Grana
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/sgra20

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Published online: 06 Oct 2011.

To cite this article: Yong-Joo Cho , In Sung Kim , Pan-gi Kim & Eun Ju Lee (2003) Deposition of airborne pine pollen in a temperate pine forest , Grana, 42:3, 178-182, DOI: 10.1080/00173130310016158

To link to this article: http://dx.doi.org/10.1080/00173130310016158

Grana 42: 178–182, 2003

Deposition of airborne pine pollen in a temperate pine forest

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Cho, Y.-J., Kim, I. S., Kim, P.-G. & Lee E. J. 2003. Deposition of airborne pine pollen in a temperate pine forest. – Grana 42: 178–182. ISSN 0017-3134.

Deposition of airborne pine pollen was examined in a temperate pine forest, Korea. Durham gravity pollen collectors were employed to measure amounts of pine pollen deposition in the field and macronutrients input by pine pollen was analyzed in the laboratory. In 1999, pine pollen deposition began just before May 4th and lasted for about three weeks. In 2000, pollen anthesis started May 5th and lasted over three weeks. Two species of pine differed in the timing of pollen release, with *Pinus rigida* beginning pollen release a few days earlier than that of *P. densiflora*. Pine pollen release dates varied between years, occurring earlier in years with warmer spring temperatures. Annual pine pollen deposition was slightly different over the two sampling years; 11.2 kg/ha (ca. 4975 grains/cm^2) in 1999 and 9.2 kg/ha (ca. 4097 grains/cm^2) in 2000. The values of nutrient deposition from airborne pine pollen were 232 g/ha N, 30 g/ha P, 109 g/ha K, 23 g/ha S, 10 g/ha Mg in 1999 and 196 g/ha N, 19 g/ha P, 70 g/ha K, 13 g/ha S, 6 g/ha Mg in 2000. Our values were about 1/300 that of pine litterfall. The contribution rate of pine pollen in annual nutrient input was about N 1/76, P 1/16 and K 1/23 that of litterfall. These values suggest that nutrient input from airborne pine pollen is small compared to that from known litterfall, highly episodic pine pollen deposition suggests that pine pollen may play a disproportionately role in the temperate pine forest nutrient input.

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(*Manuscript received 4 December 2002; accepted 9 May 2003*)

In many boreal and temperate forest ecosystems, large quantities of pine pollen deposit over a short period in spring and/or summer (Stark 1972, Saito & Takeoka 1985, Sekiguchi et al. 1986, Doskey & Ugoagwu 1989, Lee et al. 1996 *a*, *b*). Because pollen grains decompose rapidly and have high macronutrients, the pollen rain may be an important component of nutrient dynamics in natural terrestrial and aquatic ecosystems (Stark 1972). In jack pine (*Pinus banksiana*) stands of Canada, annual pollen rain provided up to 0.45 kg/ha of N, 0.065 kg/ha of P, and 0.186 kg/ha of K (Lee et al. 1996 *a*). Jack pine begins to produce male strobili at five to ten years of age (Rudolph & Laidly 1990). Pine pollen is rich in nutrients and may contribute up to one third of the nutrients cycled in some pine forest ecosystems (Maggs 1985). In Jeffrey pine (*Pinus jeffreyi*) forests of montane Nevada, Stark (1972) found pollen to be a critical source of macronutrients to the soil litter fermentation layer during the dry, summer months. Doskey & Ugoagwu (1989) determined that pine pollen was an important source of macronutrients to oligotrophic lakes in northern Wisconsin.

Despite these studies, pollen has generally been overlooked in many studies of forest nutrient cycling. Foster & Morrison (1976) did not consider pollen in their model of nutrient dynamics in the boreal jack pine forest, despite the fact that jack pine produces considerable quantities of pollen annually. Stark (1972) reported that the input of macronutrient from pollen was found to have a trigger effect on nutrient dynamics by promoting litter decomposition and increasing nutrient uptake rates. However, limited information is available on the quantities of airborne pine pollen deposition in the temperate forest itself (Saito & Takeoka 1985, Sekiguchi et al. 1986).

This study was designed to examine the atmospheric deposition of airborne pine pollen in a temperate forest, Korea. Annual pine pollen deposition was determined in a regenerating pine stand in Seoul, Korea. We estimated annual pollen macronutrient fluxes based on measured daily pollen deposition rates. We also estimated the macronutrient contents in pine pollen and discussed the possible importance of pine pollen to the temperate pine forest nutrient cycling.

