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Gap formation and susceptible *Abies* trees to windthrow in the forests of Odaesan National Park

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Abstract

Extremely strong winds and heavy rainfall caused canopy gaps in a mixed *Abies holophylla* broadleaf forest and a *Quercus mongolica*-dominated forest in Odaesan National Park, Korea in October 2006. The impact of the combination of strong winds and torrential rain on the development of forest gaps and canopy structures were investigated. The mean size of newly created gaps were 205 m^2 in the mixed forest and 86 m^2 in the *Quercus* forest, and were created by 2.8 and 1.4 gap-maker trees, respectively. Among the 73 trees lost in the mixed forest, 59% succumbed because of direct wind damage while 41% were struck by neighboring trees that fell into them. Most of these trees downed by wind were uprooted (74%), while the trees downed by neighboring tree falls snapped (78%). 21 trees in the *Quercus* forest died from direct wind damage, and 57% of them were uprooted. Although the relative density of *Abies nephrolepis* and *A. holophylla* represented only 0.2% and 6.4%, respectively, of all species in the intact mixed forest, they accounted for 27% and 15%, respectively, of all trees affected by wind on that site. In fact, 85% of the total *A. nephrolepis* and 91% of the total *A. holophylla* in the mixed forest fell directly due to strong wind. By contrast, only one *Abies* species, *A. nephrolepis*, was found in the *Quercus*-dominated forest, and it accounted for 7.3% of the species composition. These findings suggest that *A. nephrolepis* and *A. holophylla* are particularly susceptible to high winds because of their great heights and shallow root systems.

Key words: *Abies holophylla*, *Abies nephrolepis*, forest gap, tree fall, susceptibility, windthrow

INTRODUCTION

Disturbance is defined as "any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resource, substrate availability, or the physical environment" (White and Pickett 1985). Its impact depends upon the type, scale, intensity, and frequency. Two types of disturbances have been identified: 1) large-scale, occurring over a wide area and causing great destruction; and 2) small-scale, in which branches or stems are broken and trees either snap or are uprooted (Kang and Choi 2000). Although the frequency of large-scale disturbances is generally very low, some events, such as hurricanes or typhoons, can destroy an entire forest (Lorimer 1977, Bormann and Likens 1979, Canham and Loucks 1984, Boerner and Cho 1987). In contrast, small-scale disturbances occur more frequently, and are characterized by falling trees that can create a mosaic of various vegetation types and ages (Runkle 1982, Cho 1989, Cho and Boerner 1991).

A forest gap forms in the canopy when individual or multiple trees fall, or when large branches are broken on

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a single tree (Cho 1992). Strong winds are associated with approximately 97% of all gaps formed in mature forests within the southeastern United States and 80% of all new openings in Costa Rican rain forests (Barden 1981, Lawton and Putz 1988). Species with shallow root systems are especially vulnerable to high winds (Ruel et al. 2001). When large trees are uprooted, the forest floor is significantly altered because seeds lying within the soil become exposed and germinate, and the physical and chemical nature of the soil is changed by penetrating light (Greenberg and McNab 1998). In addition, soil gaps such as pits and mounds (Peterson and Pickett 1990) may lead to new microsites that can support the development of vegetation, ultimately changing the overall forest structure (Clinton and Baker 2000).

Odaesan National Park in Korea is a mosaic of various mature forests. The largest area is dominated by pure stands of *Quercus mongolica.* However, mixed forests also exist, including stands of *Q. mongolica* with broadleaf species *Tilia amurensis*, *Acer mono*, and *A. pseudosieboldianum*, or a combination of deciduous trees with conifers such as *Abies holophylla* (Lee et al. 2006).

In October of 2006, forests within this park were subjected to strong winds and heavy rainfall. Throughout the eastern coast of Gangwon-do, including Sokcho, Gangneung, Donghae, and Pyeongchang (where Odaesan is situated), this storm inflicted damage to humans, buildings, fishing boats, and roads (Shin and Park 2006). A maximum gust of 63 m/s was measured at Sokcho, along with sustained winds of 31 m/s, and precipitation during this event totaled 232 mm. Throughout that month, Yangyang, Gangneung, and Donghae received record high precipitation, as well as winds in the typhoon category that exceeded 17 m/s. The nearest weather station, 22 km away in Daegwallyeong, indicated gusts of 22.5 m/s and a historically high 171.5 mm of rain during a single day (Korea Meteorological Administration 2008). Although weather conditions were not recorded at Odaesan during this storm, the largest old-growth tree, an *A. holophylla* (diameter, 171 cm; height, 33 m) was uprooted at the time (Lee *et al.* 2006). Damage to other trees also led to the formation of forest gaps.

