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Spatial Distribution Patterns and Implications for Conservation of *Scrophularia takesimensis* (Scrophulariaceae), an Endangered Endemic Species on Ulleung Island, Korea

Yeongseok Lim[1], Sung-Tae Na[1], Sung-Jin Lee[2], Kang Hyun Cho[3], and Hyunchur Shin[1]*
[1]Department of Biology, Soonchunhyang University, Asan 336-745, Korea
[2]Research Institute of EcoScience, Ewha Woman's University, Seoul 120-750, Korea
[3]Department of Biology, Inha University, Incheon 402-751, Korea

As part of an on-going effort to conserve endangered and endemic *Scrophularia takesimensis* (Scrophulariaceae), we analyzed its spatial distribution patterns by applying an index of dispersion, plant-to-all-plant distances, and the varying quadrat size method. Three indices -- Dispersion, Morisita, and Standardized Morisita -- all revealed clumping with small aggregates, and distances between aggregates were more or less regular. The asymptote level occurred at a distance of 20 to 30 m; the distance showing 90% of cumulative frequency coincided with 20 to 21 m; 95%, 24 to 25 m; and 99%, 31 to 32 m. The 20 m×20 m and 40 m×40 m quadrats contained 25 and 40 plants, respectively. We conclude that this number of individuals and size of area are the minimum required for the conservation of this species.

Keywords: conservation, *Scrophularia takesimensis*, spatial distribution pattern, Ulleung Island

Rare plants are especially vulnerable to environmental and demographic stochastic events, which may lead to extinction. Management of such species requires prior knowledge of their abundance, spatial distribution patterns, breeding biology and genetics, together with factors that affect seed and seedling survival and establishment (Schemske et al., 1994; Osunkoya, 1999). Organisms may form random, uniform, or clumped spatial patterns in nature (Krebs, 1999). Changes in those patterns can be used to detect important alterations in ecosystem performance (Alados et al., 2003). Therefore, the study of spatial patterns is essential for assessing the status and ecology of a natural community and its conservation value (Olive et al., 2002). In fact, this spatial prediction of species distributions, based on survey data, is a significant component of conservation planning (Austin, 2002).

Scrophularia takesimensis Nakai (Scrophulariaceae), a perennial herb, is a critically endangered plant endemic to Ulleung Island, a volcanic island in the East Sea between the Korean Peninsula and Japan Islands. This site contains about 700 species of vascular plants (Sun and Stuessy, 1998). Among them, *S. takesimensis* is the unique species of that genus whereas, on the Peninsula, 8 other species are distributed, but not *takesimensis* (Lee and Yamazaki, 1983). This species is dominant in coastal vegetation found on shingles or sands, and its patches run parallel to the coastline. Therefore, the construction of coastal routes and small harbors has become the most serious threat to its conservation, and many populations have already disappeared from that island. A conservation strategy, however, has not yet been programmed, and little study has been devoted to declining populations. Here, our objective was to conduct a thorough analysis of its spatial distribution patterns in order to provide fundamental information toward the development of conservation programs for this endangered species.

*Corresponding author; fax +82-41-530-1256
e-mail shinhy@sch.ac.kr

MATERIALS AND METHODS

Number of Populations and Individuals

Based on data gathered during a survey in 2000 (Lim et al., 2000), we again examined all of the potential habitats for *Scrophularia takesimensis* on Ulleung Island in 2001 and 2002 following the occurrence of a typhoon, Maemi. Habitats were divided into subpopulations according to their obvious spatial separation among individuals in the field, and their exact locations were recorded with a Garmin VI GPS system. All individual plants within subpopulations were counted, and were assigned a pair of Cartesian (x, y) coordinates (0.1-m precision) that represented their relative positioning within the subpopulation space. At each subpopulation, the corners were marked to serve as reference points in establishing the location of each plant as well as the distances between them. Because plants of *S. takesimensis* have a clonal structure and many sprouts near the base, and because their habitats consist of pebbles or stones, we counted individuals based on their shoots, excluding those cases where clonality occurred when shoots had sprouted over the base.