MATERIAL AND METHODS

Study sites

The study area is located on the foothill of Mt. Kwanak in west-central Korea, about 12 km south of the city center of Seoul (37°27′N, 126°58′E). It is located in a suburban area and is recently influenced by urbanization. The size of a mixed temperate forest stand is about 3 ha. Mean elevation is about 225 m above the sea level. The study site lies on the northwest-facing slope of a small hilly mountain. The climate is temperate and growing season extends from March to October. Mean annual precipitation is 1340 mm, and its mean annual temperature is 13.2°C. More than half of precipitation occurs in summer (June–August) and winters tend to be dry-cold, reflecting a typical continental weather pattern. Weather statistics were based on data from the Seoul weather station, approximately 12 km north of the study site.

Vegetation survey

Forest stand information along the stand was determined using the point-centered quarter method (Mueller-Dombois & Ellenberg

1974). Fifty points were located at 10 m intervals along each stand. At each point the distance to, and basal area of the nearest tree (>2.5 cm in diameter and >2 m in height) in each of four quadrants were measured. A total of 200 trees and tall shrubs were enumerated. The study area lies on granitic rocks. Soils are generally thin with a weakly developed topsoil profile. The region lies within Sino-Japanese floristic section (Good 1953). Within the study area, Pitch pine (*Pinus rigida* Miller) and Japanese red pine (*Pinus densiflora* S. et Z.) are the co-dominant trees on the poorly developed soils. Black locust (*Robinia pseudoacacia* L.) and Korean mountain ash (*Sorbus alnifolia* K. Koch) grow at the edge of the forest. *Pinus rigida* and *P. densiflora* trees are 6–10 and 8–14 meters high with mean diameter of 15 cm and 17 cm at breast height, respectively.

Pollen deposition

Pine pollen deposition along transect was determined over two years. In 1999, sampling was undertaken from May 4th to May 24th, and *Pinus densiflora* and *P. rigida* pollen deposition was determined. The sampling period was extended in 2000 (May 4th to May 28th). Raw data and voucher slides from the 1999 and 2000 field season are available from Dr. E. J. Lee, School of Biological Sciences, and Seoul National University. Thirty gravity pollen collectors were established along transect.

Direct daily observation of collected catkins and male cones were made to determine the timing of pine pollen release. Durham gravity pollen collectors were employed in this study. This sampling device is approved by the National Pollen Survey Committee as standard for sampling atmospheric pollen by the gravity (Durham 1946). These collectors were chosen instead of mechanical devices because of: (i) cost; (ii) inaccessibility to power for mechanical samplers; (iii) need for uninterrupted data collection; (iv) likelihood of animal damage. The Durham pollen collector consists of two horizontal disks (23 cm in diameter, 15 cm apart), with the lower disk located 10 cm from ground level. A standard 2×8 cm glass slide covered with a thin film of petroleum jelly was placed on the lower disk to collect pollen. Slides were exposed for 24 hours and kept in a tightly sealed slide box before and following exposure to prevent contamination, and were examined under a stereomicroscope ($\times 100$ magnification) to identify pollen and estimate pollen numbers. Pollen deposition was determined by counting all grains within a randomly selected area of 0.25 cm^2. Amounts of pollen rain were expressed as the number of pollen grains per square centimeter. The mean volume of fifty air-dried grains for pine pollen was determined by measuring (a) length, (b) width, (c) depth of air-dried pollen, and then calculated with the equation of $4/3\pi abc$. Pollen mass was then determined from the mean volume estimates and the measured mass of 50 ml of air-dried pollen. In a 50 ml pollen container, we estimated 52.2% of the volume filled by pollen and 47.8% by space from geometrical calculation. Individual grain mass was then obtained from known mass and volume of 50 ml air-dried pollen. Pollen counts and mass were used to determine annual pollen deposition.

Pollen macronutrient analysis

Three replicate samples of 1g of air-dried *P. densiflora* and *P. rigida* pollen were collected and fresh pollen samples were obtained in the field, by gently shaking a branch (containing male cones) to which a plastic bag had been attached. Air-dried pollen samples were analyzed for nitrogen, phosphorus, potassium, sulphur and magnesium at National Instrumentation Center for Environmental Management. Total nitrogen was determined by Kjeldahl digestion method. The total P, S, K and Mg were determined using an inductively coupled plasma emission spectrometer (ICPS-1000IV, Shimadzu, Japan) after acid digestion (Sparks 1996).