Fortunately, we have been monitoring several types of forests in the Odaesan National Park since 2005. The information of these reference forests provides a great opportunity to understand the structure and dynamics of the forests at the stand and species level (Kim 1996). Therefore, we investigated how the combination of strong winds and torrential rain, which are typical for Odaesan National Park, affected the development of forest gaps, influenced representative canopy tree species, and finally selected susceptible tree species to windthrow in that location.

MATERIALS AND METHODS

Study sites

Odaesan National Park represents a typical forested area populated by deciduous broadleaf tree species in central Korea. We examined the impact of wind damage on the structure of two types of forests there: 1) a mixture of the conifer *A. holophylla* and broadleaf species (hereinafter “mixed forest”), and 2) an area dominated by *Q. mongolica* (hereinafter “*Quercus* forest”). The mixed forest is located at Somyeonggol, on the lower slope of Birobong (1563 m), which is the highest peak in the park. This is an area where changes in vegetation structure have been monitored annually since a 2-ha permanent plot was installed in 2005. In the permanent stand of the reference forest, which did not suffer from wind, the tree density was 837 stems/ha with a diameter at breast height (DBH) >5 cm and an average basal area of 28.5 m^2/ha in 2008 (Odaesan National Park Service 2008). The main tree species included *T. amurensis* and *Acer pseudo-sieboldianum*, which had importance values (IVs) of 17% and 16%, respectively. Conifer tree species, *A. holophylla* in that forest had an IV of 12.4%. The stand age of the forest was approximately 120 years old based on calculations of allometric relations (Lee et al. 2006). The IV (%) is the sum of the relative density (%) and the relative basal area (%) divided by 2.

The *Quercus* forest is located along the upper slope of Hyoryeongbong (1560 m). A reference stand that had not suffered from the wind was investigated in 2007, and its average density was 1,230 stems/ ha (DBH >5 cm), and the average basal area was 44.2 m^2/ha. The dominant species was *Q. mongolica* (IV of 43%), followed by *T. amurensis* (16.5%) and *A. pseudo-sieboldianum* (14.2%). Another conifer, *Abies nephrolepis* (IV of 7.2%), was more common in the *Quercus* forest than in the mixed forest.

Our research area has a typical continental climate. The average annual temperature at the Daegwallyeong weather station is 6.4°C, and the average monthly temperatures range from –12.5°C (January) to 22.9°C (August). The average annual precipitation is 1,717.2 mm, with most rain falling in the summer (Korea Meteorological Administration 2008).