Determination of Different Age Categories

Because we could not determine the actual age of individual plants, our assessment of population structures was based on the number of individuals at different life stages: juvenile, vegetative adult, or generative adult. Juvenility referred to immature, unbranched plants less than 5 cm high, vegetative adults were non-flowering individuals taller than 5 cm, and generative adults were plants with at least one flower.

Spatial Patterns of Individuals

Three indices of spatial distribution patterns -- Index of Dispersion (Krebs, 1999), Morisita Index of Dispersion (Morisita, 1959), and Standardized Morisita Index (Krebs, 1999) -- were estimated with Ecological Methodology software (Exeter Software). A grid, consisting of 100 contiguous 1 m x 1 m plots, was superimposed on a map made by using our previously obtained Cartesian coordinates. Therefore, only subpopulations with habitat sizes of more than 100 m^2 were investigated. Other plot sizes, i.e. 0.25m^2 to 4m^2 were included, to avoid any scale-dependent problems between quadrat size and spatial pattern (Krebs, 1999), where the same set of points can appear to be over-dispersed at one scale but clumped at another (Dale, 1999). On our plots, all individuals were counted except for immature plants.

Distances Between Individuals

To obtain more precise information about population structures, such as the size and spacing of patches, as well as how large the gaps were between them, we calculated the distances between all possible pairs of individual adult plants within a subpopulation, based on their coordinates. Our analysis of plant-to-all-plant distances was similar to the method of Galiano, and lacked any devices to avoid an edge effect (Galiano, 1982). All Euclidean distances between individual plants within subpopulations were calculated and summed, so that we obtained both a frequency distribution and a cumulative frequency distribution of distance at 1-m intervals.

RESULTS

Number of Populations and Individuals of *Scrophularia takesimensis*

Subpopulations of *Scrophularia takesimensis* were mainly distributed (87% in each year) on the northern seaside of Ulleung Island (24 and 25 in 2001 and 2002, respectively; Fig. 1), while two others were found on the south side (6% of the total) and six (7%) on the eastern side; no plots were investigated where there were cliffs. All of our examined sites were situated within 5 m of the seaside road, with immature plants being mainly distributed in a sandy substrate and adult plants growing in pebbles or stones. Subpopulations ranged from 1 to 360 plants each in 2001 (mean of 56, median of 10), and from 1 to 191 individuals in 2002 (mean of 23, median of 9). During 2001, 69% of the subpopulations contained fewer than 50 plants compared with 85% in 2002 (Table 1). Larger subpopulations,

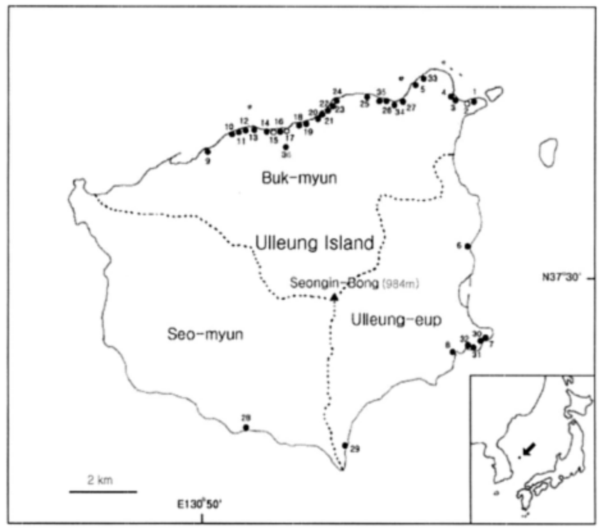

Figure 1. Study area on Ulleung Island, Korea (arrow in inset), and locations of subpopulations of *Scrophularia takesimensis*. Tallies are based on discovery sequence: 1-32, in 2001; 33-36, in 2002. Open circles indicate subpopulations discovered in 2001, but then disappearing in 2002 for various reasons, including Typhoon Maemi.