Table I. *Composition of a temperate pine forest in Mt. Kwanak, Korea.*

Based on n = 200 trees.

Species	Proportion of individuals (%)	Total basal area (cm^2/ha)	Relative basal area (%)
Pinus rigida	50.5	12690	49.8
P. densiflora	32.5	10662	41.8
Robinia pseudoacasia	6.0	852	3.3
Sorbus alnifolia	3.5	409	1.6
P. koraiensis	2.5	63	0.5
Quercus mongolica	2.0	464	1.8
Q. serrata	1.5	209	0.8
Taxodium distichum	0.5	88	0.3
Ulmus parvifolia	0.5	29	<0.1
Q. aliena	0.5	1	<0.1

RESULTS

Tree frequencies and basal area values in the study area are summarized in Table I. The common tree species are *Pinus rigida*, *P. densiflora* and *Robinia pseudoacacia* in descending order. *P. rigida* accounted for 49.8% of total basal area in the study area. *P. densiflora* was co-dominant tree (41.8%) and *R. pseudoacacia* accounted for 3.3%. *Quercus mongolica* and *Q. serrata* accounted for 2.6% in total.

Slightly warmer spring weather conditions in 1999 resulted in earlier pollen deposition than in 2000 (Table II, Fig. 1). In 1999, pine pollen deposition began just before May 4th and lasted for about three weeks. In 2000, pollen anthesis started May 5th and lasted about three weeks. Unfortunately we missed the very beginning of pollen deposition in 1999 due to abrupt air temperature rise and unexpected pollen shedding. If we took this into account, the possible pollen deposition started a few days before May 4th 1999 and amounts of pollen deposition must be greater than what we showed.

Table II. *Mean monthly temperature, precipitation and growing degree-days (temperature > 5°C) for April and May 1998–2000 at Seoul and corresponding normal values for the 30-year period 1968–1997.*

Month	Variable	1998	1999	2000	Normal 1968–97
April	Temperature (°C)	15.6	13.9	11.9	12.2
	Precipitation (mm)	120.2	97.2	30.7	71.2
	Growing degree-days	294.9	266.9	206.3	209.1
May	Temperature (°C)	19.0	17.5	17.5	17.6
	Precipitation (mm)	121.5	109.7	75.2	103.4
	Growing degree-days	451.4	403.5	387.3	412.8

