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Original article

Prediction of abundance of ants due to climate warming in South Korea

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ABSTRACT

Among the 57 species of ants collected from 366 forest sites, 16 candidate species whose abundance has a close relation with temperature were selected to predict the changes in distribution and abundance according to the A1B climate change scenario. The results showed that, when the temperature rises, the abundance of 11 species is expected to decrease, whereas five species are expected to increase. Based on the qualitative estimation, the abundance of 10 species among the 31 species is predicted to increase, whereas that of 21 species is projected to decrease. The abundance of 32 species among 57 species was expected to decrease due to climate changes, whereas 15 species was expected to increase; the number of species expected to decrease was more than two times that of species that are expected to increase.

Introduction

As environmental changes due to climate warming have recently become known as serious problems, social demands for studies focusing on the influences of climate changes on the ecosystem have gradually increased (Choi and Choi, 2011). The first step for such climate change impact research is to select indicator species suitable for the research. For insects, research studies have been most actively conducted on butterflies. Although there were many attempts to study other insects such as beetles, significant results like those found in butterflies have not yet been produced. Ants are very likely to be an indicator species for monitoring environmental changes owing to their sedentary habit, long activity season, high diversity and density, and high relation with environmental factors. For these reasons, 31 researchers in six countries proposed a standard monitoring method to activate monitoring of ants (Agosti et al., 2000). There have been many studies that have used ants as an indicator species for various environmental changes (e.g. changes in habitats). Oddly enough, studies on the influence of climate changes with ants are rare: only results of research on changes in the distribution of harmful ants that emerged as a global challenge were reported.

Based on the present distribution of the Argentine ants, *Linepithema humile* Mayr, changes in their global distribution, which were caused by climate warming, were expected through ecological niche modeling (Roura-Pascual et al., 2004). The Argentine ants have not yet established a foothold in Southwestern Asia and in the seashores of Tropical Africa, but have the potential to expand to these regions. If climate warming continues to proceed, the distribution of Argentine ants will decrease in the tropical regions but could expand to high latitude regions. This species is currently not found in Korea, but it is suitable for their inhabitation. In the 2050s, the thermal environment of the Korean peninsula will no longer be favorable for their inhabitation, whereas conditions will be better for them in Manchuria. Fire ants (*Solenopsis invicta* Baren), which are native to South America, invaded the southern regions of the United States and are now rapidly expanding. Based on the temperature and rainfall in the habitats of the species in the United States, changes in their distribution by climate warming are globally expected, according to the CLIMEX model (Sutherst and Maywald, 2005).

Choi (1985) investigated the distribution of ants in Halla, Seolak, Sokri, Sobaek, and Wolak Mountains, and then reported the vertical

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distribution of ant species that inhabited specific altitudes. The results of this report were obtained using qualitative methods such as colony collection. To determine the vertical distribution of ants, quantitative investigation using the pitfall trap method was carried out at various altitudes (200 m, 400 m, 1300 m, 1600 m, and 1900 m) in Jeju Island in 2006, confirming the vertical distribution of ants. This vertical distribution of ants is a result of the specific thermal ranges because the temperature decreases by 0.5–0.6°C for every 100 m increase in altitude in the mountains. This phenomenon is also found in 12 high mountains in South Korea by Kwon et al., (2014), who proved that the thermal regimes mainly determine the distribution of ants.

Thus, it is possible to make the distribution model of ants with respect to temperature. Based on this, it is possible to expect changes in abundance and distribution of ants caused by climate changes. This study was performed to expect changes in the distribution of ants with respect to the temperature in Korea. A total of 366 sites, including 65 sites in 12 high mountains (with altitudes >1100 m), were selected for this survey. To exclude the effects of habitats on ants, only healthy forests were selected. The results of prediction obtained in this study will be useful later for a hypothesis to verify changes in the distribution of ants caused by climate changes.

Materials and methods

Survey sites

To uniformly select the 366 sites used in this study, eight sites were selected in a grid cell of latitude 0.5° and longitude 0.5° (mean ± SD, 8.3 ± 1.8; 6–13). The study sites include 12 high mountains (with altitude >1100 m)—Halasan, Seolaksan, Jirisan, Gyebangsan, Gariwangsan, Taebaeksan, Sobaeksan, Hwaksan, Minjujisan, Deokyusan, Gayasan, and Unmunsan Mountains. Among these mountains are three of the highest mountains (Halasan, Seolaksan, and Jirisan) in South Korea. In every mountain, four to seven survey sites were selected at every 200–300 m of the altitude. For our survey sites, we selected only healthy forests that were more than 30 years old and where understory vegetation has developed. Study sites on the summits of high mountains are located in shrublands.

Sampling methods

Ants were investigated with the pitfall trap method, in which 10 pitfall traps were installed in series at every 5 m and polyethylene glycol (environment-friendly antifreezing solution) was used as the preservation solution, filling one-third of the trap depth. Polyethylene glycol cannot attract ants and is popular as a preservation solution because the amount of evaporation is small and it is suitable for preservation of insect specimens (Greenslade and Greenslade, 1971). The investigation had been carried out from 2006 to 2009. Pitfall traps were set up for 10–15 days. Plastic containers (diameter 9.5 m, depth 6.5 m) were used. When pitfall traps were returned, the liquid in the container was filtered through a fine net; dead bodies of ants were again placed in the container with the cover closed; then, they were placed in alcohol (80%) for preservation until identification in the laboratory. Ants were investigated from mid-May to mid-September. In this period, it was reported that many ants were collected in pitfall traps owing to their active foraging (Kwon, 2010).

Identification of ants

Ants were identified with the classification key described by Kwon et al. (2012). Except for *Myrmica* and *Lasius* genera, ants were identified to the level of species and morphospecies. The *Myrmica* genus was divided into *Myrmica kotokui* and the rest (*Myrmica* spp.). Although *Lasius japonica* and *Lasius alienus* are the most common species in the *Lasius* genus, individuals with the intermediate shape of the two species were frequently found. Two species, therefore, were identified into *Lasius* spp. (*japonicus* + *alienus*) (Kwon et al., 2012). All ant specimens are deposited in the forest ecology laboratory of the Korea Forest Research Institute.

Estimation of abundance

Ants in pitfall traps call their family workers with attraction activities such as sound or pheromone (Hölldobler and Wilson, 1990); therefore, the number of collected ants depends on the attraction activities of a species. When there were ant colonies around pitfalls, very large numbers of ants were sometimes collected. For this reason, the number of ants is not adequate as an indicator for the abundance of ants. To exclude the effects of attraction activities, the frequency of collected traps was transformed to the percentage to be used as the abundance. The following is an equation to obtain the rate of abundance: abundance $= 100 \times$ (the number of collected traps)/(the number of returned traps). This index is equivalent with the probability that a species is collected when one pitfall trap is installed at a site.

Relationship between abundance and environmental factors

With the Geographic Information System (GIS) method based on the coordinates of the survey sites, temperature (yearly mean, the maximum, and the minimum temperature), yearly rainfall, solar radiation, and vegetation index (Normalized Difference Vegetation Index as of May in 2005) were estimated. The temperature was estimated from the digital maps (Yun, 2010) that were provided by the Korea Meteorological Administration and National Center for Agro Meteorology. Climatic data were the mean value from 1971 to 2008, which have been usually represented by the mean values for 30 years. The length of spatial resolution lattices was 30 m. The relation of environmental factors in habitats to the abundance of 20 common species (more than 10% of occurrence frequency, the number of sites more than 37) was analyzed with correlation analysis. Significance was determined with $p < 0.05$.

Prediction of abundance

Among the 57 species of ants that were collected at the 366 study sites in forests, the abundance of the 20 common species was analyzed in relation with the temperature. After the average temperature of study sites was classified into six temperature zones (3–7°C, 7–9°C, 9–11°C, 11–13°C, 13–15°C, and >15°C), the average value and standard error (SE) of the abundance were calculated for each temperature zone. After the average values of the abundance for temperature zones were compared, 16 species with linear or bell-shaped types (normal distribution), which were later called candidate species, were selected, and then change in abundance was projected with respect to temperature. It was projected under the assumption that the average abundance of each temperature zone did not change. The years in which change in the abundance rate was expected are 2011, 2020, 2060, and 2090. After the temperature zone in each year was selected, the average abundance of the zone was applied to obtain the distribution of the abundance of each species. The overall average abundance in each year was annually compared in each species (the lower graph in Figures 5–20). There are no data on average abundance in the temperature zone of higher than 15°C because ants are hardly found at this zone. According to the A1B climate scenario, the temperature zone is expected to drastically expand after 2020 (Figure 1). The average abundance of seven species that are expected to inhabit the high temperature zone was estimated by the first to the third order polynomial regression model (Zar, 1999). Statistica ver 6.1 was used for the statistical analysis, and ArcView ver. 10.1 was used for GIS analysis.

Results and discussion

Ant abundance and environmental factors

Figure 1 shows the changes in the distribution of temperature according to the A1B climate change scenario. Although the low temperature zones where the yearly average temperature is below 7°C were distributed widely in the middle part of Korea including the provinces of Gangwon, Gyeonggi, Chungnam, and Chungbuk, they will drastically decrease and will almost disappear by 2090 (Figure 1). Contrarily, the high temperature zones (>15°C) will increase up to about 80% of the total area in 2090, whereas the cold zone (<7°C) will nearly disappear (0.2%).

A total of 57 species of ants were collected at 366 study sites in South Korea (Table 1). Kwon et al. (2012) provided information on the study sites, including photographs of the total species. The most common species was *Nylanderia flavipes*, which were collected from 287 sites, and followed by *Pachycondyla javana*, *Pheidole fervida*, and *Pristomyrmex punctatus*, which were collected from more than 200 sites. *Myrmica kotokui* that is the most abundant and the most common species found in high mountains (Kwon et al., 2014) was collected at 60 sites: it ranked 14th in occurrence frequency. Singleton species that occurred at one site were 10, including *Plagiolepis pigmaea*, which accounted for about one-sixth of all species. Table 2 shows the results of the correlation analysis of the abundance and environmental factors for 20 common species. Figure 2 shows the determination coefficients (R^2) between abundance and environmental factors in each species. The environmental factors that are most highly related with the abundance of ants were maximum temperature and average temperature. After the determination coefficients were compared using analysis of variance, significant differences were noted between environmental factors ($F_{5,114} = 4.686$, $p = 0.00063$). Species that showed the highest relation with the average temperature include *Pachycondyla javana* ($r = 0.64$, $p < 0.05$), *Myrmica kotokui* ($r = -0.63$, $p < 0.05$), and *Pristomyrmex punctatus* ($r = 0.54$, $p < 0.05$).

The abundance of 20 common species at several temperature zones is shown in Figures 3 and 4. Except for four species among the 20 species (Figure 4), the abundance showed close relations with the temperature: linear decrease along temperature gradient for *Myrmica kotokui* and *Myrmica* spp.; hump-shaped for *Camponotus atrox*, *Aphaenogaster japonica*, *Camponotus kuisuensis*, *Vollenhovia emeryi*, *Camponotus japonica*, *Temnothorax spinosior*, and *Tetramorium caespitum*; stagnation after increase for *Nylanderia flavipes*, *Pachycondyla javana*, *Crematogaster osakensis*, *Strumigenys lewisi*, *Lasius* spp. (*japonicas* + *alienus*), *Pristomyrmex punctatus*; and linear increase for *Pachycondyla chinensis.* These species were determined as candidate species to expect changes in distribution and abundance. Four species including *Formica japonica*, *Pheidole fervida*, *Ponera scabra*, and *Myrmecina nipponica* were excluded in the prediction because they did not show patterns that were expected in the normal distribution according to the temperature gradient (Figure 4).