Table 1. Variations in the number of individuals per subpopulation.

Year	<10		10 ~ 50		50 ~ 100		100 ~ 200		200~ 300		>300		Total	
	NP	ANI	NP	ANI	NP	ANI	NP	ANI	NP	ANI	NP	ANI	NP	NI
2001	15	4.1	7	23.8	5	71.2	2	135.0	1	292.0	2	330.0	32	1816
2002	17	3.4	11	23.2	3	60.3	2	153.5	0	0	0	0	33	819

NP: number of subpopulations, ANI: average number of individuals within subpopulation, NI: number of individuals.

Table 2. Numbers of subpopulations and individuals of *Scrophularia takesimensis* in 2001 and 2002.

Year	Direction	No. of subpopulations	Generative plants		Vegetative plants		Juvenile plants		Total	
			No.	%	No.	%	No.	%	No.	%
2001	East	6	31	24.4	74	58.3	22	17.3	127	6.9
	North	24	505	31.9	447	28.3	629	39.8	1,581	87.1
	South	2	46	42.6	52	48.1	10	9.3	108	6.0
	Total	32	582	32.0	573	31.6	661	36.4	1,816	100.0
2002	East	6	31	60.8	20	39.2	0	0.0	51	6.2
	North	25	384	58.0	187	28.2	91	13.7	712	87.0
	South	2	52	49.0	40	37.7	14	13.2	56	6.8
	Total	33	467	57.0	247	30.1	105	12.9	819	100.0

i.e., those with more than 300 individuals, constituted 6% of the total in the first year, but were then absent in the second.

In 2001, 1,816 individuals (including juvenile plants) were found in 32 subpopulations versus 819 in 33 subpopulations in 2002 (Fig. 1; Table 2). Of these, 1,155 (60%) in 2001 and 714 (90%) in 2002 were adults. Furthermore, only 9 subpopulations in 2001 and 8 in 2002 contained juvenile plants. The total number of adult individuals per subpopulation ranged from 1 to 254 in 2001 (mean and median of 66 and 22), and from 1 to 69 in 2002 (mean and median of 12 and 2). Overall, 4 subpopulations contained more than 50 juvenile plants in 2001 compare with only 1 the following year. We noted no distinct correlation between the numbers of juvenile and adult plants, and the range in ages also varied considerably among subpopulations.

Spatial Distribution

When juvenile plants were excluded from consideration,

Table 3. Three indices for describing the spatial distribution of *Scrophularia takesimensis* subpopulations.

Subpopulation			Index of Dispersion	Morisita Index	Standardized Morisita Index
Year	Number	Quadrat size			
2001	3-1	0.5 m x 0.5 m	2.022	7.578	0.5071
		1 m x 1 m	3.709	5.325	0.5195
		2 m x 2 m	3.917	2.429	0.5235
	3-2	0.5 m x 0.5 m	2.213	8.807	0.5086
		1 m x 1 m	4.318	6.298	0.5245
		2 m x 2 m	4.540	2.603	0.5277
	19	0.5 m x 0.5 m	1.841	5.795	0.5050
		1 m x 1 m	2.323	2.857	0.5073
		2 m x 2 m	3.079	1.805	0.5117
	27	0.5 m x 0.5 m	2.098	6.919	0.5065
		1 m x 1 m	4.212	5.297	0.5198
		2 m x 2 m	4.650	2.217	0.5211
2002	3	0.5 m x 0.5 m	2.141	9.428	0.5093
		1 m x 1 m	3.030	5.187	0.5182
		2 m x 2 m	4.103	2.816	0.5305
	19	0.5 m x 0.5 m	1.870	5.453	0.5047
		1 m x 1 m	3.306	3.927	0.5129