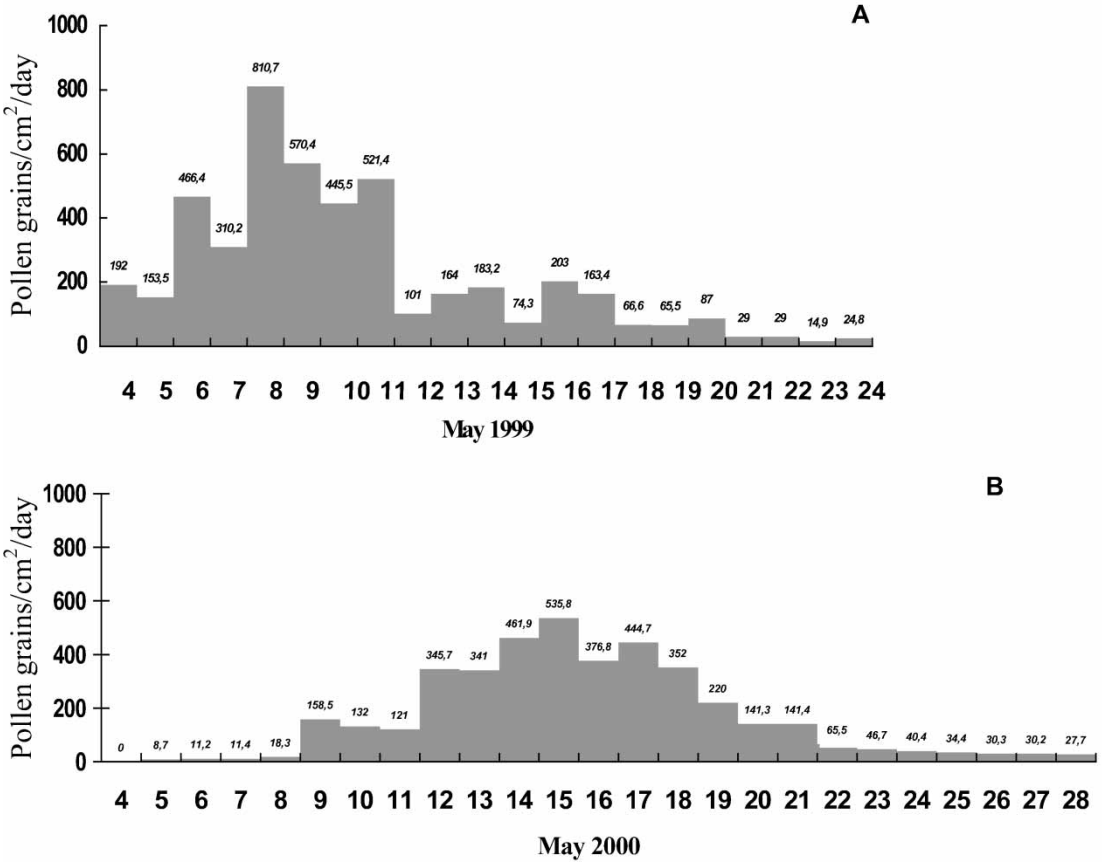

Fig. 1. Pine pollen deposition (grains/cm^2/day) in: a) 1999; b) 2000. The collections were made every 24 hours.

Pine pollen deposition pattern was somewhat different in years 1999 and 2000. Pine pollen deposition started in early May with yearly peak deposition on May 8th in 1999 (810 grains/cm^2/day) and May 15th in 2000 (536 grains/cm^2/day). The two pine species differed in the timing of pollen release, with *P. rigida* starting the pollen release one or two days earlier than *P. densiflora*. The shape and size of two pine pollen grains are quite similar, so no attempt was made to distinguish two pine pollen in counting. The pollen size of *P. rigida* (47.2 μm) is slightly larger than that of *P. densiflora* (44.6 μm). Large quantities of pine pollen were liberated over about 10–14 days, with peak deposition occurring on warm, sunny days.

Nitrogen is the most abundant macronutrient in *P. rigida* and *P. densiflora* pollen, followed by potassium, phosphorus, magnesium and sulphur (Table III). Macronutrient concentrations showed little variation from year to year but pine pollen collected in 1999 showed 1.3–1.4 times higher concentrations in phosphorus and sulphur than those of 2000. Except phosphorus *P. rigida* pollen showed higher macronutrient concentrations than those of *P. densiflora*.

Total pine pollen deposition was different over the two sampling years, about 11.2 kg/ha (ca 4925 grains/cm^2) in 1999 and about 9.2 kg/ha (ca 4097 grains/cm^2) in 2000. Macronutrient deposition by pine pollen in the two sampling years is illustrated in Table IV. Total macronutrient deposition was 1.2 times higher in 1999. The nutrient inputs as pine pollen were about 232 g N/ha, 109 g K/ha, 30 g P/ha in 1999 and about 196 g N/ha, 70 g K/ha, 19 g P/ha in 2000. Nitrogen and potassium make the greatest contribution.

DISCUSSION

Annual pine pollen deposition was estimated as about 11.2 and 9.2 kg/ha in the study site for the two sampling years. These values are similar with about 7.7–9.0 kg/ha in a pine-spruce-poplar mixed forest in Manitoba, Canada (Lee et al. 1996 *a*), and also fall within the broad 3.5–80.0 kg/ha range estimated for white pine and red pine (*P. strobus*, *P. resinosa*) stands in northern Wisconsin (Doskey & Ugoagwu 1989). But these values are greater than the 0.9–3.0 kg/ha range reported for Jeffrey pine (*P. jeffreyi*) stands in Nevada (Stark 1973) and lower than 19.6–24.6 kg/ha obtained by Lee et al. (1996 *a*) in two 25-year-old jack pine (*P. banksiana*) stands in Manitoba, Canada. However, our values are much lower than 55–96 and 89–170 kg/ha in *Pinus densiflora* forests in Japan (Saito & Takeoka 1985, Sekiguchi et al. 1986). The discrepancies in pine pollen production and deposition values in Japan and Korea may come from the estimation method. The Japanese values are obtained from counting male cone number and amount of pollen in it before the anthesis, but Korean values are obtained from measuring direct pine pollen deposition in the forest

Table III. *Macronutrient concentrations (mg/g) in pine pollen collected from the study area.*

Values indicate means ± SD (n = 3).