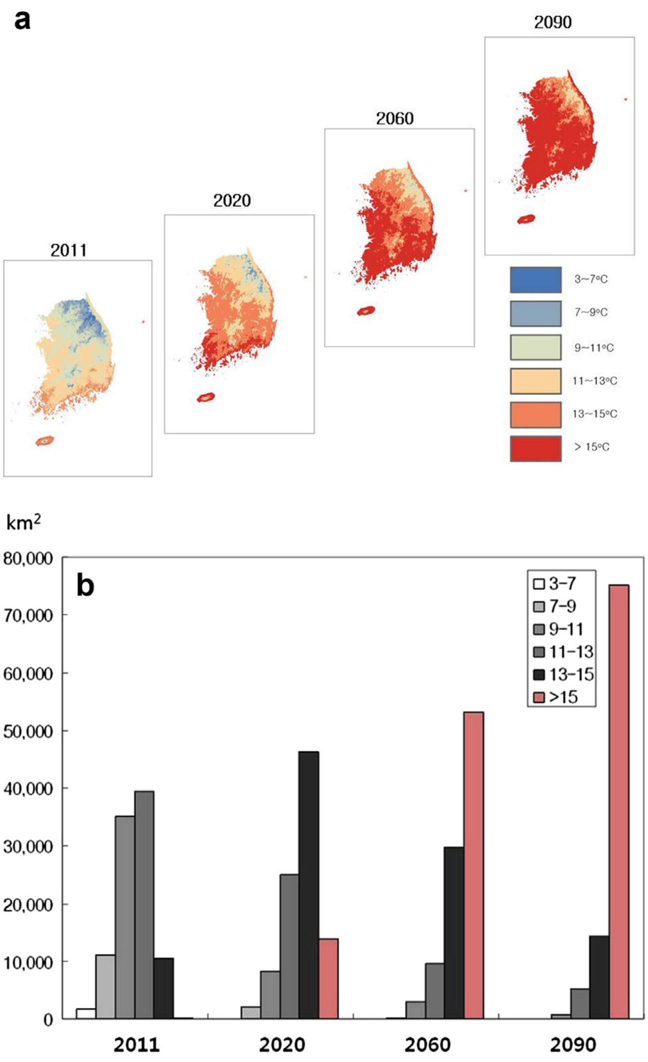

Figure 1. Temperatures in four projected years according to climate scenario A1B.

Prediction of change in abundance of ant species

Myrmica kotokui

Myrmica kotokui is a species that is most abundant in high mountains with an altitude higher than 1000 m—this is a common phenomenon in 12 high mountains (Kwon et al., 2012, 2014). Figure 5 shows the projected distribution and abundance of this species. At present, *Myrmica kotokui* shows very high abundance in high mountains; it is expected to decrease to less than 1/4 of its present abundance in 2020; it will be hardly found in high mountains by 2060, and will almost disappear in South Korea by 2090.

Componotus atrox

Componotus atrox is expected to decrease in a similar pattern to *Myrmica kotokui* (Figure 6). Although this species showed an almost similar distribution to *Myrmica kotokui*, it appeared at relatively lower altitudes, and its density does not become extremely high in high mountains. The range of temperature was 5.5–11.4°C and the median value was 8.4°C (Table 1). This species will be found at very high altitudes in 2020 and is expected to almost disappear from high mountains after 2060.

Myrmica spp.

Although *Myrmica* spp. indicates all ants pertaining to *Myrmica* spp. except for *Myrmica kotokui* in this study, it is assumed that 96% of *Myrmica* spp. belongs to either *Myrmica kurokii* or *Myrmica*

Table 1
Occurrence (number of occurred sites), temperature in occurred sites, and change in abundance of 57 ant species.

Species	Korean name	Occurrence	Temperature					Change
			Minimum	Maximum	Mid	Average	Optimum	
Aphaenogaster japonica	일본장다리개미	161	6.27	13.54	9.9	9.99	10.06	−90
Camponotus atrox	홍가슴개미	51	5.47	11.4	8.43	8.17	8.04	−99
Camponotus japonicus	일본왕개미	68	7.96	13.6	10.78	10.99	11.15	−81
Camponotus kiusuensis	갈색발왕개미	52	6.68	13.05	9.87	10.24	10.42	−92
Camponotus nipponensis	털왕개미	18	7.7	12.09	9.9	9.72	9.81	Decrease
Camponotus quadrinotatus	네눈개미	4	7.6	11.64	9.62	9.28	9.29	Decrease
Camponotus sp.1		8	9.91	13.54	11.73	11.31	11.24	Increase
Camponotus sp.2		5	12.12	13.54	12.83	12.73	12.73	Increase
Crematogaster brunea	검정꼬리치레개미	10	10.44	13.54	11.99	11.95	11.84	Increase
Crematogaster matsumurai	마쓰무라꼬리치레개미	17	9.68	12.69	11.18	11.14	10.93	Decrease
Crematogaster osakensis	노랑꼬리치레개미	98	7.6	14.21	10.91	11.53	11.57	27
Crematogaster vagula	등굽은꼬리치레개미	27	8.78	13.1	10.94	11.45	11.33	Decrease
Cryptone sauteri	장님침개미	31	6.16	13.5	9.83	10.1	10.02	Decrease
Dolichoderinae sp.		1	10.23	10.23	10.23	10.23	10.23	–
Dolichoderus sibiricus	시베리아개미	11	8.24	12.84	10.54	9.92	9.88	Decrease
Formica japonica	곰개미	81	3.21	13.6	8.4	9.61	9.22	Decrease
Formica sanguinea	분개미	1	10.02	10.02	10.02	10.02	10.02	–
Hypoponera sauteri	사우터침개미	2	11.4	13.32	12.36	12.36	12.77	Increase
Iridomyrmex sp.1		1	9.24	9.24	9.24	9.24	9.24	–
Laius crispus	주름냄새개미	1	12.37	12.37	12.37	12.37	12.37	–
Lasius hayashi	하야시털개미	1	7.9	7.9	7.9	7.9	7.9	–
Lasius meridionalis	나도황개미	10	5.09	12	8.54	9.13	8.81	Decrease
Lasius sp.(n. *morisitai*)		4	10.09	11.08	10.59	10.62	10.5	Decrease
Lasius spathepus	민냄새개미	30	6.76	12.61	9.69	10.04	9.8	Decrease
Lasius spp. (*japonicus+alienus*)	고동털개미류	162	6.42	14.21	10.31	10.43	10.78	−28
Lasius talpa	두더지털개미	2	11.96	12.64	12.3	12.3	12.32	Increase
Lasius teranishii	테라니시털개미	4	7.53	10.25	8.89	8.63	8.41	Decrease
Messor aciculatus	짱구개미	1	9.64	9.64	9.64	9.64	9.64	–
Monomorium intrudens	배검은꼬마개미	2	12.48	14.21	13.35	13.35	13.86	Increase
Myrmecina flava	노란방패개미	1	10.63	10.63	10.63	10.63	10.63	–
Myrmecina nipponica	가시방패개미	86	4.34	13.6	8.97	10.02	10.12	Decrease
Myrmica kotokui	코토쿠뿔개미	60	3.21	11.4	7.3	7.13	6.75	−99
Myrmica spp.		61	4.45	12.12	8.29	8.58	8.28	−96
Nylanderia flavipes	스미스개미	287	6.42	14.21	10.31	10.7	10.76	−40
Nylanderia sakurae	사쿠라개미	2	7.96	11.65	9.81	9.81	9.9	Decrease
Pachycondyla chinensis	왕침개미	52	7.9	14.21	11.05	11.92	12.19	190
Pachycondyla javana	일본침개미	253	7.6	14.21	10.91	11.07	11.29	8
Pheidole fervida	극동혹개미	217	5.22	14.09	9.66	10.23	10.01	Decrease
Plagiolepis flavescens	노랑잘록개미	2	8.65	9.98	9.31	9.31	9.31	Decrease
Plagiolepis pygmae	남색개미	1	12.04	12.04	12.04	12.04	12.04	–
Polyrhachis lamellidens	가시개미	23	7.7	12.77	10.24	10.56	10.68	Decrease
Ponera japonica	침개미	6	7.61	11.81	9.71	9.51	9.39	Decrease
Ponera scabra	거치른침개미	41	7.06	13.5	10.28	10.23	10.27	Decrease
Prenolepis sp. 1		1	8.65	8.65	8.65	8.65	8.65	–
Pristomyrmex punctatus	그물등개미	182	7.7	14.21	10.96	11.44	11.49	32
Proceratium itoi	배굽은침개미	16	8.98	14.09	11.53	12.14	12.18	Increase
Pyramica japonica	톱니비늘개미	2	9.94	9.94	9.94	11.58	11.39	Decrease
Solenopsis japonica	일본열마디개미	12	9.64	14.09	11.87	11.57	11.63	Increase
Stenamma owstoni	오스톤개미	20	3.96	12.48	8.22	7.94	7.7	Decrease
Strumigenys lewisi	비늘개미	90	7.7	14.21	10.96	11.09	11.2	11
Tapinoma sp.		1	5.43	5.43	5.43	5.43	5.43	–
Technomyrmex albipes	흰발납작자루개미	3	11.37	13.54	12.45	12.49	12.14	Increase
Technomyrmex gibbosus	납작자루개미	10	10.2	12.84	11.52	11.48	11.48	Increase
Temnothorax nassonovi	낫소노브호리가슴개미	25	6.42	11.59	9	8.8	8.68	Decrease
Temnothorax spinosior	긴호리가슴개미	43	9.75	13.54	11.64	11.75	11.85	−70
Tetramorium caespitum	주름개미	55	7.6	13.6	10.6	11.34	11.42	−77
Vollenhovia emeryi	에메리개미	85	4.88	14.21	9.55	10.52	10.7	−83

Abundance is a proportion (%) of occurred traps in returned traps, which is equivalent with probability of collecting each species by a pitfall trap. Changes in 17 candidate species were calculated using the following equation: $\text{Change}_i = 100 \times (\text{Abundance}_{2090} - \text{Abundace}_{2011})/(\text{Abundance}_{2011})$, where Change_i is the change of species_i, Abundance_{2090} is the national average abundance in 2090, Abundance_{2011} is national average abundance in 2011. Change for other species was qualitatively determined from mid value of temperature range. From the regression model in Figure 21, a species with >11.3°C was determined to increase, and a species with <11.3°C was determined to decrease. Singleton species that occurred at a site were not determined.

carinata (Kwon et al., 2012). However, there is a possibility that these two species are the same (Kwon et al., 2012). Because ant taxonomists in Korea showed considerable differences on the classification system of the *Myrmica* genus and there are likely a few synonymous species (Kwon et al., 2012), species other than *Myrmica kotokui*, which were remarkable in their shapes, were classified into the same group of species, rather than dividing them into uncertain species. *Myrmica kotokui*, which is the most abundant species, is classified into a different species by some researchers (e.g. *Myrmica ruginodis* by Dongpyo Ryu). Whereas *Myrmica kotokui* occurred at the temperature zone of 3.2–11.4°C, *Myrmica* spp. occurred at higher temperatures of 4.5–12.1°C (Table 1). The reduction rate of this species is expected to be smoother compared with *Myrmica kotokui*. This result comes from

Table 2
Correlation between abundance of common (>10% occurrence) ant species and environmental factors.