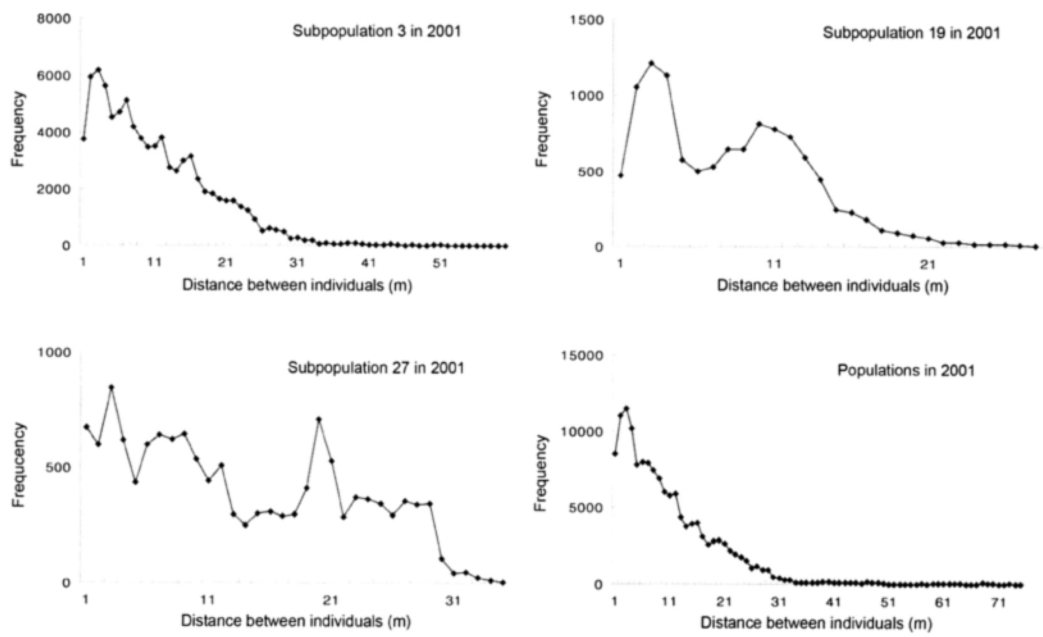

Figure 2. Frequency of distances between individuals within subpopulations in 2001. Peaks correspond to 3, 7, 12, and 16 m in Subpopulation 3; to 3 and 10 m in Subpopulation 19; and to 3, 7-9, and 20 m in Subpopulation 27. These peaks also were similar when all individuals were considered as one population.