Year	No.grains/cm^2 (range)	Deposition (kg/ha)	N	P	K	S	Mg
1999	4925 ± 1693 (1970 – 8120)	11.2	232.3	29.9	108.8	22.7	9.8
2000	4097 ± 1251 (1295 – 5995)	9.2	196.0	19.2	70.2	12.8	6.4

Table IV. *Annual pine pollen deposition in a temperate pine forest and macronutrient input (g ha^{-1}) by pine pollen in the study area.*

Species	Year	N	P	K	S	Mg
Pinus densiflora	1999	19.9 ± 0.17	2.8 ± 0.01	8.7 ± 0.02	1.6 ± 0.03	0.8 ± 0.04
	2000	18.4 ± 0.23	2.1 ± 0.02	7.0 ± 0.11	1.1 ± 0.05	0.6 ± 0.39
P. rigida	1999	21.6 ± 0.08	2.5 ± 0.01	10.7 ± 0.14	2.4 ± 0.02	1.0 ± 0.08
	2000	21.1 ± 0.32	2.1 ± 0.04	8.2 ± 0.10	1.7 ± 0.08	0.9 ± 0.33

floor during pine anthesis. The amount of pollen intercepted by the tree trunk and leaves in the process of deposition and carried-out pollen could be liable for the discrepancies. Moreover, we have to consider pollen dispersal distance and pattern in- and outside the forests. Buell (1947) reported that there was a gradual decrease in the amount of pollen deposition with increasing distance from the source trees. We believe, that considerable number of pine pollen is carried out from our relatively small study site.

Pine pollen release varied between years, reflecting differences in air temperature in April and early May. Previous studies have found that the timing and extent of pollen release is strongly dependent on ambient air temperature (Boyer 1973, Bringfelt et al. 1982). In the study area large quantities of pine pollen were liberated over a short period (2 – 3 weeks), with the peak pollen deposition on May 8th, 1999 and May 15th, 2000. In Manitoba (Canada), pine pollen anthesis lasted for 10 – 14 days and peak deposition during June 3 – 12. Annual variations in amount and duration of pollen production are reported in several studies (Saito et al. 1991, Lee et al. 1996 *b*). Saito & Takeoka (1985) found that in Japan pollen production rates ranged from 55 to 96 kg/ha/yr in a 35-year-old *Pinus densiflora* forest during 1979 – 1983. Sekiguchi et al. (1986) also reported that the annual pollen production in 1983 (170 kg/ha/yr) was about double that of 1982 (89 kg/ha/yr) in an 85-year-old *Pinus densiflora* forest in Japan.

High tree pollen production often occurs in years following a warm, dry spring and summer (Hyde 1952). Our observation of higher amounts of pine pollen in 1999 than 2000 is consistent with this finding. Total growing degree-days (temperature > 5°C) from April to May 1998 were ca 746, compared with 670 for the same period in 1999. However, additional years of pollen deposition data are needed to confirm this assumption. Our field observation showed that pollen deposition occurred mainly in the afternoon, when temperature is high and relative humidity is low.

Pollen macronutrient concentrations are similar between *Pinus rigida* and *P. densiflora*. Total macronutrient levels in *P. rigida* and *P. densiflora* are generally similar to pollen of other pine species (e.g., *P. banksiana* in Canada). Even though the difference is not apparent in the study area, the sulphur concentration is higher (ca. 200%) and phosphorus concentration lower (ca. 80%) in *P. rigida* and *P. densiflora* pollen than in the pollen of other pine species. These differences may depend on the soil quality and the different nutrient uptake, but further studies are needed to elucidate this fact.