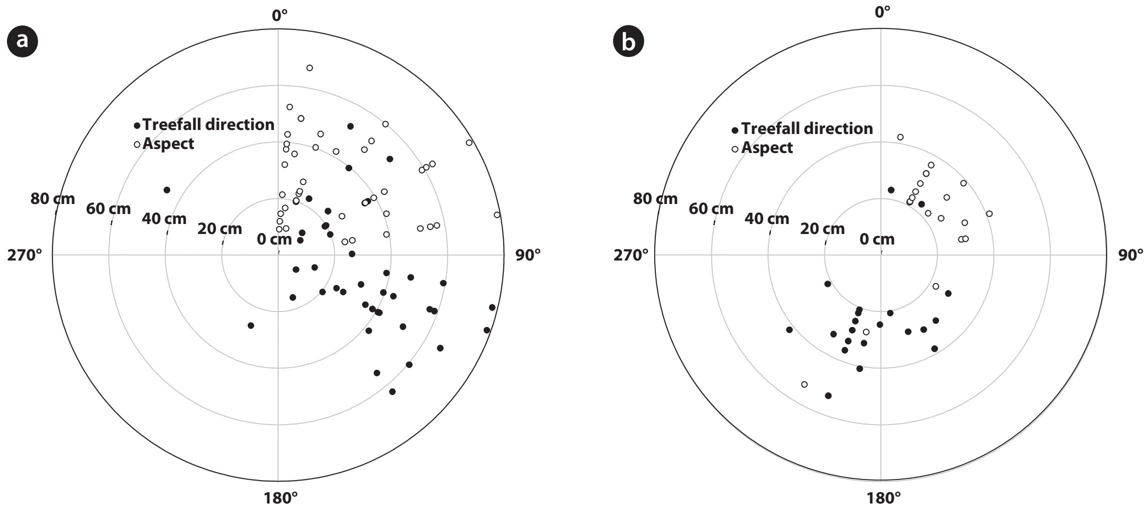

Fig. 1. Distribution of DBH and tree-fall direction for gap-maker trees. (a) mixed forest; (b) *Quercus* forest. DBH, diameter at breast height.

Measurement of forest gaps and identification of gap-maker tree species

The total number of forest gaps that formed following the storms on October 23rd and 24th of 2006 was determined for the mixed and *Quercus* forests by using data that was obtained from a survey of stems and leaves from fallen trees in March 2007. The damaged area for the mixed forest was about 15 ha. Although there is no definitive value when describing the size of a forest gap (Barden 1989), we used measurements of the bases of gap-bordering canopy trees for our estimations (Runkle 1981). For border trees, the criterion was based on trees in the canopy layer. If the height of a mid-layer tree was more than two-thirds of the average for canopy trees, it was considered to be part of the border. Gap sizes were measured by positioning the base of bordering trees via a GPSMAP 60CS (Garmin Ltd., Olathe, KS, USA).

Gap-maker trees (DBH of ≥5 cm) were defined as those that contributed to the creation of gaps because they had either been uprooted or broken directly by the wind, or were struck by neighboring trees that had fell. The species of windthrown trees were identified, their DBHs were measured with the direction in which they fell, and they were labeled as either uprooted or snapped. The elevation, aspect, and slope of each gap were determined with an altimeter, compass, and clinometer, respectively. The soil depth at each site was measured by poking a 5-mm-diameter steel pipe into the ground six times.

RESULTS

Formation of forest gaps

The topographical characteristics of the canopy gaps in the two forest types are shown in Table 1. A total of 26 gaps were confirmed in the mixed forest. They appeared on the steep northeast-facing slope (average 37°) at an elevation of 990 to 1160 m, where the soil was very shallow, i.e., 13.8 cm. Because that area was a scree, it was difficult to determine the depth to which the trees had rooted. In contrast, the *Quercus* forest had 15 gaps, which were located at 1225 to 1405 m, elevations that were higher than for the mixed forest. In the *Quercus* forest, 86% of the trees grew on the northeast-facing slope (average 30°). Although damage in

Table 1. Topographical characteristics associated with canopy gaps formed in two forest types

Site	Elevation (m)	Aspect (°)	Slope (°)	Soil depth (cm)
Mixed forest (n=26)	1044 ± 58[1] (960-1160)	39 ± 29 (5-80)	37 ± 6 (20-50)	14 ± 6 (8-25)
Quercus forest (n=15)	1342 ± 58 (1225-1405)	73 ± 59 (10-210)	30 ± 11 (10-45)	nd[2]

[1] average ± standard deviation with ranges in parentheses

[2] not determined

n, number of canopy gaps.

