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Distribution patterns of *Monochamus alternatus* and *M. saltuarius* (Coleoptera: Cerambycidae) in Korea

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Abstract : Distribution patterns of two pine sawyer species (*Monochamus alternatus* which is the main vector insect and *M. saltuarius* which is the potential insect vector of the pine wood nematode) were investigated in Korea. The data were collected at 89 study sites which were chosen to cover the whole region of South Korea. The selected pine trees were killed in early April and left for 1 year in the pine stands to be egg-laid by the pine sawyers. Emergence of the beetles from the dead pine trees was checked from early April to late July. *M. saltuarius* was the most abundant in the mid to northern areas of South Korea, whereas *M. alternatus* in Jeju-do, southernmost island of Korea. Considering temperature distribution patterns in areas where the two species occur, their thermal distribution boundary may be formed around 13.2°C of annual mean temperature. The hypothesized distribution map of the two *Monochamus* species under the invasion of pine wilt disease is suggested on the base of thermal distribution of Korean peninsula.

***Key words* :** Bursaphelenchus xylophilus, *pine wilt disease, temperature, vector beetle*

Introduction

Pine wilt disease (PWD) is the one of most destructive tree diseases in North East Asia including Korea, Japan, and China, and Europe (Kishi, 1995; Mota *et al.*, 1999). In Korea, the first infection was reported in Busan in 1988, and the disease has been dispersed to Gyoungnam-do in the late 1990s, to Jeonnam-, Gyeongbuk-, Gwangwon-, and Jeju-dos in the 2000s, showing the accelerated dispersal of the disease. If the disease is continuously dispersed with such a rate, most pine stands in Korea would be infected by PWD in next several decades (Kwon, 2005).

PWD is caused by the pinewood nematode (PWN), *Bursaphelenchus xylophilus*, of which lengths of adult female and male are 0.7-1.0 mm, and 0.6-0.8 mm, respectively (KFRI, 2004). At the early stage of the infection, the nematode inhabits the resin canals of both xylem and cortex. The nematode infection results in a cessation of oleoresin exudation in 2-3 weeks as an early symptom of the disease. Then nematode population increases rapidly and spreads through the wood tissue in dying pine trees. The nematode can not move to other pine trees without an aid of vectors, the pine sawyers (Kishi, 1995).

The species of vector beetles of PWN varies at different regions: *Monochamus alternatus* in most areas of Japan, *M. saltuarius* in the cold regions of Japan (Takizawa and Shoji, 1982), *M. carolinensis, M. mutato, M. scutellatus, M. titillator* in North America (Linit, 1988), and *M. galloprovincialis* in Portugal (Sousa *et al.*, 2001). In Korea, only *M. alternatus* is known as a vector, and other *Monochamus* species are not found yet in the nem-

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atode-infected trees (KFRI, 2005).

M. alternatus had been collected at various sites covering the whole seaside area of Gyongnam-do and Jeonnam-do in the survey from 1989 to 1994 (Moon *et al.*, 1995), indicating the wide distribution of *M. alternatus* in the southern coastal areas of Korea. Meanwhile, *M. saltuarius* occurred in pine logs in the central area of Korea, Chungnam-do (Kim C.S., unpublished) and Gangwon-do (Lee and Lee, 2000; *M. saltuarius* was erroneously identified as *M. sutor* in this paper). This indicates different distribution patterns of the two species, *M. alternatus* in the southern region of South Korea and *M. saltuarius* in the northern region.

PWN dispersal may change the current distribution pattern of the two dominant *Monochamus* species in Korea. The disease has expanded rapidly to the northern area of Korea since 2000 (KFRI, 2005), presenting a possibility that the disease can invade northern areas inhabited solely by *M. saltuarius* within next several years. However, the epidemic dispersal with *M. alternatus* is limited by cold climate (Kishi, 1995). The dispersal may result in coexistence of the two species so that single vector system of *M. alternatus* would be changed due to the presence of *M. saltuarius* in the northern areas of South Korea.