Chang & Ko (1982) reported that *Pinus rigida* stands in the study area delivered 3157 kg of litterfall annually and this value was equivalent to N 16.4 kg/ha, P 0.4 kg/ha and K 2.1 kg/ha. Corresponding values for nutrient deposition by pollen (9.2 – 11.2 kg/ha/yr) are N 0.20 – 0.23 kg/ha, P 0.02 – 0.03 kg/ha and K 0.07 – 0.11 kg/ha, suggesting that pine pollen contributes relatively little to the overall stand nutrient dynamics. But it must be recognized however, that pollen deposition occurs over a brief, three-week period in May. Previous study showed that the majority of water-extractable pine pollen macronutrient was solubilized within 24 hours in water (Lee et al. 1996 *a*). Stark (1972) concluded that pine pollen grains were broken down within two months suggesting that pine pollen must be an important source for macronutrients during the critical early growing period. In the study of *P. densiflora* canopy through fall and stem flow, Kim (1994) noted "increasing of large quantities of macronutrients from May to August samples…" and did not give an explanation on this abrupt increase. In his study, Mg amount peaked in samples collected in June and July. Foster (1974) reported "leaching of large quantities of potassium from pollen, which contaminated some of precipitation samples during May and June" and excluded it from further analysis.

Stark (1972) reported that pine pollen enhanced decomposition by providing an early-summer macronutrient pulse to decomposers in the litter fermentation layer. He also noted that after the spring pollen rain, the fermentation layer showed an increase in nitrogen and phosphorus. Amounts of nutrient in pollen, which added to the temperate pine forest floor are not likely to be significant to tree growth directly. In Stark's study, the total potential elemental input of litter/ha/yr is 615

times of that of pollen (for the 10 elementals studies). But in his study, pollen deposition was only 0.9 – 3.0 kg/ha/yr in the Jeffrey pine stand in Nevada. In the temperate *P. rigida* forest in the study area, pine tree delivered 3157 kg/ha of litter fall and N 16.4 kg/ha, P 0.4 kg/ha, K 2.1 kg/ha (Chang & Ko 1982). This value of our study (9.2 – 11.2 kg/ha/yr) is about 1/280 – 340 times of *P. rigida* litter fall at the study area. If we consider pine pollen nutrients into account, the contribution rate of the pine pollen in annual nutrient input is higher in our study (N 1/71 – 82, P 1/13 – 20, K 1/19 – 30 that of litter fall).

Hutchison & Barron (1997) showed that many lignicolous fungi are capable of degrading pollen. Lee (2000) reported that pine pollen nutrients are of value to ectomycorrhizal fungal growth. Therefore, the annual contribution of nutrient mass by pine pollen is small compared to that of litter fall in a temperate pine forests. The rapid turnover rate of pine pollen nutrients combined with episodic deposition suggests that pine pollen may provide considerable amount of macronutrients into temperate pine forests nutrient cycling.

Further studies should be carried out toward acquiring a better understanding on the role of pine pollen rain in the temperate forest ecosystems.

CONCLUSIONS

1. Pine pollen release dates varied between years, occurring earlier in years with warmer spring temperatures.
2. Two pine species differed in the timing of pollen release; the pollen release of *Pinus rigida* starting a few days earlier than that of *P. densiflora*.
3. Pine pollen deposition was slightly different over the two sampling years, 11.2 kg/ha (ca. 4975 grains/cm^2) in 1999 and 9.2 kg/ha (ca. 4097 grains/cm^2) in 2000 in a temperate pine forest, Korea.
4. Pollen macronutrient concentrations are similar between *P. rigida* and *P. densiflora*. Total macronutrient levels in *P. rigida* and *P. densiflora* are generally similar to the pollen of other pine species (*P. banksiana* in Canada).
5. The values for pine pollen nutrient deposition in 1999 are: N – 232 g/ha, K – 109 g/ha, P – 30 g/ha, S – 23 g/ha, Mg – 10 g/ha; In 2000: N – 196 g/ha, P – 19 g/ha, K – 70 g/ha, S – 13 g/ha, Mg – 6 g/ha.
6. Our results show that the pine pollen deposition is about 1/280 – 340 that of pine litter fall in biomass. The contribution rate of pine pollen in annual nutrient input is for N 1/76, P 1/16 and K 1/23 that of litter fall.
7. These results are suggesting that nutrient input by pine pollen is small compared to that of litter fall. Highly episodic pine pollen deposition suggests that pine pollen might be important in the temperate pine forest cycle.

ACKNOWLEDGEMENTS

This study was supported by Brain Korea 21 fund and Seoul National University research fund to E. J. Lee and Y.-J. Cho.

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