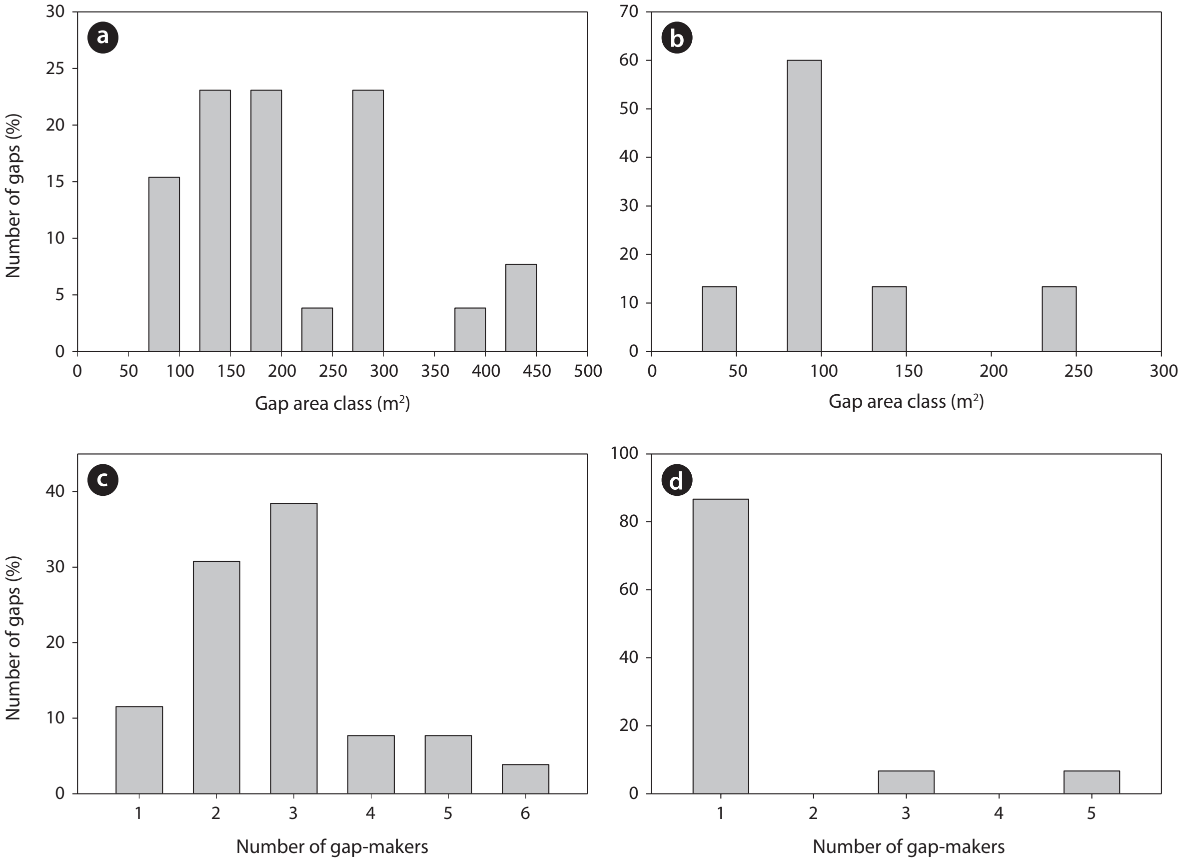

Fig. 2. Size of canopy gaps (a and b) and number of downed trees that created individual gaps (c and d). (a) and (c) mixed forest; (b) and (d) *Quercus* forest.

the mixed forest occurred mostly on the northeast slopes, 46 trees (56%) that were downed in the windstorm fell toward the southeast (Fig. 1). For the *Quercus* forest, 90% of the 21 damaged trees fell either southeast or southwest (Fig. 1).

The 26 gaps in the mixed forest covered an average area of 205 m^2 (75-442 m^2), with 73% of them being 100 to 300 m^2 in size (Fig. 2a). In contrast, the 15 gaps in the *Quercus* forest averaged 86 m^2 (23-217 m^2), with most being smaller than 100 m^2 (Fig. 2b).

A gap develops when a tree or trees in the upper canopy fall. Here, the average number of gap-maker trees was 2.8 and 1.4 in the mixed forest and *Quercus* forest (Fig. 2c and Fig. 2d), respectively. Approximately 69% of the gaps in the mixed forest was formed when two or three trees fell (Fig. 2c), while 87% of the gaps in the *Quercus* forest resulted from a single tree-fall (Fig. 2d). In the mixed forest, some gaps were formed after the collapse of six tree makers. This we attributed to the fact that broadleaf trees with multiple stems, such as the *T. amurensis*, collapsed simultaneously.

Characteristics of gap-maker species

The 26 gaps in the mixed forest resulted from the fall of 73 trees. Among these, 46 (63%) were downed by wind, while the remaining 27 were struck by neighboring trees as they fell (Table 2). The average diameter of trees directly damaged by wind was 41.5 cm compared with 25.4 cm for those that were indirectly damaged by falling trees. Most of the windthrown trees (73.9%) had thick trunks and, thus were uprooted, while those hit by neighboring trees (67.8%) had narrower trunks and, instead, were primarily snapped (Fig. 3). The 15 gaps in the *Quercus* forest were produced in response to the loss of 21 trees, all of which had fallen directly due to the wind (12 were uprooted and 9 snapped) (Table 2). The average diameter of those damaged trees was 30.4 cm.