The control methods for PWD (e.g. season of aerial spray) may vary according to vector species due to the different phenology between two species. Therefore, it is urgent to investigate the natural distribution pattern of these species for designing proper regional control methods for PWD in Korea. This study was carried out to find the current distribution patterns of the pine sawyers in Korea, and predict their potential distribution patterns when PWD expands over the whole areas of Korea.

Materials and Methods

1. Sampling of *Monochamus* beetles

We surveyed the distribution pattern of *Monochamus* species in north regions (GG: Gyenggi-do, and GW: Gangwon-do) in South Korea for 2 years from 2001 and in south regions (CN: Chungcheongnam-do, CB: Chungcheongbuk-do, JB: Jeollabuk-do, JN: Jeollanam-do, GB: Gyeongsangbuk-do, GN: Gyeongsangnam-do: G, and JJ: Jeju-do) for 2 years from 2003 (Figure 1). The 89 pine stands were selected as study sites, and the tree species of the stands were *Pinus densiflora* at the 61 stands, *P. thunbergii* at 13, and *P. koraiensis* at 15. The pine species are abundant in South Korea and susceptible to PWN (Moon *et al.*, 1993). The study sites were selected from map to cover the whole regions of South Korea, although the study sites were limited. Locations of the study stands were determined using GPS. We excluded the southern coastal area in Jeollanam-do (JN) and Gyeongsangnam-do (GN) where only *M. alternatus* is found in this area (Yi *et al.*, 1989; Lee *et al.*, 1990; Park *et al.*, 1992; Moon *et al.*, 1995).

Two or three pine trees (larger than 20 cm in DBH) were chosen at each study site in 2001, and five trees in 2003. The selected trees were debarked around 1 m height from ground by hatchet in early April to kill the trees in order to make the *Monochamus* beetles lay eggs in the barks of the trees. After one year, the logs and twigs of the killed trees were cut and moved to regional forest research institutes. Each of the logs and twigs with 1 m length being covered with 0.5 mm mesh was maintained in the iron screen cage under outdoor conditions. The adults of long-horned beetles were collected daily from early April to late July, and identified to the species level according to Lee (1982, 1987). The species of genus *Monochamus* were further recognized by cerambycid taxonomists and ecologist. The specimens of long-horned beetles are kept in the insect specimen storage room of Korea Forest Research Institute.

In addition, we used distributional information of the *Monochamus* species obtained from long-term monitoring on vector species of PWN (KFRI, unpublished), from bibliographies and from the survey on the pine sawfly specimen of museum collections in Korea Univ., Kwangwon Univ., Seoul Univ., National Institute of Agricultural Science and Technology (NIAST), being provided by Lim J.O. and Lee S.H in Seoul University (unpublished). The data of bibliographies and museum specimens were too coarse to be used for determining exact locality in distributional modeling described below. Hence, they were utilized to test validity of modeled distribution pattern.

2. Modeling of distribution patterns

Although our collection data is not sufficient to represent the overall distributional patterns of the two *Monochamus* species for the limited study sites and for some failures in killing pine trees in the southern regions (see results and discussion), we made hypothesized distributional patterns using the limited distributional data in this study and GIS tool. We assumed that mean temperatures may determine the distribution of the *Monochamus* species on the base of Japanese distributional patterns showing cool regions of *M. saltuarius* occurrence (Kishi, 1995). Although mean temperatures do not have a direct meaning to biology of *Monochamus* beetles, their thermal thresholds for completing larval stage and termination of larval diapause may be approximately set up by mean temperatures. It should be recalled that this study is the preliminary step to the precise distributional patterns of the two *Monochamus* species.

Spatially interpolated data of annual mean temperature from 1981 to 1994 in the Korean Peninsula were driven using the regression model developed by Yun and Lee (2000). The computation and mapping were conducted in the environment of the Arc/View GIS software (version 3.2, ESRI). The annual mean temperature was used to evaluate the potential distribution areas of *M. saltuarius* and *M. alternatus* in Korea.