Species	Korean name	Environmental factor					
		Precipitation	Insolation	Mean temperature	Minimum temperature	Maximum temperature	Vegetation index
Myrmecina nipponica	가시방패개미	−0.13	−0.11	−0.03	−0.17	0.09	0.05
Camponotus kiusuensis	갈색발왕개미	−0.08	−0.06	0.02	−0.07	0.10	0.17
Ponera scabra	거치른침개미	−0.06	−0.09	0.01	0.00	0.02	0.10
Lasius spp. (*japonicus+alienus*)	고동털개미류	−0.17	0.05	0.17	0.07	0.21	−0.06
Formica japonica	곰개미	0.17	0.06	−0.19	−0.12	−0.19	0.07
Pristomyrmex puntatus	그물등개미	−0.31	0.04	0.54	0.36	0.55	−0.41
Pheidole fervida	극동혹개미	−0.16	−0.08	−0.08	−0.27	0.10	0.07
Myrmica spp.		0.08	0.02	−0.36	−0.24	−0.37	0.14
Crematogaster osakensis	노랑꼬리치레개미	−0.08	0.02	0.35	0.30	0.28	−0.14
Strumigenys lewisi	비늘개미	−0.10	−0.03	0.24	0.14	0.24	−0.09
Nylanderia flavipes	스미스개미	−0.40	−0.06	0.45	0.13	0.56	−0.26
Vollenhovia emeryi	에메리개미	−0.13	−0.11	0.10	−0.02	0.18	0.03
Pachycondyla chinensis	왕침개미	−0.06	−0.03	0.31	0.34	0.22	−0.14
Camponotus japonicus	일본왕개미	−0.12	0.03	0.18	0.08	0.20	−0.08
Aphaenogaster japonica	일본장다리개미	−0.04	−0.03	−0.05	−0.12	0.04	0.20
Pachycondyla javana	일본침개미	−0.33	−0.05	0.64	0.38	0.68	−0.36
Tetramorium caespitum	주름개미	−0.11	0.03	0.22	0.16	0.19	−0.18
Myrmica kotokui	코토쿠뿔개미	0.51	0.05	−0.63	−0.27	−0.74	0.27
Camponotus atrox	홍가슴개미	0.19	0.08	−0.38	−0.24	−0.42	0.25
Temnothorax spinosior	긴호리가슴개미	−0.05	−0.05	0.27	0.20	0.24	−0.13

Abundance is a proportion (%) of occurred traps in total traps. The underlined values indicate significant correlation ($p < 0.05$).

the fact that this species group is composed of several species. *Myrmica* spp. (probably *Myrmica kurokii*) will exist at a low density around the summits of high mountains in Gangwon-do, whereas *Myrmica kotokui* will almost disappear by 2090 (Figure 7).

Aphaenogaster japonica

Aphaenogaster japonica can thrive only in healthy forests and have disappeared in disturbed forests (Kwon et al., 2011). Owing to very wide temperature range of this species (6.3–13.5°C), its distribution is also very wide (Figure 8). Based on the results of our investigation in high mountains, its abundance was at maximum at altitudes of 800–1000 m; its distribution showed the intermediate type between lowland species and highland species. The temperature range of this species showed a typical normal distribution, and its abundance was maximum at 9–11°C (Figure 3). Considering this distribution, it is assumed that this species is likely optimal in the thermal environment of South Korea. *Aphaenogaster japonica* uniformly inhabits the country's southwestern regions at present; it will drastically decrease in 2020, will almost disappear from the southern regions by 2060, and will be found only in the high mountains of Gangwon-do by 2090. This species coexists with *Myrmica kotokui* and other *Myrmica* species in the forests of high mountains with altitudes lower than 1000 m: interspecific competition is very severe due to their similar sizes (Kwon and Lee, 2013). Consequently, this species is expected to temporarily replace *Myrmica kotokui* and other *Myrmica* species in the highlands. It is, however, destined to disappear eventually.

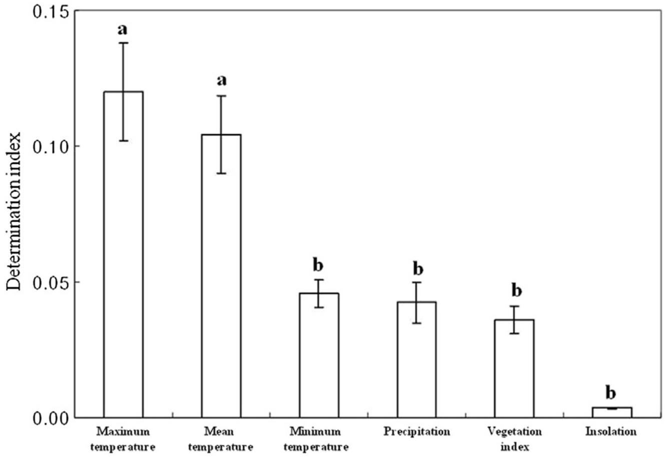

Figure 2. Influences of environmental factors on abundance of common (>10% occurrence) ant species. Determination index is r^2, and its value is expressed as mean with standard error. Data for this figure are shown in Table 2. Different letters on the bars indicate a significant difference between factors in Fisher least significant difference multiple comparison test after one-way analysis of variance ($F_{5,\ 114} = 4.686$, $p = 0.00063$).

Camponotus kuisuensis

Camponotus kuisuensis was the fifth cold-adapted species among the 20 species, and its median value of the temperature range (6.7–13.1°C) was low (9.9°C) (Table 1). This species is now widely distributed with a low density in most regions except for the high mountains in Gangwon-do (Figure 9). Although the density of this species will increase in 2020 in the high mountains of Gagwon-do (where it is currently not found), this species will disappear in the southern regions. It is expected to survive only in the mountains in Gangwon-do by 2090. This species is one of the 100 species that were designated as indicators of climate changes by the Ministry of Environment. In this study, this species was classified as one that is expected to increase.

Vollenhovia emeryi

Vollenhovia emeryi is likely a predator that mostly eats mites (Youngjun Jang, personal communication). From the results of indoor growing of this species, it was observed that individuals of this species were very inactive within their colony and were quiet in groups. Therefore, it is likely that this species does not severely compete with other species of ants on forest grounds. The range of temperature for this species was relatively wide (4.9–14.2°C) (Table 1). At present, it is found in most regions except for the high mountains in Gangwon-do (Figure 10). In 2020, it will expand to the high mountains of Gangwon-do; it will gradually disappear in

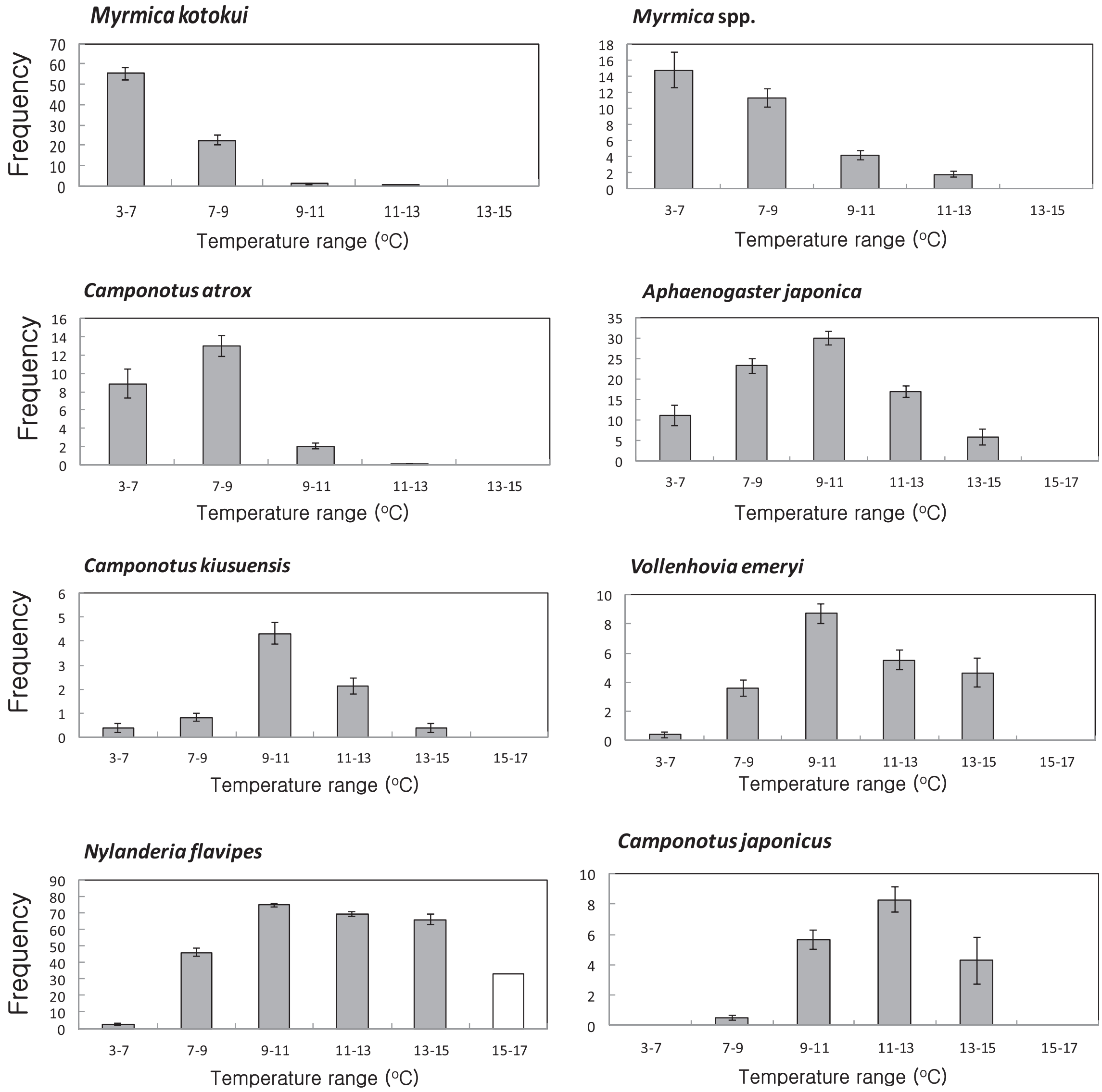

Figure 3. Abundance of 16 candidate ant species in six temperature bands. Abundance is the proportion (%) of occurred traps in returned traps. Error bars indicate 1 standard error. Frequency in the highest band (15–17°C) is calculated by the first- to third-order polynomial regression equation. Temperature is the annual mean temperature for 30 years at the study site. The mean value of abundance in six temperature bands was used for the calculation of abundance in the projected years (2011, 2020, 2060, and 2090) according to climate scenario A1B.

the southwestern regions after 2060, and this decreasing trend will extend to Gyeonggi-do by 2090.

Camponotus japonicus

Camponotus japonicus is frequently observed around grasslands or houses rather than forests, and only inhabits forests at a low density (Figure 11). The range of temperature for this species was 8–13.6°C, and its median value was 10.8°C (Table 1). Although this pertains to a relatively high temperature range among the species that were analyzed, it is expected that the reduction rate of the abundance according to the rise in temperature is very high. In high mountains, *Camponotus atrox*, which has a similar size and shape to this species, dominates. *Camponotus japonicus* will invade the habitats of *Camponotus atrox*, which will rapidly disappear after 2020. After a severe competition between two species, it will replace *Camponotus atrox* in the high mountains. As it is difficult to find *Camponotus japonicus* in the high mountains, it is expected that its competition with *Camponotus atrox* in terms of distribution and expansion will be interesting as well as its changes in ecology and behaviors.

