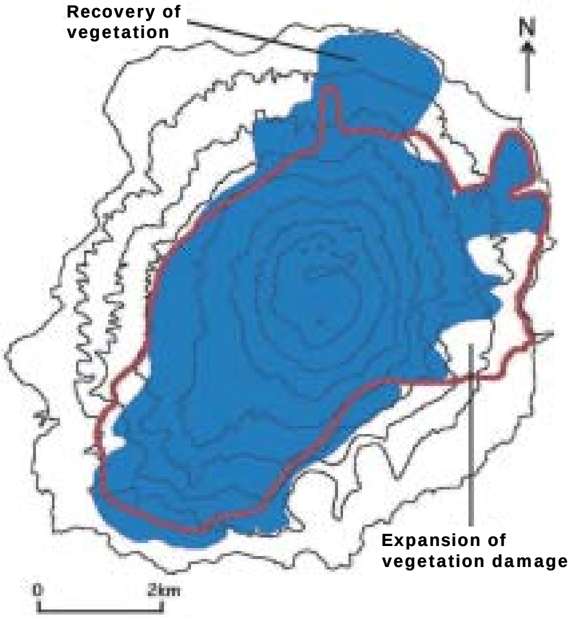

Fig. 11 A map showing a shift in damaged vegetation from March 2001, blue area, to September 2001, red line (Kamijo *et al.*, 2002). The damaged area extended toward the eastern leeward side, while recovery of vegetation was observed on the north side of the island.

2.2 Recovery process of vegetation on Miyake-jima Island

"Stem sprouting" is the major mode of recovery shown by completely defoliated trees (Fig. 12), similar to the tendency in recovery processes after the previous eruption in 1983 (Hamada, 1984; Matsuda & Honma, 1987). In June and July 2001, Kamijo *et al.* (2002) conducted *ad hoc* tree censuses selecting regarding more than 30 trees (>10 cm in DBH) at 41 randomly-chosen plots located between altitudes of 40 and 510 m a.s.l. Stem sprouting was often found in tree species, such as *Alnus sieboldiana*, *Prunus speciosa*, *Styrax japonica* var. *kotoensis Castanopsis sieboldii*, *Machilus thunbergii*, *Camellia japonica*, *Eurya japonica*, *Ligustrum ovalifolium* var. *pacifirum* and so on. More than 50% of tree individuals showed stem sprouting even at plots where canopy leaves were completely defoliated. Figure 13 indicates proportions of six main tree species that were sprouting at five plots in the southwestern part of the island. Each of the five plots was located at the altitude of 400-510 m, where all trees (>5 cm in DBH) completely shed their leaves. According to these censuses, more than 80% of individuals of both *Prunus speciosa* and *Ligustrum ovalifirm* var. *pacifirum* were sprouting from their stems, whereas less than 50% of those of *Styrax japonica* var. *kotoensis* and *Eurya japonica* were sprouting; there were significant differences among these species.

Buried seeds and vegetative organs (*e.g.*, roots and stems) are also important resources for vegetation recovery. Recovery from root crowns once buried in volcanic ash was found relatively often in such perennial species as *Reynoutria japonica*, *Miscanthus condensatus* and *Carex oshimensis* (Fig. 14). Some of the buried seeds in the soils under the ash layer will germinate and contribute to vegetation recovery, if the ash layers are eroded. Many species, such as *Cyperus* spp., *Rubus trifidus* and *Weigela coraeensis* var. *fragrans*, have successfully germinated from soils that were experimentally dug out on Miyake-jima Island (Shimokawa *et al.*, personal communication).

Colonization of seeds and spores is an important process of vegetation recovery, and is only one process of vegetation recovery at sites where biosystems were completely destroyed, resulting in commencement of primary succession. Some seedlings of *Alnus sieboldiana*, *Styrax japonica* var. *kotoensis* and *Mallotus japonica* were found on the ash in defoliated forests during several censuses. Monitoring should

Fig. 12 Photographs of stem sproutings after the 2000 eruption. (A) *Prunus speciosa* and (B) *Machilus thunbergii*.