Results and Discussion

1. Distribution pattern of two *Monochamus* species

We identified 17 species of long-horned beetles with

Table 1. Number of individuals of the cerambycid beetles collected in nine study regions (GG: Gyeonggi-, GW: Gangwon-, CB: Chungcheongbuk-, CN: Chuncheonggnam-, JB: Jeollabuk-, JN: Jeollanam-, GB: Gyeongsangbuk-, and JJ: Jeju-dos).

Species	GG	GW	CB	CN	JB	JN	GB	JJ	Total
Acalolepta sejuncta				1	5				6
Acanthocinus carinulatus		5	1	5	16		32	1	60
Anastrangalia scotodes		5						1	6
Arhopalus rusticus	7				5	1			13
Asenum striatum		8		1	1				10
Corymbia rubra	8			1	1		2	5	17
Corymbia sp.			2						2
Gaurotes ussuriensis		1							1
Leptura aethiops		8	3		1		8		20
Leptura arcuata		1	1		4				6
Moechotypa diphysis		3							3
Monochamus alternatus								6	6
Monochamus saltuarius	81	293	6	2	45		72		499
Rhagium inquisitor		1							1
Rhaphuma gracilipes		1							1
Semanotus bifasciatus		2							2
Unidentified spp.					2			1	3
Total	96	328	13	10	78	1	114	13	653

Table 2. Number of individuals of the cerambycid beetles collected in each of three pine species.

Species	*Pinus densiflora*	*P. koraiensisi*	*P. thunbergii*	Total
Acalolepta sejuncta	3	1	2	6
Acanthocinus carinulatus	44	2	14	60
Anastrangalia scotodes		5	1	6
Arhopalus rusticus	11	2		13
Asenum striatum	2	6	2	10
Corymbia rubra	11		6	17
Corymbia sp.			2	2
Gaurotes ussuriensis		1		1
Leptura aethiops	13		7	20
Leptura arcuata	2		4	6
Moechotypa diphysis	3			3
Monochamus alternatus			6	6
Monochamus saltuarius	243	220	36	499
Rhagium inquisitor	1			1
Rhaphuma gracilipes	1			1
Semanotus bifasciatus	1		1	2
Unidentified spp.	1	1	1	3
Total	335	237	81	653

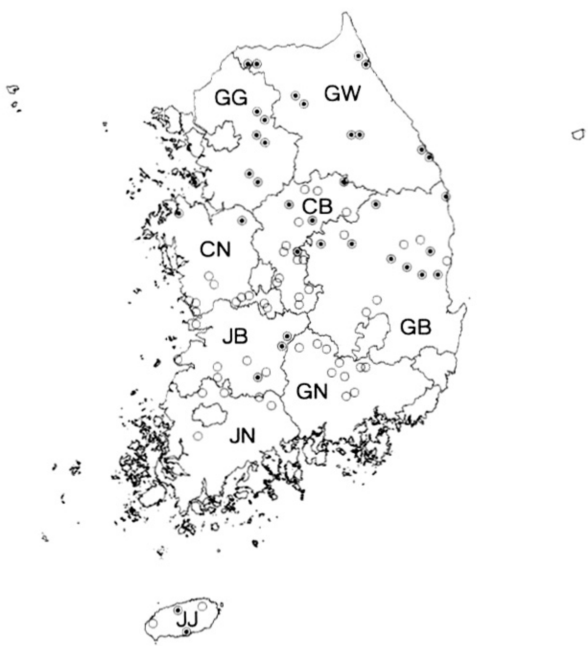

Figure 1. Map of the study sites. Both open circles and dark inner circles indicate study sites. Dark inner circles represent the sites where *Monochamus alternatus* or *M. saltuarius* had been collected in this study (2002 or 2004). GG: Gyeonggi-, GW: Gangwon-, CB: Chungcheongbuk-, CN: Chungcheongnam-, JB: Jeollabuk-, JN: Jeollanam-, GB: Gyeongsangbuk-, GN: Gyeongsangnam, and JJ: Jeju-dos.