In the mixed forest, the gap-maker trees were members of 18 species. The largest proportion (27.3%) was the *Abies nephrolepis* with 20 trees, followed by *A. holophylla* (11 trees, or 15.1%) (Fig. 4a). These two species accounted for 85.0% to 90.9% of the tree-falls directly related to wind,

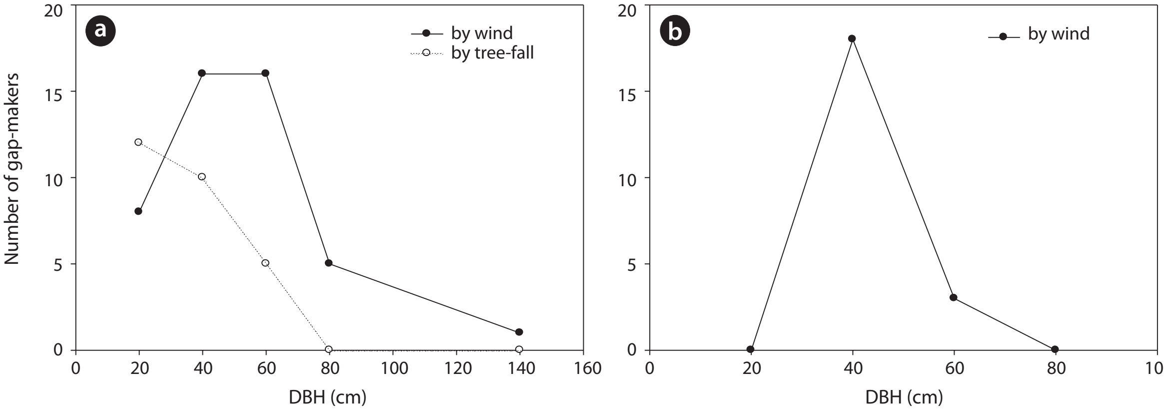

Fig. 3. DBH distribution of gap-maker trees that either fell in direct response to wind or were struck by neighboring tree. (a) mixed forest; (b) *Quercus* forest. DBH, diameter at breast height.

and their frequencies were much higher than any other species in that forest type. Only one species, *A. nephrolepis*, was a gap maker in the *Quercus* forest, and all fell directly due to the wind (Fig. 4b). Trees of that species also had the largest basal area of 2.9 m^2, followed by *A. holophylla*'s basal area of 2.4 m^2. Although the number of *A. nephrolepis* trees was similar in both the *Quercus* and the mixed forests, their average basal area was only 1.6 m^2 in the mixed stand.

Of the gap-maker trees in the mixed forest, 60% of *A. nephrolepis* and 82% of *A. holophylla* were uprooted, indicating their susceptibility to such damage (Fig. 4c). Even though *T. amurensis* is a deep-rooted deciduous species, many of them were either directly damaged by wind or

Table 2. Causes of tree-fall and death of trees in two forest types

Site	Cause	Wind		Neighboring tree-fall	
		No. of trees (%)	DBH (cm)[1]	No. of trees (%)	DBH (cm)[1]
Mixed forest	Uprooting	34 (73.9)	40.3 ± 19.7	6 (22.2)	27.0 ± 15.2
	Snap-off	12 (26.1)	44.8 ± 31.4	21 (77.8)	24.9 ± 11.9
	Total	46 (100.0)	41.5 ± 23.0	27 (100.0)	25.4 ± 12.4
Quercus forest	Uprooting	12 (57.1)	31.6 ± 7.0		
	Snap-off	9 (42.9)	28.8 ± 10.0		
	Total	21 (100.0)	30.4 ± 8.3		

[1] average ± standard deviation
DBH, diameter at breast height.

Table 3. Species composition of gap-maker trees directly damaged by wind in mixed forest compared with population in nearby undisturbed reference forest (DBH ≥5 cm)

Species	Gap-makers			Reference forest		
	Density (No. of stems)	Relative density (%)	Mean DBH (cm)	Density (No. of stems/ ha)	Relative density (%)	Mean DBH (cm)
Abies nephrolepis	17	37.0	41.2	2	0.2	50.6
Abies holophylla	10	21.7	51.0	54	6.4	19.2
Tilia amurensis	7	15.2	31.2	95	11.4	24.1
Acer mono	3	6.5	29.8	37	4.4	19.2
Acer tegmentosum	2	4.3	15.8	63	7.5	11.2
Quercus mongolica	2	4.3	94.2	13	1.6	48.6
Betula schmidtii	2	4.5	44.0	7	0.8	40.8
Acer pseudo-sieboldianum				219	26.1	9.0
Others	3	6.5	27.7	347	41.7	13.8
Total	46	100.0	41.5	837	100.0	15.4

DBH, diameter at breast height.