Tetramorium caespitum

Although *Tetramorium caespitum* is frequently found around human dwellings and its habitats are grasslands rather than forests, it is known to inhabit forests at a low density (Figure 12). Intraspecific competition of this species is very severe, and struggles between colonies are frequently found in summer (Hölldobler and Wilson, 1990). The range of temperature is 7.6–13.6°C and the median value is 10.6°C, which are similar to the values found for *Camponotus japonicus*. Changes in its distribution and abundance, therefore, are almost the same as those in *Camponotus japonicus* (Figure 12). In most cases, *Camponotus japonicus* and *Tetramorium caespitum* were collected in the same places because they have similar habitats and temperature ranges. It is thought that the two species can coexist because the competition between them is not severe owing to the difference in sizes. The reason why this species

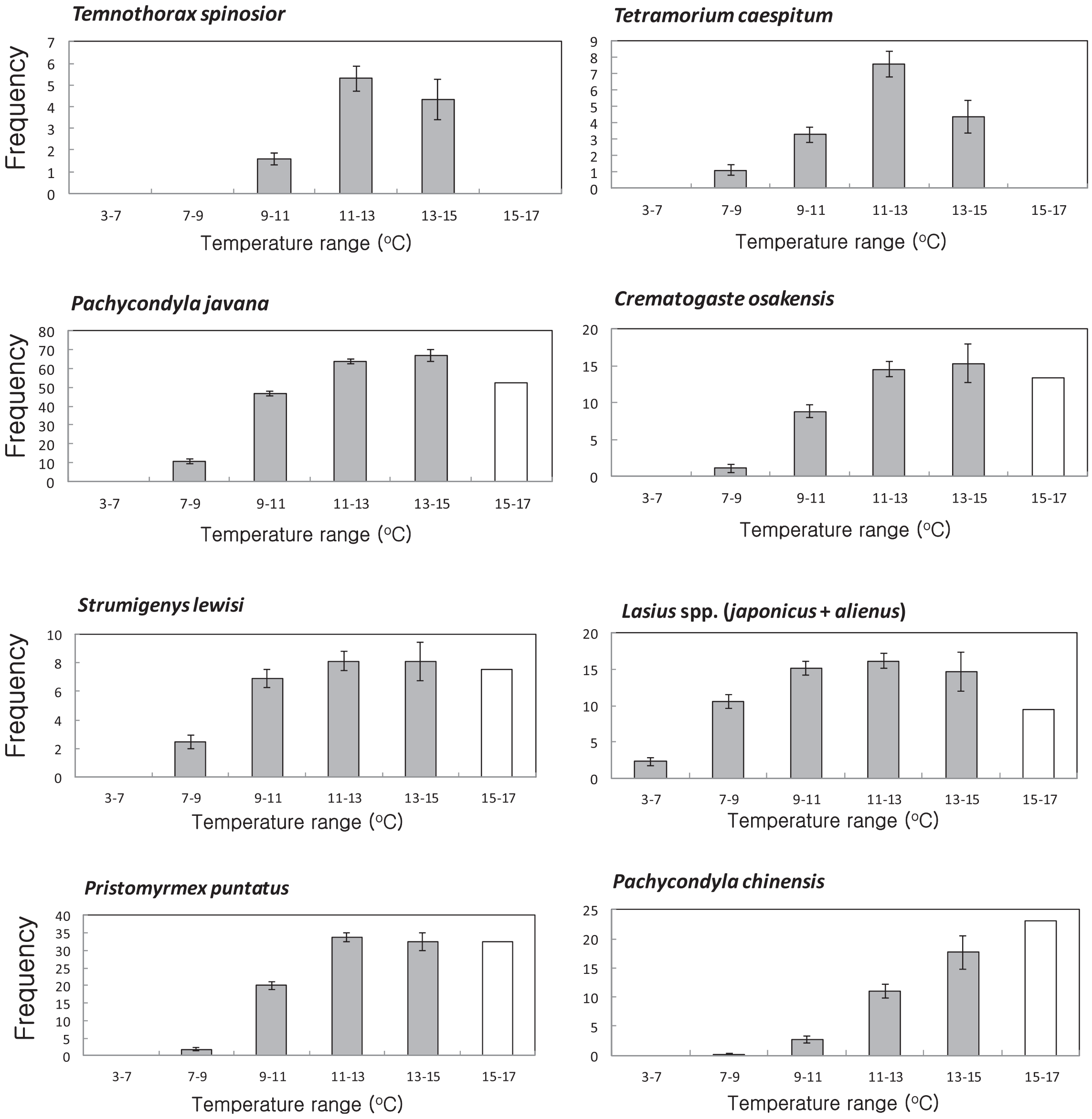

Figure 3. (*continued*).

is not found in grasslands and shrubs on the summits of high mountains, which are suitable for *Camponotus japonicus* and *Tetramorium caespitum*, might be the difficulties in survival because of the low temperature. After 2060, however, the two species can be easily found in grasslands and shrubs on the summits of high mountains (Figures 11 and 12).

Lasius spp. (L. japonicus + alienus)

Lasius spp. coexists with aphids, and it has wide-ranging habitats, including gardens, grassland, and forests (Kwon et al., 2011). In contrast to *Camponotus japonicus* and *Tetramorium caespitum*, this species lives in forests with a relatively high density. The range of temperature is 6.4–14.2°C and the median value is 10.3°C (Table 1). In 2020, it is expected to expand to high mountains; it will gradually disappear after 2060, and the distribution areas will be limited to Gangwon-do and Jiri mountain by 2090 (Figrue 13). The reduction rate of this species will be smoother than that of other species.

Nylanderia flavipes

Nylanderia flavipes is the most abundant ant species in Korea. This species mostly forms colonies in dead branches in forests. Although it mostly inhabits forests, it also lives in grasslands, shrublands, and forest edges. In 2009, a colony of this species was found even in the flowerpots of an apartment in Nowon-gu in Seoul. In most lowland forests (altitude < 800 m), it can thrive at a high density (Figure 14). In 2020, it will be easily found in high lands (altitude >1000 m), and will be very dense there after 2060. Contrarily, its density will gradually decrease in lowland forests. Change in its abundance is relatively smoother than that of other species that are predicted to decrease. In contrast to other species that will decrease in abundance, there will be no areas in which this species will disappear.

Temnothorax spinosior

In this study, two species of ants in the *Temnothorax* genus were collected (Table 1). Recently, the *Leptothorax* genus that inhabits in

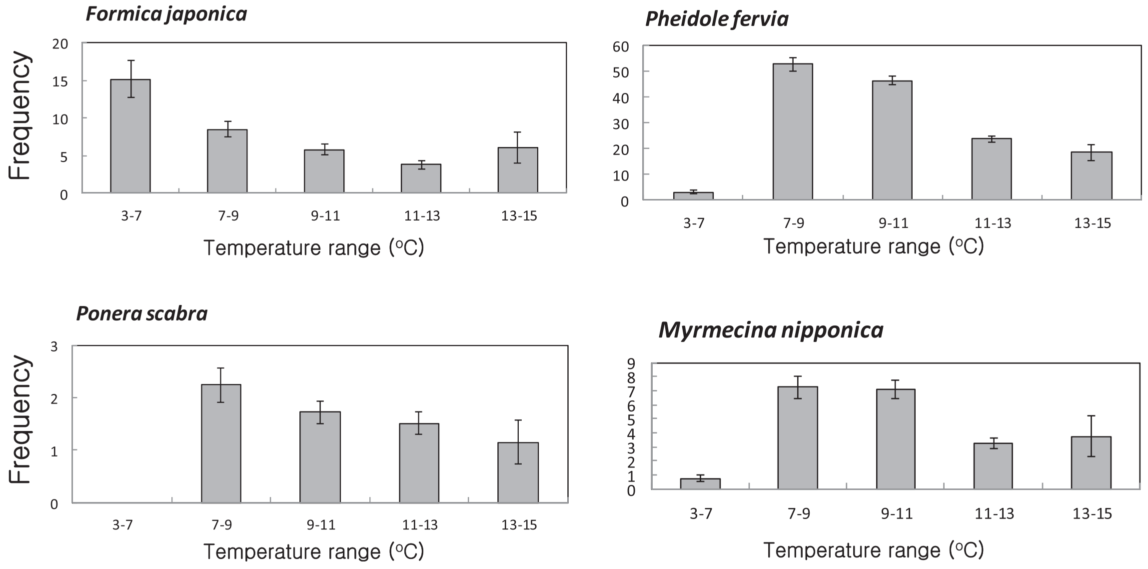

Figure 4. Abundance of four noncandidate common (>10% occurrence) ant species in five temperature bands. Abundance is the proportion (%) of occurred traps in returned traps. Error bars indicate 1 standard error. Temperature is the annual mean temperature for 30 years at occurred sites. These species were not used for prediction of abundance, because their abundance patterns are irregular rather than continuous (linear or curved). *Formica japonica*, whose frequencies are continuous, is excluded because its frequency in the highest temperature band (13–15°C) unexpectedly increased.

Korea was renamed *Temnothorax* (Radchenko, 2004). This species is mostly distributed in the middle southern regions, whereas *Temnothorax nassonovi* is distributed in the middle north regions. The latter mostly appears at altitudes of 800–1200 m in high mountains (Kwon et al., 2012). The ranges of temperature for the two species show a large difference: 6.4–11.6°C for *Temnothorax nassonovi* and 9.8–13.5°C for *Temnothorax spinosior*. *Temnothorax spinosior* will expand to all the regions of Korea until 2020, but it will drastically decrease after 2060 (Figure 15). Considering the low temperature range for *Temnothorax nassonovi*, it will continuously decrease, whereas *Temnothorax spinosior* will increase in 2020. The reduction rate of *Temnothorax nassonovi* will be high (Table 1).

Pachycondyla javana

Pachycondyla javana ranks second in terms of occurrence frequency (Figure 16, Table 1). The temperature range of this species is

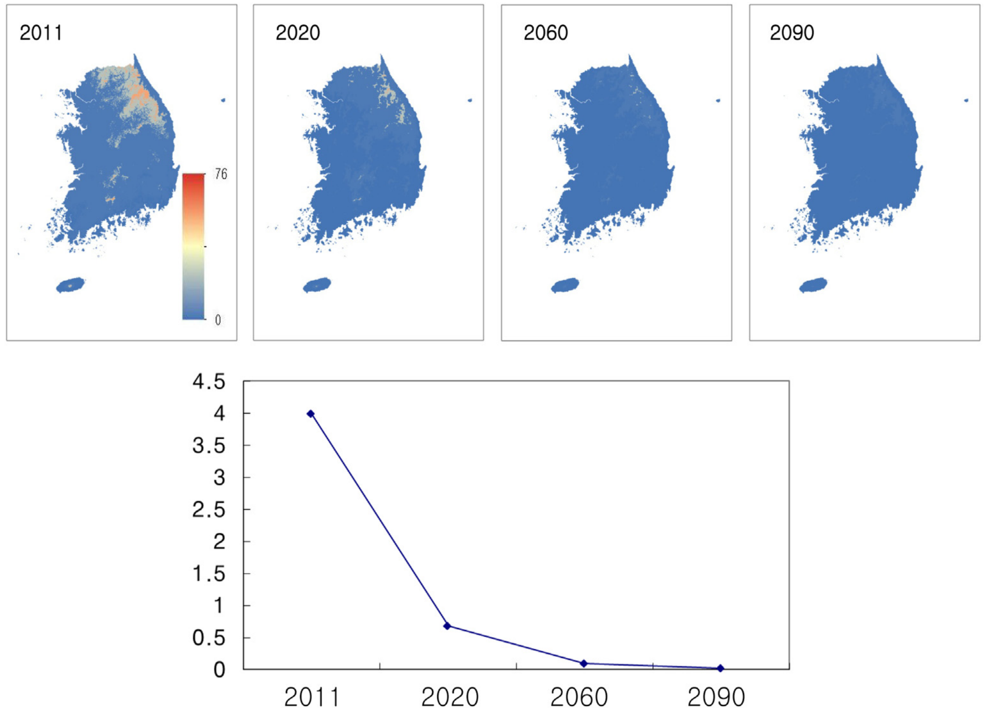

Figure 5. Abundance of *Myrmica kotokui* in four projected years according to climate scenario A1B. In the map, darker red indicates higher abundance and darker blue indicates lower abundance. Abundance is a proportion (%) of occurred traps in total traps, which is equivalent with a probability (%) of collecting this species by a pitfall trap. The lower graph indicates the national averages of abundance in the four projected years. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