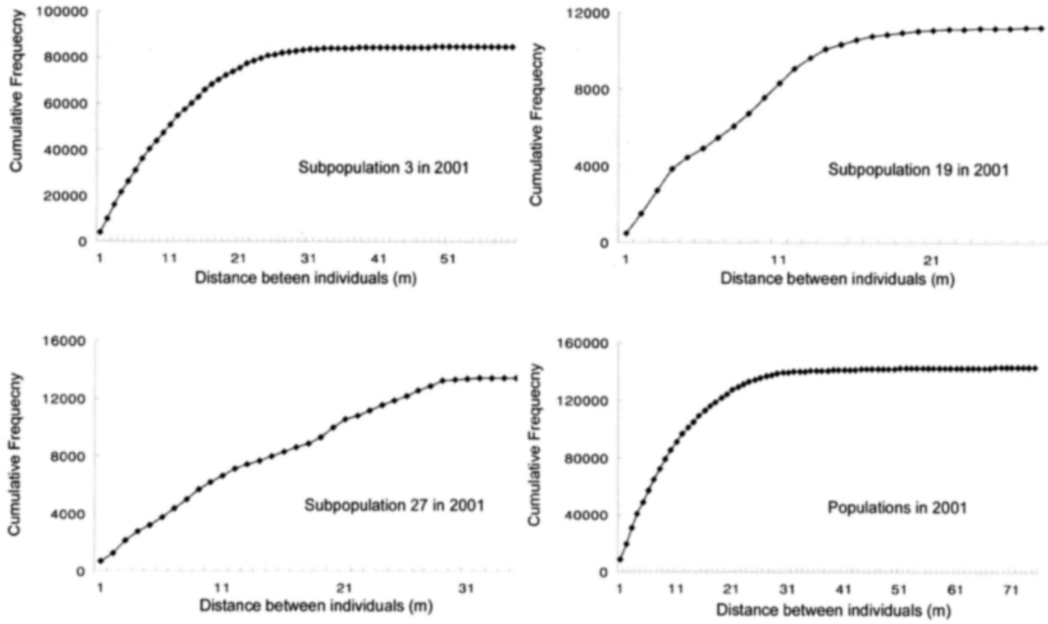

Figure 3. Cumulative frequency of distances between individuals within subpopulations in 2001. Asymptote levels occurred at distances of 20 to 30 m in Subpopulations 3, 19, and 27. Similar distances were calculated when all individuals were considered as one population.

only 3 subpopulations in 2001 and 2 in 2002 were large enough to accommodate 10 m×10 m quadrats that could be analyzed for spatial patterns. In one such scenario in 2001, a subpopulation was so large that we divided it into two groups and treated them independently, thereby resulting in six subpopulations there. All indices of spatial distribution exhibited clumping for every subpopulation at the 95% confident level (Table 3). This was indicated by values greater than '1' for both the Index of Dispersion and the Morisita Index, as well as a value greater than '0' for the Standardized Morisita Index. For all subpopulations, the intensities of spatial aggregation rose slightly with increasing quadrat size, except for the Morisita Index, which was somewhat decreased. We did not evaluate the spatial distribution of juvenile plants because 87% of those were found in only 3 populations, and were also severely aggregated. For example, at the maximum, 40 juvenile plants were aggregated within a 10 cm×10 cm area.

Distances between Individuals

From the 32 subpopulations identified in 2001, we selected 3 that contained more than 100 individuals each (Fig. 2, 3). Four peaks were obvious, at distances of 3, 7, 12, and 16 m, in Subpopulation 3, which had 291 plants. In addition, 2 peaks were found at 3 and 10 m for Subpopulation 19, with 106 individuals, while Subpopulation 27 had 116 individuals and 3 peaks, at distances of 3, 7 to 9, and 20 m. These peaks were also found when all examined subpopulations were summed at distances of 3, 5 to 6, 12, 16, and 20 m (Fig. 2). When the cumulative frequencies were examined without considering populations, the asymptote level occurred at 20 to 30 m, a level also found for each subpopulation (Fig. 3). A cumulative frequency of 90% coincided with the distance of 20 to 21 m, 95% at 24 to 25 m, and 99% at 31 to 32 m.

Table 4. Number of individuals as a function of quadrat size.

Size of quadrat (m x m)	No. of quadrats occupied by plants		Average no. of individuals	
	2001	2002	2001	2002
1.25 x 1.25	466	305	2.14±0.94	1.94±1.32
2.5 x 2.5	294	198	3.35±1.65	3.58±3.73
5 x 5	159	108	6.93±4.54	6.42±7.42
10 x 10	67	56	15.88±13.26	18.54±11.26
20 x 20	33	26	30.89±24.59	17.94±10.02
40 x 40	13	9	61.18±47.36	39.50±21.82
80 x 80	2	2	177	77

Number of Individuals as a Function of Quadrat Size

The number of individuals according to quadrat size was examined for 24 subpopulations in 2001, excluding the subpopulation with less than 5 plants. In all, 466 quadrats, each 1.25 m×1.25 m, were occupied by an average of 2.14 plants each (Table 4). This average value per quadrat increased drastically to a diminishing point between quadrat sizes of 20 m×20 m and 40 m×40 m, beyond which expanding the area resulted in the addition of only a few more individuals (Fig. 4). The number of individuals in quadrat size 20 m×20 m was about 25; for 40 m×40 m, about 40.