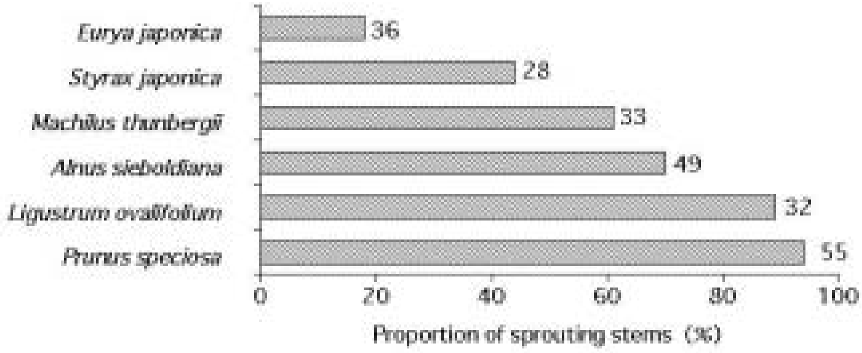

Fig. 13 Proportions of six main tree species that were sprouting at five plots in the southwest of the island (Kamijo *et al.*, 2002). The number of sampled trees of each species is shown.

Fig. 14 Recovery of *Carex oshimensis* from a root crown buried in volcanic ash.

be continued on such seedlings to determine whether they could survive.

The current volcanic activity is characterized by long duration of activity after the first eruption, with still SO_2 gas emitted from the newly formed crater. Therefore, the forest ecosystem on this island now seems to undergo "recovery" and "decline" concurrently, that is, recovery from being covered with volcanic ash by means of stem sprouting and/or sprouting from buried root crowns, and decline due to volcanic gas. Vegetation in areas where the influence of volcanic gas is relatively less, is predicted to recover steadily. On the other hand, recovery and recession will be repeated in areas where the influence of SO_2 is much more severe, which may eventually result in increased damaged area. Consecutive investigation is necessary to understand various changes in the ecosystem, including recovery and regression.

3. Implications for Restoration of Miyake-jima Island's Ecosystem

Several engineering works (*e.g.*, check dam construction and revegetation work) have already gotten underway on Miyake-jima Island, on demand for improvement of the island's security. Check dams will stop mud flows triggered by rainfall, and revegetation work is expected to prevent surface erosion on bare land. Such construction, on the other hand, is likely to have an unfavorable influence on the indigenous flora and fauna of the island. The insular ecosystem of Miyake-jima Island itself is a precious entity. Also, it will play an important role in offering various resources for environmental education and tourism (so-called eco-tourism) when islanders can re-settle. Restoration programs that consider utilization as well as conservation of the indigenous nature should be established and put into practice immediately.

Reforestation projects on the island are another big issue of concern. Problems resulting from utilization of introduced or non-indigenous plant species have been reported as the negative outcome of improper greenery projects from many oceanic islands, (*e.g.*, Hawaiian Islands, Vitousek & Walker, 1989; Ogasawara Islands, Shimizu, 1989; Yoshida & Oka, 2000; Oh-shima Island, Kuramoto, 1986). In the Ogasawara Islands, biological invasion of both *Leucaena leucocephala* and *Bischofia javanica* threaten indigenous plant species with displacement and extinction (Shimizu, 1989; Yoshida & Oka, 2000). Kuramoto (1986) reported that an endemic variety species, *Rhododendron odtusum* var. *macrogemma* on Oh-shima (the northernmost island of the Izu Islands) is confronted with genetic pollution caused by planting of introduced *Rhododendron* spp. Hence, several studies are underway, aiming at minimizing any ecological disturbance that could be accompanied by re-vegetation projects on Miyake- jima Island. To minimize the risk of genetic pollution one study is tried to select potential nursery sites in consideration of genetic similarity among conspecific populations. This study currently focuses on some of the indigenous plant species including *Alnus sieboldiana* (Tsumura & Iwata, 2002).

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