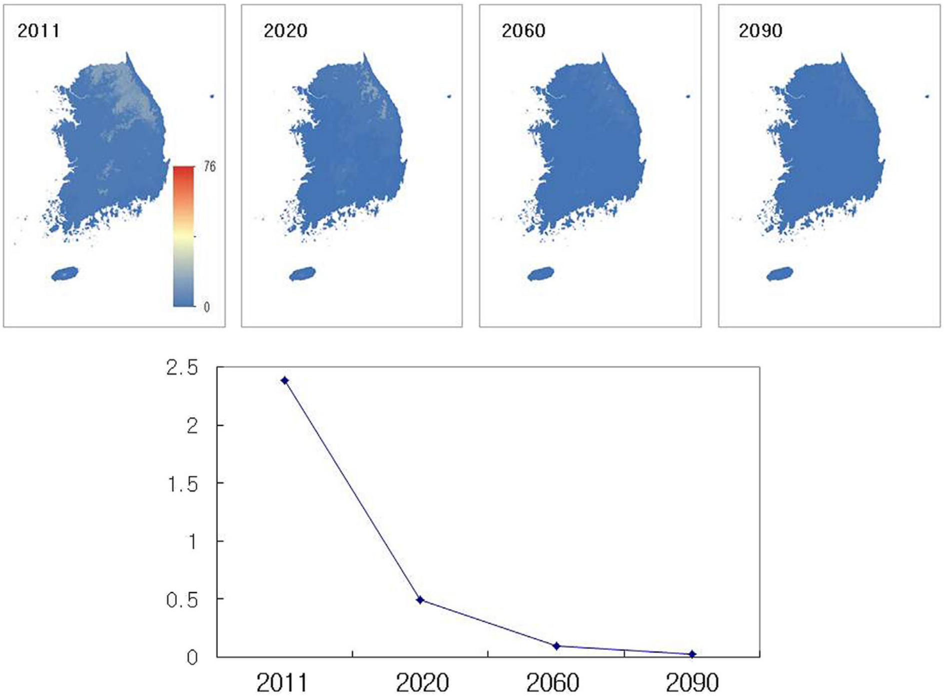

Figure 6. Abundance of *Camponotus atrox* in four projected years according to climate scenario A1B. In the map, darker red indicates higher abundance and darker blue indicates lower abundance. Abundance is a proportion (%) of occurred traps in total traps, which is equivalent with a probability (%) of collecting this species by a pitfall trap. The lower graph indicates the national averages of abundance in the four projected years. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

7.6–14.2°C and its median value is 10.9°C. Its temperature range ranked fourth among warm-adapted species, together with *Crematogaster osakensis*, among 16 candidate species (Table 1). Its temperature range is the same as that of *Crematogaster osakensis*, whereas its rate of abundance is different. *Crematogaster osakensis* will increase until 2020 and will be saturated later, whereas *Pachycondyla javana* will gradually decrease after 2020. This decrease comes from a gradual reduction in its density because of temperature rises in low areas in Gyenggi-do, Chungcheong-do, Geolla-do, and Geongsang-do, where they will be most abundant in

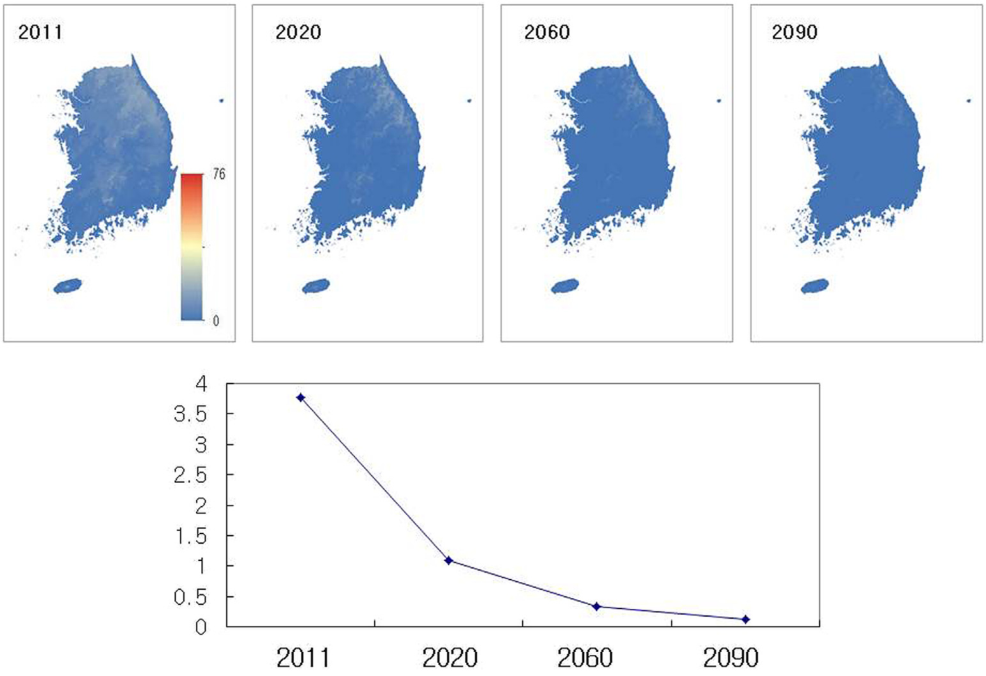

Figure 7. Abundance of *Myrmica* spp. (*Myrmica species* except *Myrmica kotokui*) in four projected years according to climate scenario A1B. In the map, darker red indicates higher abundance and darker blue indicates lower abundance. Abundance is a proportion (%) of occurred traps in total traps, which is equivalent with a probability (%) of collecting this species by a pitfall trap. The lower graph indicates the national averages of abundance in the four projected years. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

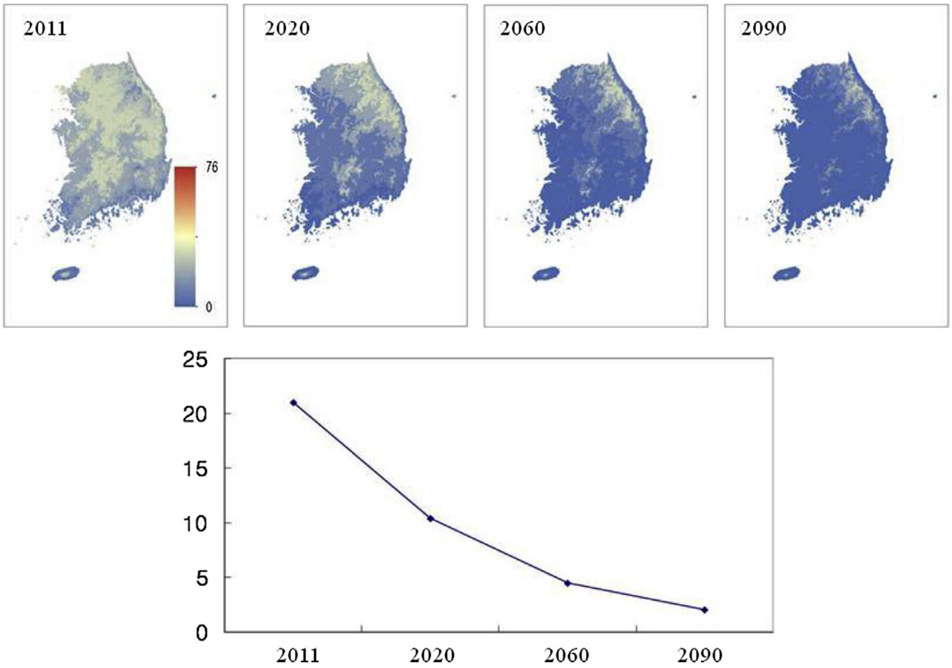

Figure 8. Abundance of *Aphaenogaster japonica* in four projected years according to climate scenario A1B. In the map, darker red indicates higher abundance and darker blue indicates lower abundance. Abundance is a proportion (%) of occurred traps in total traps, which is equivalent with a probability (%) of collecting this species by a pitfall trap. The lower graph indicates the national averages of abundance in the four projected years. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2020 (Figure 16). In 2060 and 2090, however, this species will take the most dominant role, instead of *Nylanderia flavipes*. *Pachycondyla javana* now can be found at an altitude of 800 m (Kwon et al., 2012); it will be found up to altitudes of 1000 m by 2020, and will appear at all altitudes after 2060. In contrast to the current trend, its distribution is expected to be denser at higher altitudes by 2060.

Crematogaster osakensis

Crematogaster osakensis is relatively frequently collected in pitfall traps as it mostly forages on the ground, whereas three other species of *Crematogaster* (*Crematogaster vagula*, *Crematogaster teranishii*, and *Crematogaster matsumurai*) mostly forage in vegetation. The temperature ranges for all four species are

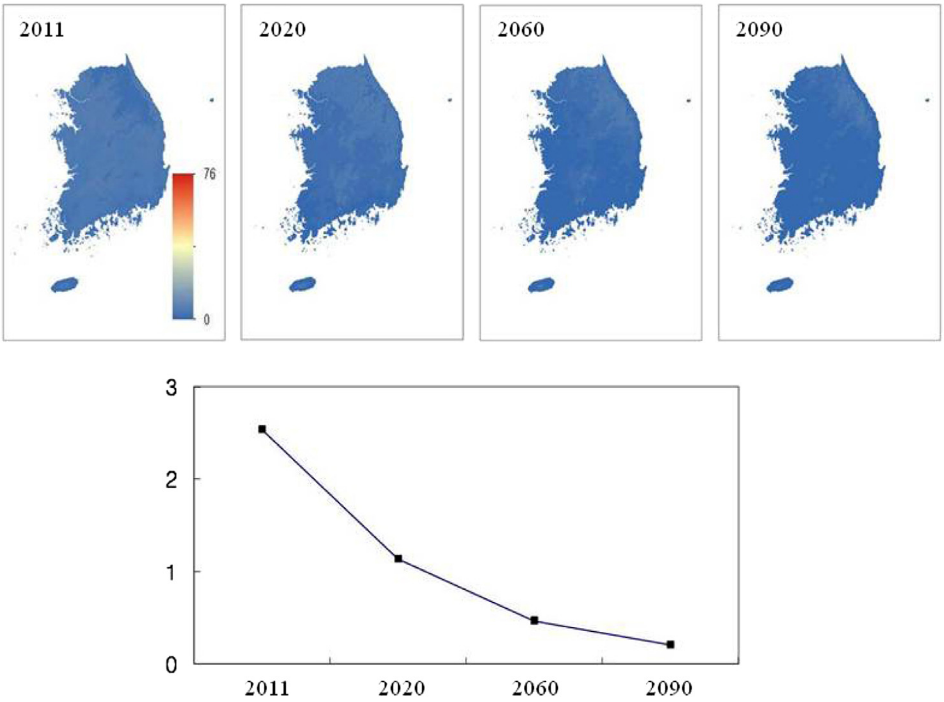

Figure 9. Abundance of *Camponotus kuisuensis* in four projected years according to climate scenario A1B. In the map, darker red indicates higher abundance and darker blue indicates lower abundance. Abundance is a proportion (%) of occurred traps in total traps, which is equivalent with a probability (%) of collecting this species by a pitfall trap. The lower graph indicates the national averages of abundance in the four projected years. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