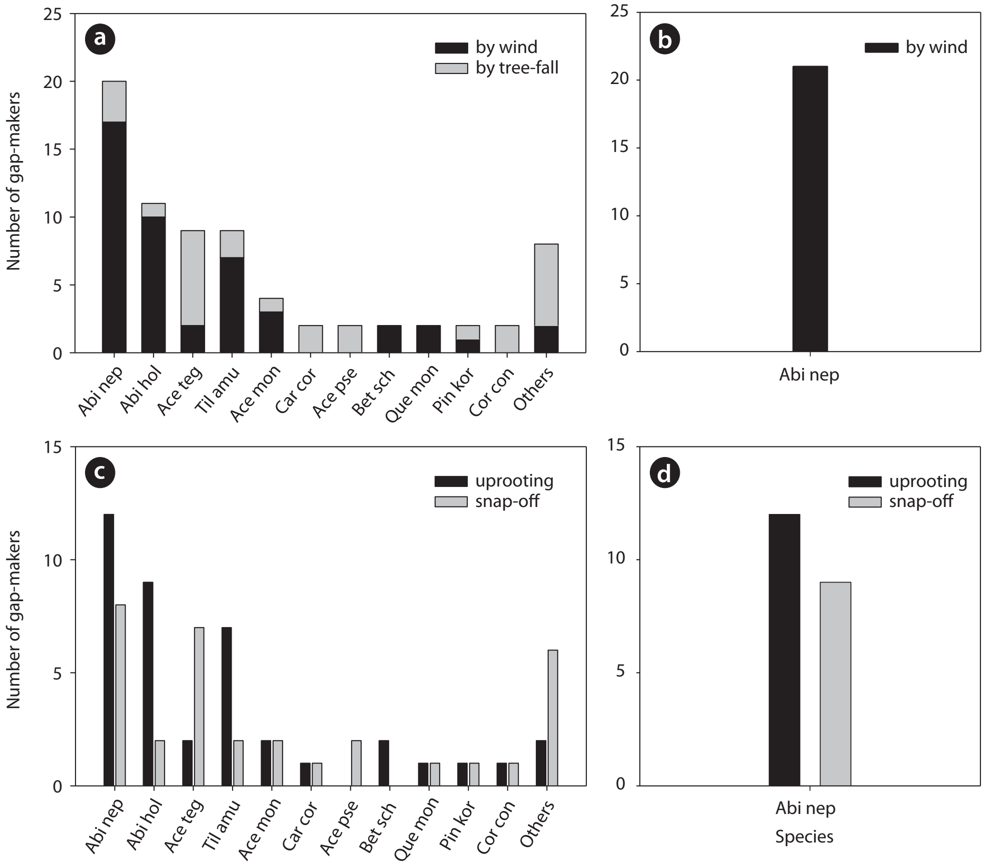

Fig. 4. Species-specific causes of death based on number of gap-maker trees (a, b) and type of damage (c, d). (a) and (c) mixed forest; (b) and (d) *Quercus* forest. Abi nep, *Abies nephrolepis*; Abi hol, *Abies holophylla*; Ace mon, *Acer mono*; Ace pse, *Acer pseudo-sieboldianum* Ace teg, *Acer tegmentosum*; Bet sch, *Betula schmidtii*; Car cor, *Carpinus cordata* Cor con, *Cornus controversa*; Pin kor, *Pinus koraiensis*; Que mon, *Quercus mongolica*; Til amu, *Tilia amurensis.*

uprooted. This was due to their clumping habit, in which multiple stems develop when trees re-sprout following a disturbance. The proportion of *A. nephrolepis* trees that were uprooted by wind (57%) was similar between the *Quercus* forest and the mixed forest (Fig. 4d).