DISCUSSION

Reductions in *Scrophularia takesimensis* Populations

On Ulleung Island, plants of *Scrophularia takesimensis* were once thought of being widely distributed through all seaside habitats (Hyun, 2001). This was confirmed in numerous specimens deposited at several Korean herbaria. However,

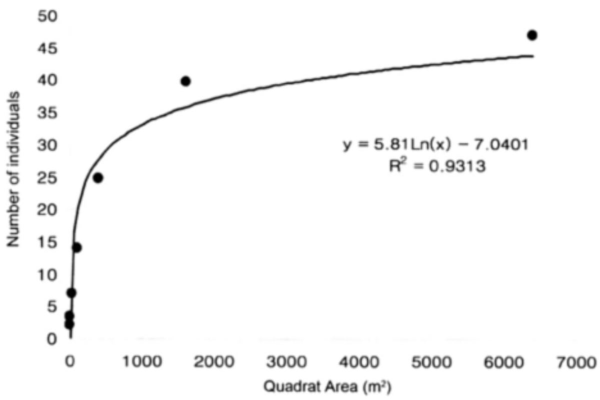

Figure 4. Average number of individuals based on quadrat size, with tallies increasing drastically up to area of 10 m x 10 m, then remaining mostly constant.

our study in 2001-2002 showed that only two subpopulations occurred in the southern region, with another six being found in the eastern region. By 2004, only three remained. In contrast, the number of subpopulations did not decrease significantly over our observation period in the north, a region that is relatively underdeveloped compared with the south, while also being protected from typhoon damage, two aspects that seem to allow for the sustaining of numerous subpopulations.

Storms cause significant geomorphological changes, including shoreface sediment entrainment and near-shore profile adjustment (Forbes et al., 2004). Typhoons are common and a key factor in determining the structure of plant communities on some Micronesian Islands (Wiles et al., 1996). Typhoons Maemi in 2002 and Songda in 2004, followed by heavy rainfalls, completely destroyed several small subpopulations, consisting of fewer than 10 individuals, which were located on the eastern side of Ulleung Island. Another threat to *S. takesimensis* is human activity along the coast, including road construction, waste discharge, and beach reconstruction, all of which inflict similar damage to other seaside plants (Quilichini and Debussche, 2000; Lee et al., 2004; Zahreddine et al., 2004) and island species (Jordan et al., 2003; Kingston et al., 2004).

Generally, the stability of population structure for an herbaceous species depends upon its environment; if conditions are constant and favorable, plants can survive for long periods without great changes in their numbers, but if unstable, herb densities rise or fall annually (Min, 2007). In our study areas, typhoons and the construction and maintenance (e.g., weeding and sweeping) of roads adjacent to the coast have caused many subpopulations of *S. takesimensis* once located in the southern region to become unstable and disappear.

Spatial Distribution of *Scrophularia takesimensis*

Plant spatial patterns are the manifestation of several ecological processes occurring at different physical and temporal scales. They can be influenced by numerous factors beyond spatial variation in the environment (Alados et al., 2003). In the temperate zone, members of most species seem to be clumped for at least two reasons: 1) as a reproduction strategy, in which either the seeds or fruits tend to fall close to a parent, or else runners or rhizomes produce vegetative offspring near a parent; and 2) positioning, where the habitat is homogeneous at the macroenvironmental level but, at a finer level, may consist of many different microsites that permit the establishment of a species with varying degrees of success. Those microsites that are most suitable for a species will tend to become more densely populated with that species (Barbour et al., 1980).