653 individuals in study sites (Tables 1, 2). Among them, *Monochamus saltuarius* was the most abundant in all regions with 499 individuals showing 76% of total individuals. They were collected from 35 out of the 89 study sites (Figure 1). In Chungcheongnam-do *Acanthocinus carinulatus* was most abundant and followed by *M. saltuarius* (Table 1). *M. saltuarius* was abundantly observed in all three pine species (*Pinus densiflora*, *P. thunbergii*, and *Pinus koreiensis*) (Table 2), showing wide and abundant distribution of *M. saltuarius* in the mid to north areas of South Korea (Figure 2). In this study, *M. alternatus* was collected in southern island, Jeju-do, but any individuals of pine sawyers were not collected in the regions of Gyeongsangnam-do and Jeollanam-do, where PWD flourish. The sites for occurrence of the two *Monochamus* species are indicated in Figure 2. Distribution data of *M. alternatus* were obtained from Moon *et al.* (1995) and KFRI (unpublished) indicating PWD-infected areas of a vector of *M. alternatus*.

Moon *et al.* (1995) reported that *M. alternatus* was collected at many different sites in the southern coastal areas of Gyeongsangnam-do and Jeollanam-do in 1989-1994 when PWD did not invade there yet. This indicates that *M. alternatus* was widely distributed in the southern parts of Korea prior to the invasion of PWD, and rejects the hypothesis that *M. aleternatus* might invade the Korean Peninsula with PWN (Enda, 1989). The northernmost locality of *M. alternatus* is Gumi where *M. alternatus* have been collected from PWD infected trees (Figure 2). Meanwhile, the southernmost locality of *M. saltuarius* is Jangsu, Andong, and Sangju which are located 52.5-72.5 km from Gumi.

Contrarily to our intention to collect adults of both *M. alturnatus* and *M. saltuarius,* adults of *M. saltuarius* were collected in the mid to northern regions, whereas no adults of *M.* species from the southern regions of Gyeongsangnam-, Jeollanam- dos (Figure 1). The distributional boundary between two *Monochamus* species may be formed around area covering the blanked study stands in these southern regions. Accordingly, further studies are required to recognize occurrence of the *Monochamus* species in northern parts of Jeollanam- and Gyeongsangnam-dos. Failure of collection of *Monochamus* beetles were mainly due to low mortality of debarked trees (10-30% of mortality in southern regions of JN, GN, and JJ, and 50-80% in other regions) and reasons are remained unclear yet. This study shows that cutting trees rather than debarking is required to kill pine trees in the southern seaside regions of Jeollanam-, Gyoungsangnam- and Jeju-dos, being warm and having high rain falls. The abundance of *M. saltuarius* in mid to northern regions may partly be due to the season of debarking pines. Adults of *M. saltuarius* emerged late April to late May with peaks in mid May in all the study regions, showing a month earlier compared with that of *M. alternatus* (Kim *et al*, 2003). Accordingly, females of *M. saltuarius* would lay firstly their eggs on pine logs killed on early April, and females of *M. alternatus* and of other cerambycid species would avoid the pine logs oviposited previously. This may result in risk of underestimation of distribution of *M. alternatus*. Nonetheless, the general abundance of *M. saltuarius* and the complete absence of *M. alternatus* in the 33 study pine stands in these regions may indicate nonexistence or rareness of *M. alternatus* in mid to northern regions of South Korea, coincided by other studies (Lee, 1982; Lee, 1987; Lee and Lee, 2000; Kim C.S., unpublished) and museum collection data (Lim J.O. and Lee S.H., unpublished) indicating northern biased distribution of *M. saltuarius*.