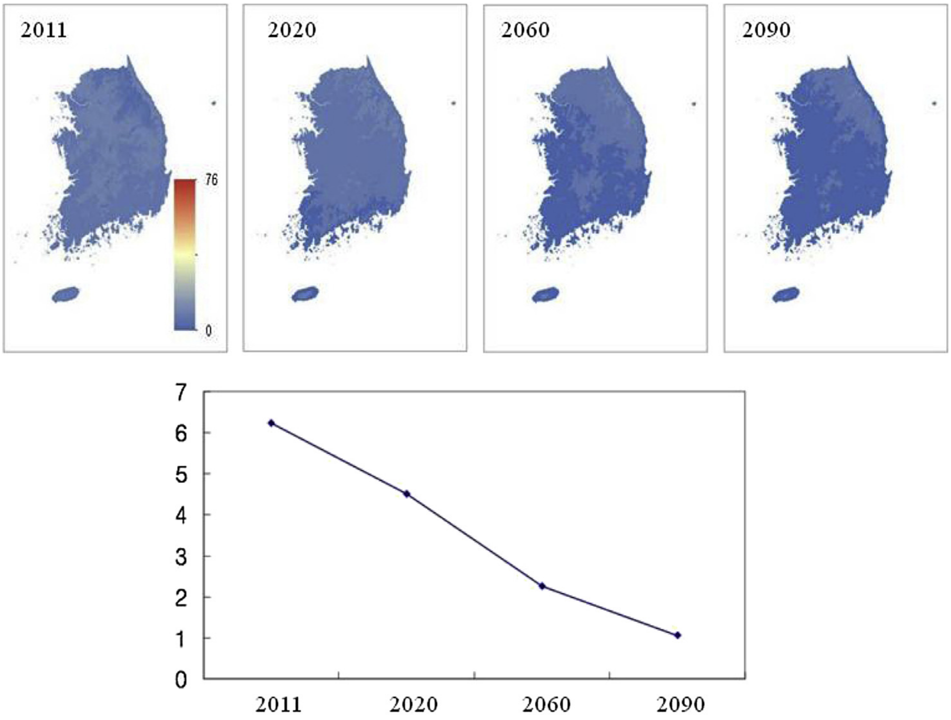

Figure 10. Abundance of *Vollenhovia emeryi* in four projected years according to climate scenario A1B. In the map, darker red indicates higher abundance and darker blue indicates lower abundance. Abundance is a proportion (%) of occurred traps in total traps, which is equivalent with a probability (%) of collecting this species by a pitfall trap. The lower graph indicates the national averages of abundance in the four projected years. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

high: 7.6–14.2°C for *Crematogaster osakensis* (median value: 10.9°C), 8.8–13.1°C (median value: 10.9°C) for *Crematogaster vagula*, 9.7–12.7°C (median value: 11.2°C) for *Crematogaster matsumurai*, and 10.4–13.5°C (median value: 12°C) for *Crematogaster teranishii*. *Crematogaster osakensis* is currently not found in high mountains, but will eventually expand to high mountains; it is projected to be easily observed in most high mountains by 2090 (Figure 17).

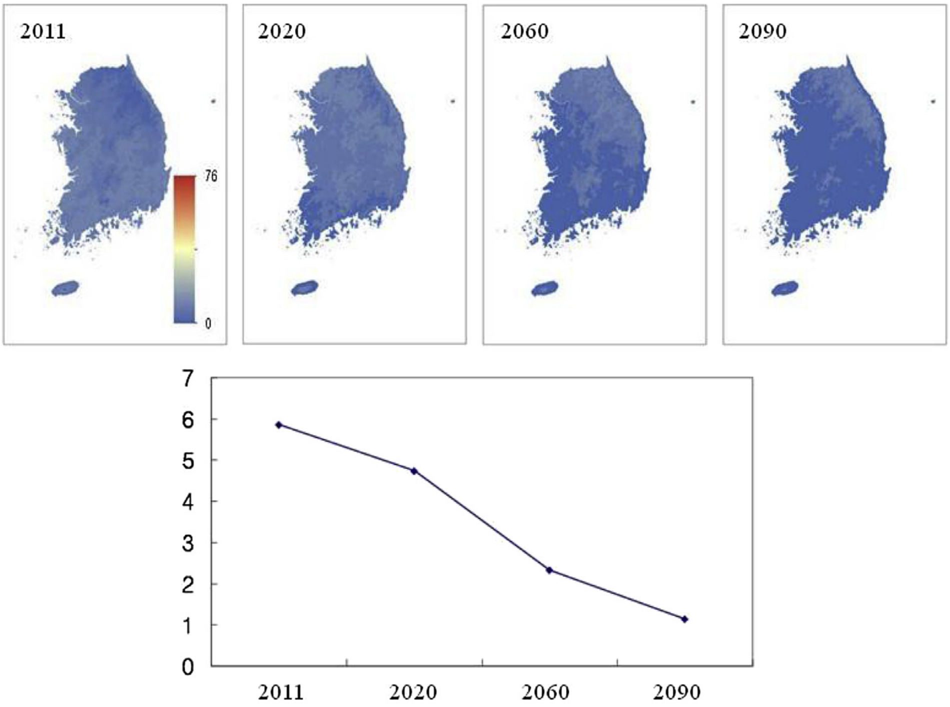

Figure 11. Abundance of *Camponotus japonicus* in four projected years according to climate scenario A1B. In the map, darker red indicates higher abundance and darker blue indicates lower abundance. Abundance is a proportion (%) of occurred traps in total traps, which is equivalent with a probability (%) of collecting this species by a pitfall trap. The lower graph indicates the national averages of abundance in the four projected years. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

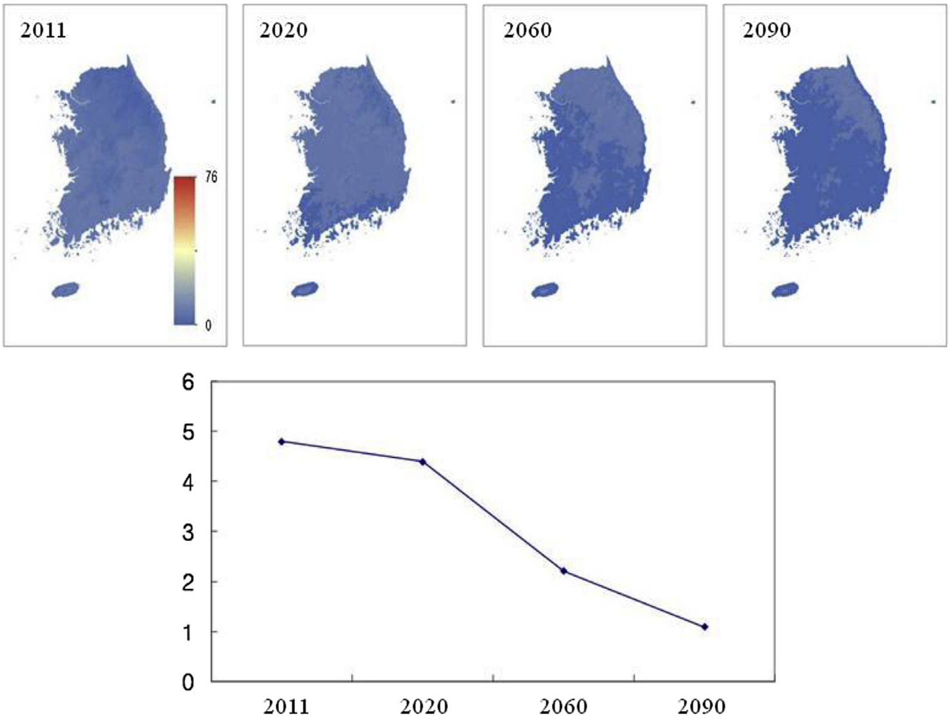

Figure 12. Abundance of *Tetramorium caespitum* in four projected years according to climate scenario A1B. In the map, darker red indicates higher abundance and darker blue indicates lower abundance. Abundance is a proportion (%) of occurred traps in total traps, which is equivalent with a probability (%) of collecting this species by a pitfall trap. The lower graph indicates the national averages of abundance in the four projected years. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Strumigenys lewisi

Strumigenys lewisi, a predator insect that mostly eats springtails (JAID, 2010), is widely distributed in all regions of Korea (Figure 18). The temperature range of this species is 7.7–14.2°C (median value: 11°C), which covers a relatively high temperature zone. Because of its wide temperature range, it can be found in all regions of the country except for high mountains. As the temperature rises, it will expand to high mountains but its density in lowland forests will

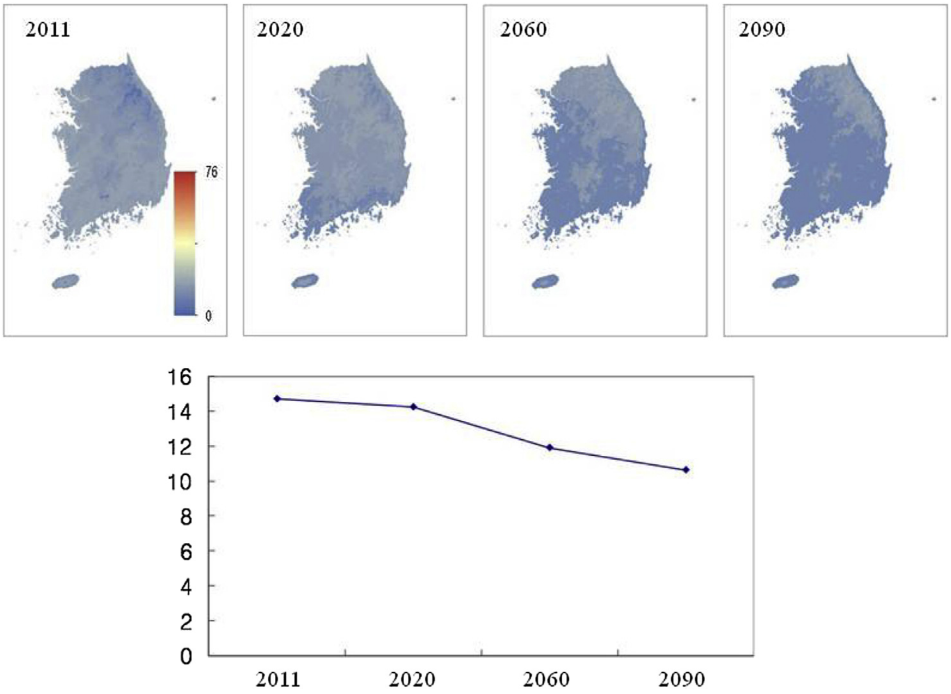

Figure 13. Abundance of *Lasius* spp. (*japonicas* + *alienus*) in four projected years according to climate scenario A1B. In the map, darker red indicates higher abundance and darker blue indicates lower abundance. Abundance is a proportion (%) of occurred traps in total traps, which is equivalent with a probability (%) of collecting this species by a pitfall trap. The lower graph indicates the national averages of abundance in the four projected years. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

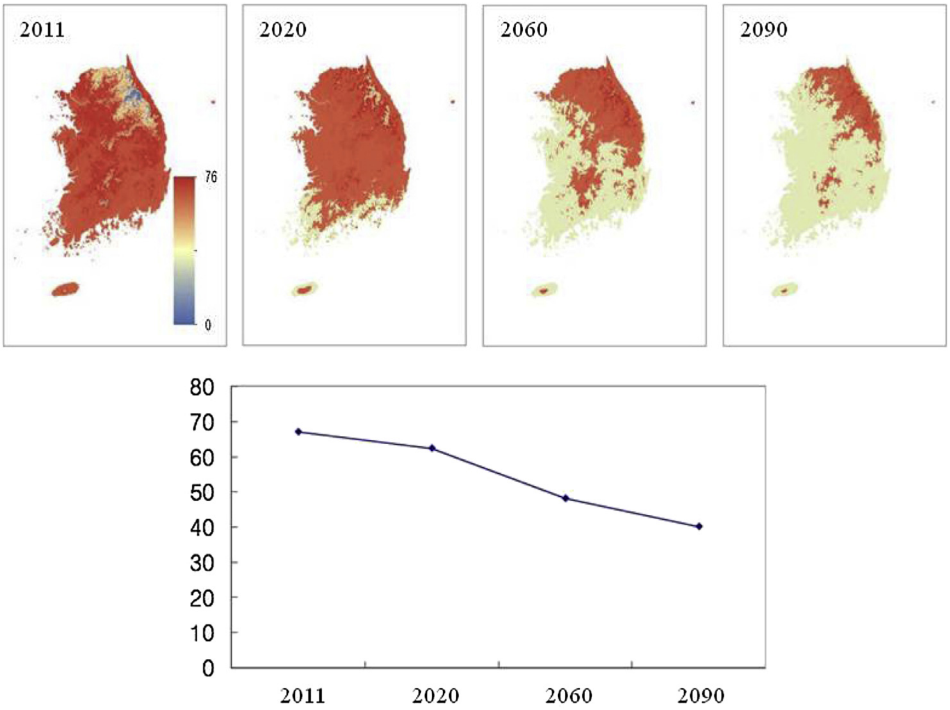

Figure 14. Abundance of *Nylanderia flavipes* in four projected years according to climate scenario A1B. In the map, darker red indicates higher abundance and darker blue indicates lower abundance. Abundance is a proportion (%) of occurred traps in total traps, which is equivalent with a probability (%) of collecting this species by a pitfall trap. The lower graph indicates the national averages of abundance in the four projected years. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

gradually decrease. The abundance will drastically increase until 2020, and then it will smoothly decrease.