To investigate whether particular tree species are more vulnerable to wind damage, we compared species composition between our designated windthrown forests and nearby undamaged reference plots. The relative density of *A. pseudo-sieboldianum* was very high at the reference

Table 4. Species composition of gap-maker trees directly damaged by wind in *Quercus* forest compared with population in nearby undisturbed reference forest (DBH ≥5 cm)

Species	Gap-makers			Reference forest		
	Density (No. of stems)	Relative density (%)	Mean DBH (cm)	Density (No. of stems/ha)	Relative density (%)	Mean DBH (cm)
Abies nephrolepis	21	100.0	30.4	90	7.3	19.2
Quercus mongolica				360	29.3	26.9
Acer pseudo-sieboldianum				295	24.0	8.5
Tilia amurensis				225	18.3	16.6
Betula schmidtii				50	4.1	21.9
Sorbus commixta				45	3.7	11.4
Pinus koreansis				45	3.7	18.9
Others				120	9.8	13.3
Total	21	100.0	30.4	1230	100.0	17.7

DBH, diameter at breast height.

sites for the mixed forest, followed by *T. amurensis* (Table 3). In contrast, the relative density for the gap-makers *A. nephrolepis* and *A. holophylla* was 39% and 23%, respectively, which was different from their calculated 0.2% and 6.4%, respectively, in the reference forest.

In the reference plots for the *Quercus* forest, *Q. mongolica* dominated, followed by *A. pseudo-sieboldianum* and *T. amurensis*. Although *A. nephrolepis* accounted for just 7.3% of the total, only trees of that species were damaged, leading to the formation of gaps in the damaged *Quercus* forest (Table 4).

DISCUSSION

The types of vegetation that become established in particular regions depend upon numerous factors, such as parental rock materials or topography, as well as the opportunities that make species distribution amenable. Even under similar environmental conditions, forests in a certain area can comprise of a mosaic of stands with different successional stages and vegetation types. This results from not only natural or artificial methods of regeneration, but also from large- or small-scale disturbances, the frequencies of those events, and the ways in which sites recover from such challenges.

The forests within Odaesan National Park are heterogeneous, but trees of at least 100 years old are widely distributed here, suggesting that large-scale harvests or forest fires have not taken place for the time being. This assumption is based on signs of selective logging for certain species and scattered clumps that have regenerated via sprouting. Fires might have been a threat in the past; however, at present it probably is not true in that park because the most common species on that mountain have proven to be highly resistant (Choung et al. 2004). Furthermore, these forests have been protected by rigorous forest management policies since the 1970s (Odaesan National Park Service 2008). Therefore, natural mortality and occasional high winds are the major disturbances that now form canopy gaps. The development of such gaps is largely a function of forest type, the prevailing disturbance regime, and geographical location (Foster 1988). Daegwallyeong, an area that borders this park, is known in Korea for having very strong winds (average speed of 5.8 m/ s), a velocity that is second to Jeju Island's 8.9 m/s (Kim 2005). Because of that, the region is now the site of a wind farm. The high frequency and strength of these winds mean they have the potential to also cause major disturbances. Odaesan National Park is topographically vulnerable to wind damage because of its high elevation, steep slopes, and shallow soils on numerous scree sites. Moreover, when strong winds are accompanied by heavy rainfall, as it happened in October of 2006, the saturated soil becomes unstable, causing tall trees to fall, as they act as masts (Clinton and Baker 2000).

In both of our forest types, canopy gaps tended to form on the slopes, suggesting that such locations are more affected by strong winds than mountain ridges or flat areas (Kim 1996). The direction in which gap-makers fall is influenced by topography and the type and extent of the disturbance (Cho 1992). In particular, because trees on flat land are considerably affected by wind direction, they tend to fall in a certain direction that makes it possible to estimate the severity of a particular disturbance (Falinski 1978). When no specific disturbance has occurred, however, the fall direction is largely influenced by topography. Cho (1992) showed that in the neighboring area of Gwangneung Natural Forest at Soribong, most of the dead trees fell along the slope aspect in the absence of any disturbance. However, we found that trees growing on northeast-facing slopes in our mixed and *Quercus* forests tended to fall primarily to the southeast (86%) and southwest (90%), respectively. This suggested that the direction of tree-fall is affected more by wind rather than the slope.