2. Hypothesized distribution of *M. alternatus* and *M. saltuarius*

Annual mean temperature at occurrence areas of *M. saltuarius* ranged from 8.2°C to 13.2°C (mean±S.D, 11.5±0.9), whereas that of *M. alternatus* from 13.2°C to 14.6°C (mean±S.D, 14.1±0.3), showing significant difference (t-test, p <0.0000) between two species (Figure 3). We assumed that the distribution boundary for the two

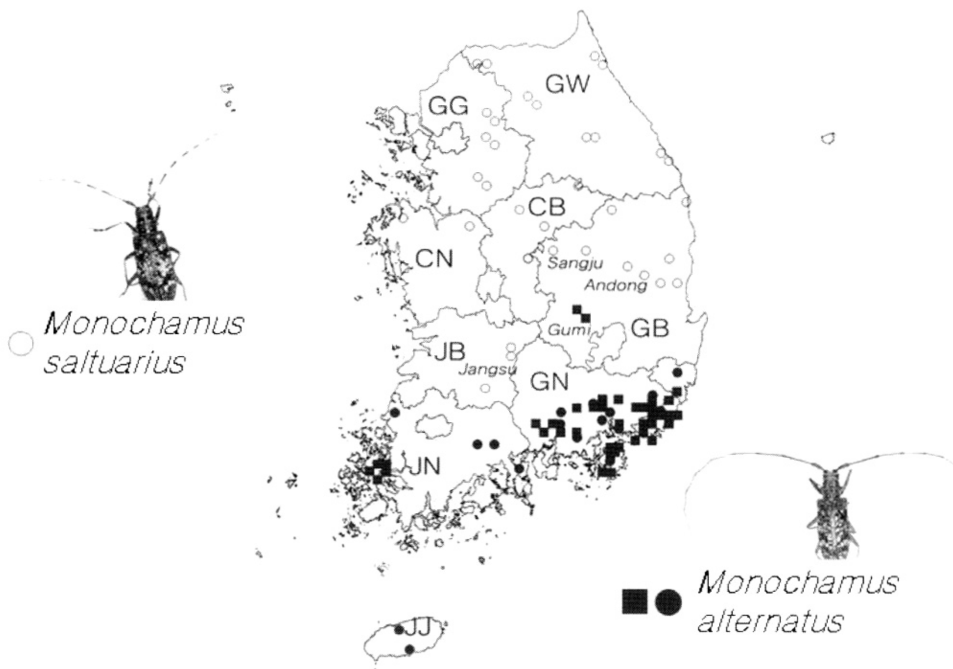

Figure 2. Map showing occurrence of *M. alternatus* and *M. saltuarius*. The solid rectangles for *M. alternatus* indicate the PWD-infected sites with the vectors of *M. alternatus*, and the solid circles show sites where *M. alternatus* beetles were collected in the study of Moon *et al.* (1995) except Jeju-do (JJ) where *M. alternatus* beetles were collected in this study.

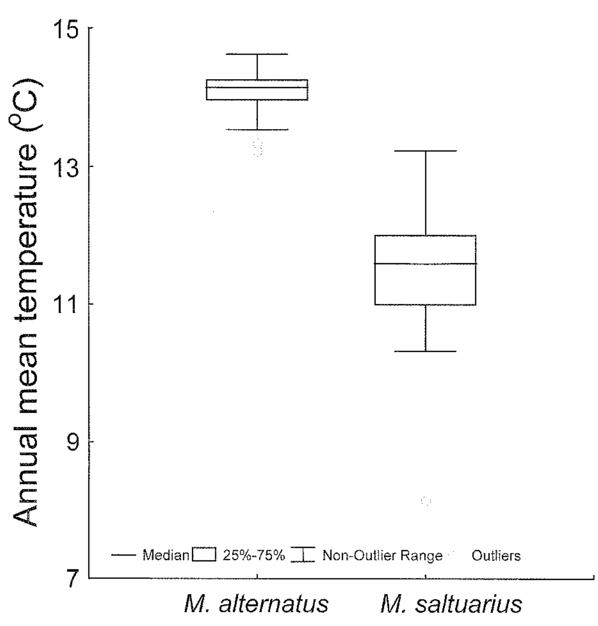

Figure 3. Comparison of annual mean temperatures between study sites where *M. alternatus* and *M. saltuarius* were collected. Statistical test showed significant difference between two species (t-test, p <0.0000).