Pristomyrmex punctatus

Pristomyrmex punctatus (*pungens*, previous) is widely distributed in South Asia and has peculiar ecological characteristics: it has no queen ant and some ants among worker ants are responsible for reproduction and reproduce by parthenogenesis (Terayama and Kubota, 2009; Tsuji, 1994). The temperature range of this species is 7.7–14.2°C and its median value is 11°C. Its occurrence frequency ranks fourth, but it is very low in ant surveys on 12 high mountains (Kwon et al., 2012) because of its high temperature range. This

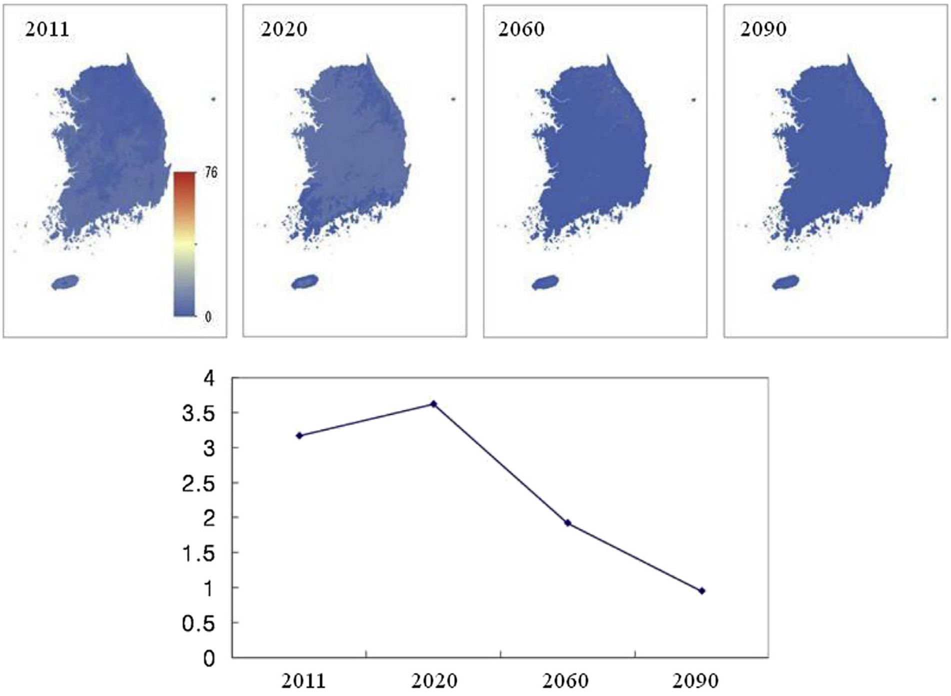

Figure 15. Abundance of *Temnothorax spinosior* in four projected years according to climate scenario A1B. In the map, darker red indicates higher abundance and darker blue indicates lower abundance. Abundance is a proportion (%) of occurred traps in total traps, which is equivalent with a probability (%) of collecting this species by a pitfall trap. The lower graph indicates the national averages of abundance in the four projected years. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

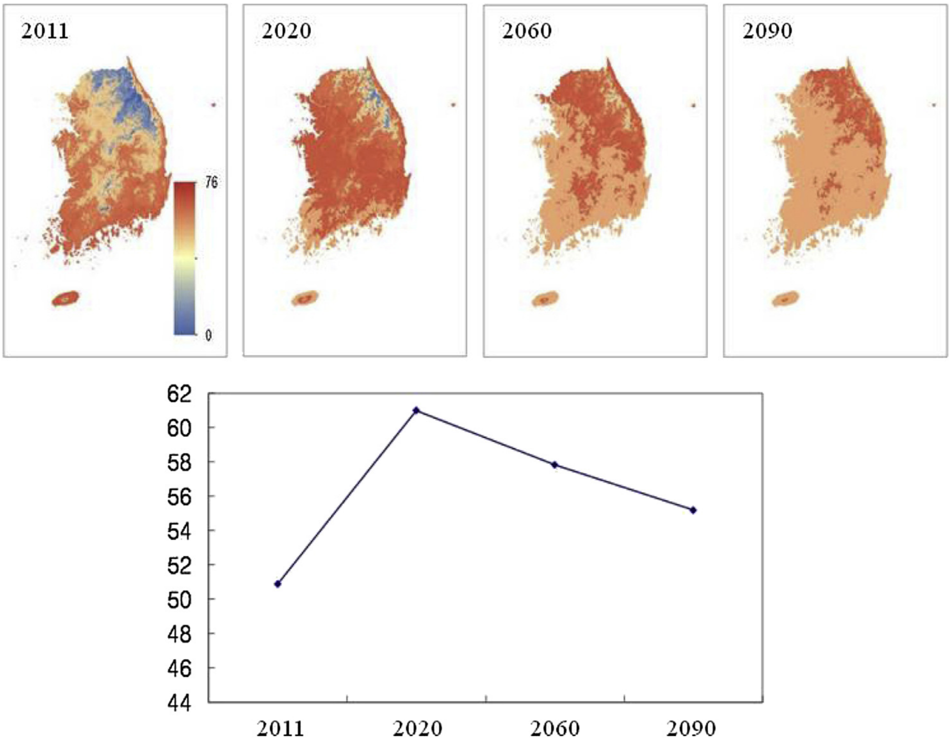

Figure 16. Abundance of *Pachycondyla javana* in four projected years according to climate scenario A1B. In the map, darker red indicates higher abundance and darker blue indicates lower abundance. Abundance is a proportion (%) of occurred traps in total traps, which is equivalent with a probability (%) of collecting this species by a pitfall trap. The lower graph indicates the national averages of abundance in the four projected years. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

species is now distributed in many regions except in high mountains, and is expected to rapidly expand to high mountains as the temperature rises (Figure 19). In 2090, it is expected to inhabit most high mountains in Gangwon-do. Its abundance will rapidly increase until 2020 and then will be saturated. This result comes from the fact that places where its abundance increases will offset places where it decreases. The abundance of *Pristomyrmex punctatus* is expected to be very homogenous as the temperature rises.

Pachycondyla chinensis

Pachycondyla chinensis was selected as an indicator species of urbanization by Choi and Lee (1999). According to the investigation conducted in Hongreung forest in Seoul, this species was found only in healthy forests (Kwon et al., 2011). It is the only species that is expected to continuously increase until 2090 among the 16 candidate species. This is because its temperature range is the highest among its peers (7.9–14.2°C, median value: 11.05°C), and its density increases at higher temperatures (Figure 20). Because its occurrence is restricted to high temperature regions, its density is high in the lowland forests of Gyeonsang-do, Jeolla-do, and Chungcheong-do, but very low in the lowland forests in Gangwon-do and Gyeonggi-do. It is expected that it will expand to the middle north regions as the temperature rises. Because it inhabits areas with very high temperature, it will be difficult for this species to inhabit the high mountains of Gangwon-do even in 2090 (Figure 20). As climate warming continues to proceed, however, it will eventually expand to the highest mountains.

Another 41 ant species

Change in the abundance of 16 candidate species in 2011 and 2090 (Figures 5–20) was compared with the median values of the temperature range in Figure 21. The change rate shows a significant correlation with the median values ($p < 0.05$). Figure 21 shows a regression equation in which the median value is an independent variable and the change rate is a dependent one. Based on this regression equation, it was determined as decrease for the median value lower than 11.3°C, or increase for that higher than 11.3°C. Singleton species collected in a survey site was not determined. Because species that were qualitatively determined were not verified on significant relation with temperature, the confidence of prediction was lower compared to that in candidate species. Based on the results of the quantitative and qualitative analyses, 32 species among a total of 57 species are expected to decrease in abundance, whereas 15 species are expected to increase in 2090 compared to 2011. Similar to results obtained for spiders, in which 68 species decreased whereas nine species increased (Kwon et al., 2013), these results show a trend in which the number of decreasing species exceeded that of increasing species.

Feasibility of predictions and diversity change following distributional change

Using the species distribution model, many studies related to changes in the distribution of organisms (Peterson et al., 2002), changes in diversity (Cheung et al., 2009; Li et al., 2013), and prediction on extinction (Thomas et al., 2004) have been continuously reported. The most popular model was the ecological niche model, in which the multidimensional ecological niche theory proposed by Hutchinson (1957) was its theoretical basis. The ecological niche models such as GARP and MEXENT, which were recently popular, are using artificial intelligence, statistical models, and GIS analysis methods. The merits of these models are integration into automation systems by which even novices can easily make complex prediction models. Actually predictable factors among the

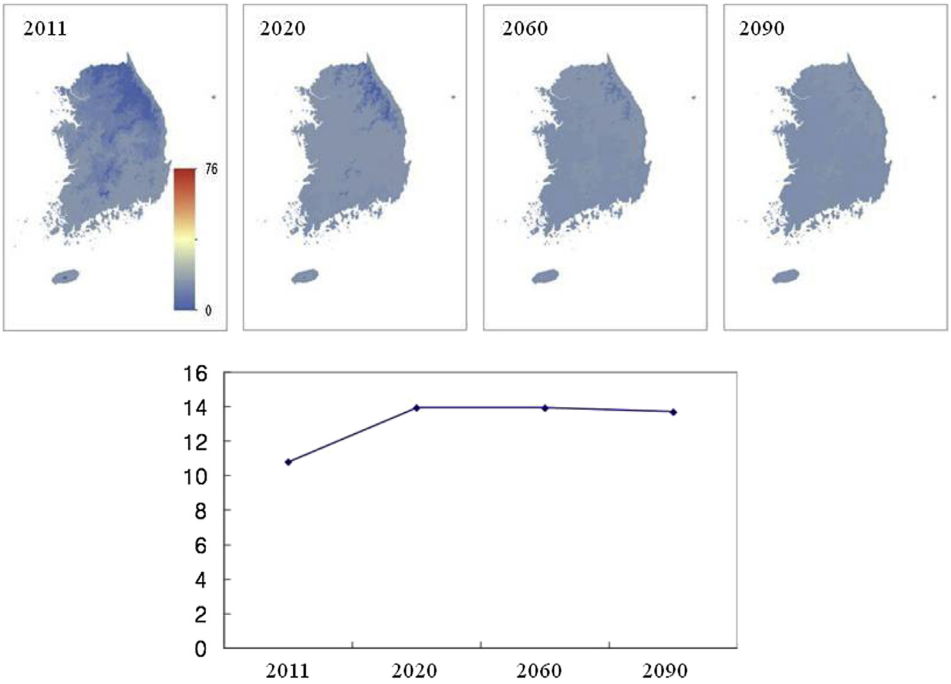

Figure 17. Abundance of *Crematogaster osakensis* in four projected years according to climate scenario A1B. In the map, darker red indicates higher abundance and darker blue indicates lower abundance. Abundance is a proportion (%) of occurred traps in total traps, which is equivalent with a probability (%) of collecting this species by a pitfall trap. The lower graph indicates the national averages of abundance in the four projected years. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

environment factors in these complex models are temperature and rainfall. Because the rate of rainfall significantly changes depending on regions and period (Yun et al., 2013), it is very difficult to exactly predict as in the case of temperature. In complicated models with various environment factors, including statistical models, artificial intelligence models, and artificial neural network models, it should be predicted under the assumption that other factors rather than temperature do not change (Manyong Shin, personal communication). Because other environment factors rather than temperature complicatedly changes in connection with change in temperature,