Gap sizes in the mixed forest averaged 205.0 m^2 (75-442 m^2). This is approximately similar to the 246 m^2 reported from a study of deciduous broadleaf trees in a mature forest at Gwangneung (Cho 1992), where the vegetation structure was almost the same as what we recorded in our current survey. In contrast, our *Quercus* forest had gaps averaging 86 m^2 (23-217 m^2), which was less than half the size of those measured in our mixed forest. We might attribute this variation to the difference in the number of gap-makers per gap, i.e., 2.8 in the mixed forest compared with 1.4 in the *Quercus* forest. Because the canopy of a single large tree covers 30-40 m^2 (Park 2001), the gaps formed in our forest types could be considered relatively large (given the number of tree-falls) and might be related to species, height, and age. Trees of *A. nephrolepis* were the most frequently damaged in both forest types, even though the mixed forest also included many specimens of *A. holophylla*. Trees of the latter species can be 30 m tall (Kim 2006). They also tend to take up more air space because they have larger canopies. In fact, the reason that the mixed forest had more gap-makers was because trees that were downed by strong winds there created a chain reaction that caused the other trees to fall along the slope. This was especially true for taller trees of *A. holophylla*, which were more heavily damaged on steeper slopes that comprised mostly of stony soils.

In the mixed forest, the majority of windthrown gapmakers belonged to *A. nephrolepis* (38.6%) and *A. holophylla* (22.7%). However, in its reference, i.e., the undamaged forest nearby, *A. holophylla* accounted for 6.4% and *A. nephrolepis* for only 0.2% of all trees, while the remainder was broadleaf species such as *A. pseudo-sieboldianum* and *T. amurensis*. This suggested that the two *Abies* species are more susceptible to wind damage. Altogether, 60.0% of the *A. nephrolepis* and 81.8% of the *A. holophylla* trees were uprooted; these are rates much higher than for any other tree species at that location. In studies conducted on the same forest, the method of death has varied by species (Kanzaki and Yoda 1986) and those that were shallow-rooted have been easily uprooted (Ruel et al. 2001). Thus, considering the lack of deep soil on our study sites, it is not surprising that those two shallow-rooted species (mean rooting depth of 138 cm for *A. holophylla* in the mixed forest) would be more susceptible to windthrow (Lee et al. 2006, Jeon 2009). Clinton and Baker (2000) have demonstrated that large trees are more prone to falling because they act as masts in very windy conditions. Here, the average diameter for trees downed directly by wind was larger than for those of the same species that were growing in the undisturbed reference forests. For *A. nephrolepis*, we cannot conclude the same because we were unable to make any valid comparisons due to the reference forest having only two trees of that species.

The undamaged sites within the *Quercus* forest were dominated by several broadleaf species, e.g., *Q. mongolica, A. pseudo-sieboldianum*, and *T. amurensis*, whereas *A. nephrolepis* occupied only 7.3% of the total density. Nonetheless, trees of that coniferous species, with their larger stem diameters, succumbed to windthrow more frequently, most likely due to morphological characteristics already discussed for the mixed forest.

A singularly strong wind accompanied by a blast of rainfall selectively uprooted trees of *A. nephrolepis* and *A. holophylla* at Odaesan National Park. These shallow-rooted conifers were growing in an area where the soil was shallow. Those conditions contributed to their falling in relatively higher proportions compared with other species on those sites. A secondary cause of death was having their branches broken when nearby broadleaf trees fell during the storm. Nagel and Diaci (2006) found that *Abies alba* was more susceptible than *Fagus sylvatica* to intermediate wind disturbance in Slovania. However, they discussed that tree size (DBH) was more important than the species. In a way, this is consistent with our study in that for some species, larger trees were more susceptible. However, *Q. mongoica* and *B. schmidtii*, that were thicker than those of reference forests had no windthrow at all.

Therefore, we think that the susceptibility of the *Abies* species is a combined result of species, tree size (particularly height) and rooting depth, even though we cannot support this argument statistically due to the small number of trees.

Such small-scale disturbances alter site conditions and change the levels of resources, including light and moisture available for the remaining trees to grow. These scenarios also lead to the rapid regeneration of the existing canopy species or saplings and seedlings that are found in the understory layer according to the gap size.

Overall, these findings suggest that *A. nephrolepis* and *A. holophylla* are particularly susceptible to high winds because of their great heights and shallow root systems.

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