Monochamus species might be separated around 13.2°C of annual mean temperature. *M. saltuarius* is generally known to be distributed in the cold regions such as northern China, Mongolia, Siberia, Sahalin, and northern Europe (Lee, 1987), but it was also reported to occur in southern Europe, Portugal (Oliveira, 1982). Meanwhile, *M. alternatus* has been recorded from mainland China, Taiwan, Laos, Vietnam, Korea, and Japan, showing the distribution in the warmer climate region (Nobuchi, 1975; Lee, 1987) compared with *M. saltuarius*.

In Japan, the northern limit of *M. alternatus* distribution was Fukui and Kanagawa prefectures in 1933 when PWD was restricted in the southern region of Japan (Kishi, 1995). Annual mean temperatures for 30 years of Fukui and Kanagawa prefectures were about 13.9°C and 15.1°C, respectively. As PWD dispersed, the northern limit gradually moved northward, and its limit line is now in Iwate and Akita prefectures of which annual mean temperatures are 11.0°C and 9.8°C, respectively.

Based on these results, the thermal limit of *M. alternatus* in the regions infected by PWD may be assumed to be set around 10°C of annual mean temperature in the Korean Peninsula. Based on the temperature distribution in Korea, *M. alternatus* would extend their range with PWN to the region showing 10-13.2°C of the annual mean temperature range (the light gray area in Figure 4). But the vector species may not invade northward areas showing lower than 10°C of annual mean temperature such as Japan (the white area in Figure 4). Any ecological or physiological mechanisms are not known for the reason why the northern limit of *M. alternatus* moved northward as PWD dispersed.

The warmer areas showing higher than 13.2°C of annual mean temperature locate over the southern parts including most areas of Gyeongsangnam-, Jeollanam- and

Jeju-dos, about an half area of Jeollabuk-do, and small parts of Gyeongsangbuk-do in Korea. All PWD-damaged pine forests are found in these areas (Figure 2). Therefore, absence of *M. sartuarius* in PWD infected pine stands in southern parts indicates that *M. alternatus* may monopolize the *Monochamus*-niche in these areas. The moderate temperature areas showing 10-13.2°C of annual mean temperature are most wide in Korea, by scattering in the southern regions of Jeollanam-, Gyoungsangnam-, and Jeju- dos, and by covering most parts of Gyeongsangbuk, Chungcheongbuk, and Chungcheongnam-dos in South Korea, and of Hwanghae-do, Pyeongannam-do in North Korea. This study indicates that *M. alternatus* may not distribute in these area (Figure 2), whereas *M. saltuarius* would monopolize the *Monochamus*-niche there, but *M. alternatus* would invade the niche as PWD disperses these areas and resultantly compete with *M. saltuarius*. Finally relatively cool areas showing less than 10°C of annual mean temperature include most parts of Gangwon-do in South Korea and North Korea. It is likely that *M. saltuarius* can keep monopolizing the niche in these areas even in the invasion of PWD for the cold climate. Otherwise, it is likely that PWD could not invade the cold regions of Korea as Japan. Although *M. saltuarius* was not collected in the southern regions of Jeollanam-, Gyoungsangnam- and Jeju-dos in this study, the map predicted that *M. saltuarius* may be distributed there. The southernmost localities of the museum specimen of the pine sawyer species are Mt. Baekun in Jeollanam-do and Hampyong- and Sancheong-guns in Gyongsangnam-do (Lim and Lee, unpublished; see three bold open circles in southern region in Figure 4). Most of the localities of the other specimen of *M. saltuarius* were located in Gyounggi- and Gangwon-dos (Lim and Lee, unpublished). The species was also reported to be collected in Jeju-do without any detailed information for the locality (Jeju-do Folklore and Natural History Museum, 1995; *M. saltuarius* was identified as *M. sutor* in this article; Lim J.O. pers. comm.). The map shows that *M. saltuarius* would occur in the highlands of more than about 500 m of elevation in the Jeju island.