Ulleung Island is located in the temperate zone (Chang and Jeon, 2003), which might explain the clumped spatial distribution pattern for *S. takesimensis*. In addition, individual plants that result from seeds produced by cross-pollination germinate easily near their parental plants, especially in sand. Here, seed production by one individual was estimated to be >30,000; one capsule contained more than 150 seeds, a single inflorescence averaged about 20 flowers, and one individual produced more than 10 inflorescences (personal observation). However, although the juvenile plants, mainly occurring in sandy area, accounted for 36.4% of the total individuals in 2001 and 12.9% in 2002, they did not contribute to the development of vegetative or reproductive plants, because they may have disappeared when their substrate was removed by typhoons and heavy rainfall before they were able to mature to the adult stage. In 2001, three subpopulations, with habitats located mainly on sand, contained 116, 254, and 176 juvenile plants; the next year, those respective numbers had decreased to 1, 69, and 6. This trend also occurred between 2003 and 2004 (data not shown). In contrast, the subpopulation found in a habitat of primarily pebbles or stone comprised many reproductive and vegetative adults but fewer than 10 juveniles. Meanwhile, subpopulations that occupied habitats of pebbles, stones, or sand presented numerous adult and juvenile plants in 2001, but then lost many of the latter that were distributed in a sandy environment.

Although few studies have been conducted on the population dynamics of *S. takesimensis*, recruitment of this species appears to be supplied partially via sprouting. We observed that some individuals had many sprouts (>20) arising from their stem bases, near the topsoil or within the soil. In coastal regions, where environmental stresses are stronger, plants either regenerate mainly by sprouting from the base or stem (Ueno et al., 2000), or reproduce by vegetative propagation, although seed production also is high (Zahreddine et al., 2004). Furthermore, after storms, they recover by re-sprouting from damaged plants (Ennos, 1997; Bond and Midgley, 2001). Rare wind events, such as hurricanes or storms, also alter forest ecology by destroying trees rather than by changing their distribution or pattern of growth (Ennos, 1997). Likewise, typhoons in our study regions had eradicated many plants of *S. takesimensis*, but did not alter their distribution pattern.

Endangered Species and Analysis of Spatial Distribution

Many methods are available for estimating spatial distribution patterns (Dale, 1999; Krebs, 1999). The Morisita Index of Dispersion is relatively simple and independent of population density, but is affected by sample size, whereas the Standardized Morisita Index is one of the best measures of

Table 5. Indices of spatial distribution and sizes of areas examined in previous studies.

Index	Examined area	Reference
Ripley's K Function	70 x 70 m	Chokkalingam and White, 2001
	100 x 200 m	Chen and Bradshaw, 1999
	25 x 25 m (4 plot)	Arevalo and Fernandez-Palacios, 2003
	440 x 200 m	Aldrich et al., 2003
	9 x 9 m, 1 x 100 m	North and Greenberg, 1998
Morisita Index	100 x 200 m	Miyadokoro et al., 2003
	200 x 200 m	Ueno et al., 2000
	200 x 200 m	Hoshino et al., 2001
	1 x 0.5 km	Bunyavejchewin et al., 2003
	15 x 15m	Shaukat and Siddiqui, 2004
Standardized Morisita Index	20 x 20 km	Soehartono and Newton, 2000

dispersion because it is independent of both density and sample size (Krebs, 1999). However, none of these means of univariate analysis, e.g., the Morisita Index, Standardized Morisita Index, and Galiano's Distance (Galiano, 1982) give a clear picture of the characteristics of spatial patterns, because such a distribution is scale-dependent (Dale, 1999). That is, as scale changes, so does the level of resolution, and new spatial patterns emerge (Getis and Franklin, 1987).

An alternative second-order analysis was introduced by Ripley (1976, 1978), then refined by Getis and Franklin (1987). Ripley's K Function is considered to be the best available technique (Dale, 1999). However, these methods are used only in large populations, and organisms are assumed to exist under homogeneous and isotropic conditions, so that everywhere on the surface on which the organisms are to be located is equally available, and no direction is more or less likely to be favored for their placement (Getis, 1984; Dale, 1999).

In many previous studies (see Table 5), the areas examined were larger than those we surveyed here, and some of those earlier sites also had buffer zones to minimize edge effects (North and Greenberg, 1998; Aldrich et al. 2003). However, in the case of *S. takesimensis*, an endangered and endemic species that is distributed only on the small Ulleung Island, this setting did not allow sufficient area for us to plot a buffer zone, although the requirement for homogenous and isotropic conditions was satisfied because this species tends to be found along the coastline, especially in pebbles and stones. Only two subpopulations covered plot sizes of 60 m×20 m, with the rest inhabiting smaller areas.