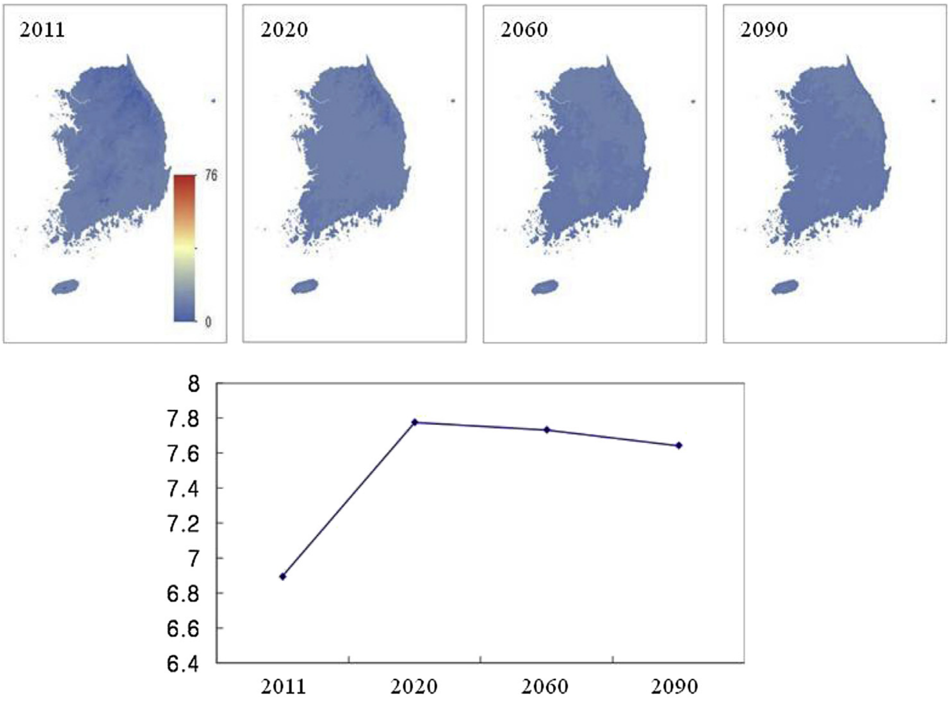

Figure 18. Abundance of *Strumygenys lewisi* in four projected years according to climate scenario A1B. In the map, darker red indicates higher abundance and darker blue indicates lower abundance. Abundance is a proportion (%) of occurred traps in total traps, which is equivalent with a probability (%) of collecting this species by a pitfall trap. The lower graph indicates the national averages of abundance in the four projected years. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

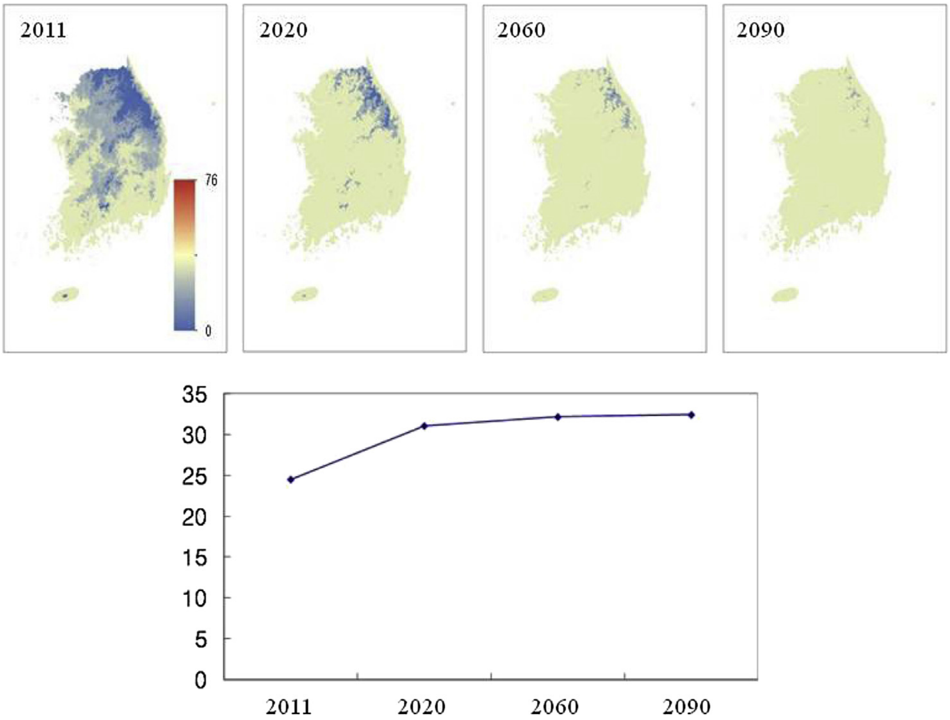

Figure 19. Abundance of *Pristomyrmex punctatus* (*pungens*, previous) in four projected years according to climate scenario A1B. In the map, darker red indicates higher abundance and darker blue indicates lower abundance. Abundance is a proportion (%) of occurred traps in total traps, which is equivalent with a probability (%) of collecting this species by a pitfall trap. The lower graph indicates the national averages of abundance in the four projected years. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

however, this assumption is significantly different from reality. Instead of complex models considering various factors rather than temperature, therefore, the temperature distribution model that only considers temperature seems to remarkably reduce uncertainty in prediction that originates from the complexity of the models.

In the cases of models that only consider temperature (like this study), instead of considering variation of the abundance, it is

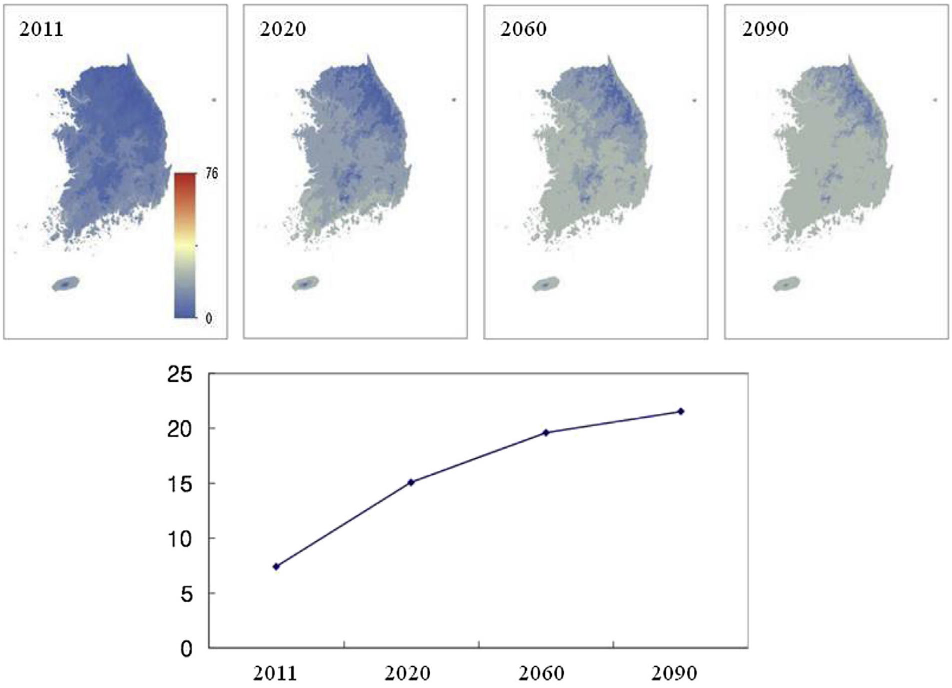

Figure 20. Abundance of *Pachycondyla chinensis* in four projected years according to climate scenario A1B. In the map, darker red indicates higher abundance and darker blue indicates the less abundance. Abundance is a proportion (%) of occurred traps in total traps, which is equivalent with a probability (%) of collecting this species by a pitfall trap. The lower graph indicates the national averages of abundance in the four projected years. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

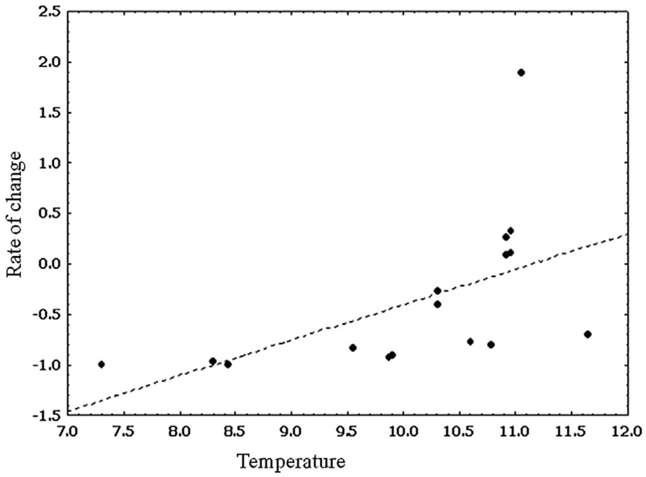

Figure 21. Mid value of temperature ranges and abundance change in 16 candidate ant species. Data for this figure is provided in Table 2. Abundance change is ratio of abundance in 2011 vs. that in 2090. In regression, $F_{1,14}$=5.77, $p < 0.05$, r^2= 0.24, $Y = -3.906 + 0.35 \times X$.

general practice to use data with more simple binary forms, such as presence or absence, by the logistic regression model, the general linearized model, or general additive model, which have been recently popular (Li et al., 2013; Hill et al., 2002). In this case, a clearer prediction is possible because the result is simple (e.g. models of this type can clearly predict when a species becomes extinct). Actual distribution, however, follows the normal distribution, instead of the binary distribution in which there "exists" or "not exists" (e.g. *Aphaenogaster japonica* in Figure 3). When the range of temperature in the existing statistical methods was estimated, it is different from the result obtained in this study. For example, *Aphaenogaster japonica* was collected in the range of 6.27–13.54°C and the median value was 9.9°C, which might be near the optimal temperature (Table 1). In the weighted averaging regression model that is frequently used to investigate the distribution of fossil species, and was recently used to predict changes in the distribution due to climate changes (Li et al., 2013), the temperature range of this species was estimated to be 9.07–12.44°C, which is much narrower than the actual range (Kwon, unpublished data). Popular models, therefore, do not always ensure confidence in their use. The values of various models that are now being used to predict climate changes should be determined by prediction performance rather than popularity or the theoretical excellence of the models. The values of the models, therefore, should be verified by the accuracy of predictions.

Prediction of the abundance of ants in this study included a simple change in temperature and did not consider competition between species. In cases where the majority of species decreased whereas the minority increased (as found in this study), the minority is likely to have a much higher increase than predicted because it occupies habitats where other species disappeared. In particular, this phenomenon will be more apparent in cases where there is little difference in habitats or foods, as in the case of ants. As the density of many species decreases at low altitude whereas that of other species significantly increases, it is expected that diversity will widely decrease in lowlands. In high mountains, however, diversity in species is expected to increase as species from lowlands invade. The altitudinal patterns of monotonic decrease will change to the bell-shaped type, in which the diversity is at maximum at the intermediate altitude, and species compositions will be drastically changed (Kwon, unpublished manuscript). Ants play very important roles as predators because they control the density of the other insects and determine the distribution of plants by spreading their seeds (Hölldobler and Wilson, 1990). There are many species, such as lycaenid butterflies, that require symbiosis with ants for their survival (Kim and Seo, 2012). *Spindasis takanonis*, which is an endangered species, has a symbiotic relation with *Crematogster matsumurai* (Lee et al., 2011). Larvae of butterflies in the *Maculinea* genus require the care of *Myrmica* ants (Choi and Kim, 2012; Elmes et al., 1998; Thomas et al., 1998). Based on the results of this study, most *Myrmica* spp. are expected to disappear in the high mountains within 50 years (Figures 5 and 7). In this case, butterflies in symbiotic relationship with ants will be seriously affected by the decrease in the number of host ants. If the distribution of ants in Korea changes, as expected in this study, this change will not just affect ants.

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