Yi *et al.* (1989) observed the emergence of *M. alternatus* in a field experiment in Seoul, and showed the possibility of the occurrence of *M. alternatus* in this area. Based on the annual mean temperature of Korea, Enda (1989) also predicted that *M. alternatus* can live throughout the whole region of South Korea. Although the pine sawfly species doest not occur naturally in mid to northern parts of South Korea (Figure 2), it may spread over these areas with PWN as discussed previously. In these areas, *M. saltuarius* may act as the minor vector of PWN like *M. saltuarious* in Japan (Jikumaru and Togashi, 1996; Sato *et al.* 1987). In 2005, a pine

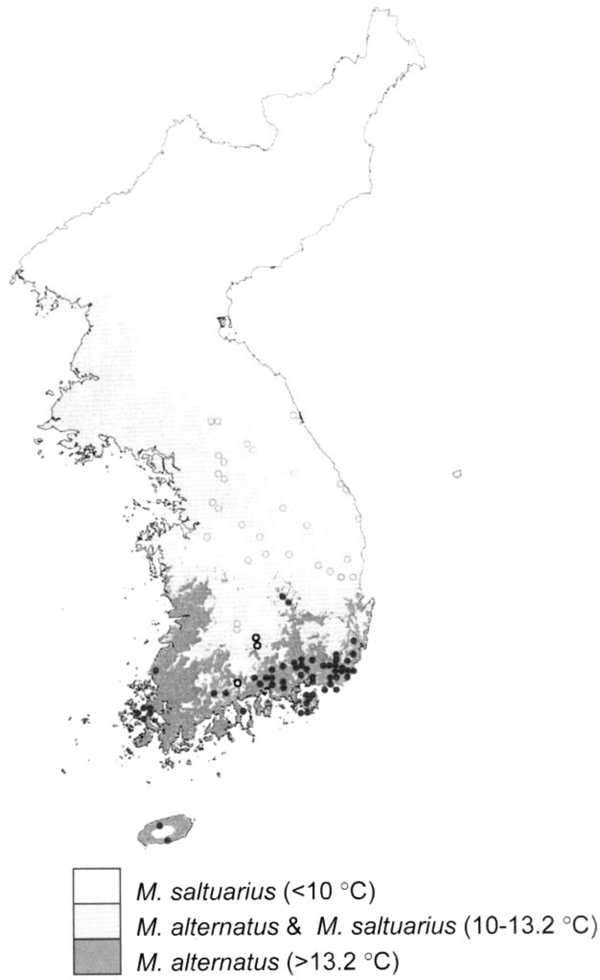

Figure 4. Distribution patterns of *M. alternatus* and *M. saltuarius* estimated based on temperature limitation in three categories in the Korean Peninsula. Temperature limitation is indicated in the parenthesis. Solid circles (●) indicate the collected sites of *M. alternatus*, and open circles (○) are the sites of *M. saltuarius* in this study. Bold open circles (O) show the collected sites of *M. saltuarius* based on specimen in museums in Korea (Lim and Lee, unpublished). See texts for details of three annual mean temperature boundary zones.

trees infected with PWN were found at Andong in Gyoungsangbuk-do (GB), and at Donghae and Ganglewung in Gangwon-do (GW) (Kwon, 2006) where *M. saltuarius* may occur exclusively without invasion of PWD. The vector species are not yet recognized there.

In conclusion, *M. alternatus*, a vector for PWN in Korea, is confined in southern areas in Korea, whereas *M. saltuarius* occurs widely in the mid to northern areas in Korea. We suggest the hypothesized distribution map (Figure 4) for the pine sawyers, using our limited data and GIS tool. The ongoing spread of PWD will change the current distribution of the two species in the following years. The dispersal rate of PWD will be possibly related with vector species, and the control method such as aerial spraying should be adjusted by the vector species for the different phenology of *M. saltuarius* such as adult emergence period. In this study, adults of *M. saltuarius* emerged usually from late April to late May with peak in mid May across all the study sites as described previously. The emergence period may be about one month earlier compared with that of *M. alternatus* in Korea, being comparable the data in Japan (Kishi, 1995). This shows that the correct information for the distribution pattern of the two vector beetle species should be urgent for the control of PWD. Our hypothesized distribution map for the vectors should be updated and tested by the further extensive data on the distribution of the *Monochamus* species for the prediction of PWD dispersal and its proper control.

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