Therefore, conditions in our study, without a buffer zone to minimize the edge effect, differed somewhat from those investigated by Galiano (1982). Here, we calculated and analyzed plant-to-all-plant distances to examine the spatial distribution pattern, and concluded that this procedure also may be applied to other endangered species that are found only in minimal local populations, such as those on a small island. Unfortunately, we were unable to compare our results with any from other studies that might have concerned the spatial distribution pattern of endangered species that are only locally distributed.

Clump Size and Number of Individuals per Clump

Based on results from previous plant-to-all-distances analyses, individuals that occur in simple clumps will demonstrate a bimodal frequency of distribution that includes short distances between neighbors within the same clump and longer distances between those in adjacent clumps (Dale, 1999). Steepness of the curve is related to aggregate size, i.e., sharp falls indicate small aggregates and more gentle falls are interpreted as larger aggregate sizes (Galiano, 1982). Our frequency graph presented several peaks that corresponded to distances of 3, 5 to 7, 11 to 13, 15 to 16, and 18 to 20 m when all distances were summed (Fig. 2). This meant that plants of *S. takesimensis* were distributed along the coastline in clumps with diameters of about 3 m, and gaps between clumps of about 1 to 2 m (Fig. 4). Therefore, this species was distributed in an aggregate, rather than a random or regular, spatial pattern. Furthermore, those aggregates were divided into several small aggregates (3-m diam.) that were spaced at 1- to 2-m intervals.

The cumulative frequency graphs showed the asymptote level at a distance between 20 and 30 m; this level also occurred for each subpopulation (Fig. 3). This meant that, after one individual was found, 90% of all other individuals could be found within a 20-m diameter, or 99% within 30 m, of the first plant. Such results implied that subpopulations of *S. takesimensis* did not exceed a 30-m-diameter area and, at the 90% level, did not go beyond 20 m. This estimated area was larger in 2002 than in 2001; cf., 90% within 30 m and 99% within 39 m in the previous year, because many individuals disappeared in 2002 due to the typhoon.

We estimated the number of individuals within a 20-m-diameter area by using a varying quadrat size analysis for 25, which was the number of individuals in a quadrat of 20 m x 20 m. That number was 40 for a quadrat size of 40 m x 40 m. Therefore, we concluded that natural subpopulations of *S. takesimensis* should comprise 25 to 30 individuals within a 20-m diameter. However, in 2001, among the 11 subpopulations with more than 30 individuals each, 10 occupied areas of about 20 m x 20 m. In contrast, of the 11 subpopulations with fewer than 30 individuals, 7 occupied areas smaller than 5 m x 5 m.

Conservation Implications for *Scrophularia takesimensis*

Plants of *S. takesimensis* showed a clumped distributional pattern. Cumulative frequency graphs revealed an asymptote level at a distance of 20 to 30 m, and the number of individuals within a 20-m-diameter area was approximately estimated using varying quadrat size analysis for 25. These values seemed to reflect the minimum area and number of individuals required for the conservation of that species because the asymptote level was close to those values. Therefore, to protect endangered plants, we recommend that one should select and monitor habitats that occupy a diameter of more than 20 m, and which contain more than 25 individuals. Here, 10 subpopulations were deemed appropriate. In addition, buffer zones might need to be 8 to 20 m wide to minimize the effects of herbicide spray drift on plants during road maintenance (Marrs et al., 1993; Endels et al., 2002). We found that only two subpopulations remote from the coastal road (i.e., >5 m away) required urgent conservation. Future research should also examine the effect of wind disturbance, a phenomenon not well studied to this point, but which can influence regions of up to thousands of hectares per event (Peterson, 2000). Finally, knowledge of both ramet and genet dynamics should be investigated for the conservation of *S. takesimensis*, because these provide a more complete picture, and genets cannot always be easily identified (Menges, 2000).

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