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Management of pine wilt disease in Korea through preventative silvicultural control

Tae-Sung Kwon[a], Joon Hwan Shin[a], Jong-Hwan Lim[a], Young-Kul Kim[a], Eun Ju Lee[b,*]

[a] Division of Ecology, Korea Forest Research Institute, Seoul 130-712, Republic of Korea
[b] School of Biological Sciences, Seoul National University, Seoul 151-742, Republic of Korea

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ABSTRACT

Pine wilt disease (PWD) represents a major threat to forest ecosystems worldwide. Although PWD is now better understood, effective control measures for this disease have still not been devised. Here, we report several years of field studies on preventative silvicultural control of PWD. Silvicultural control through preventative clear-cutting and the manual removal of logs was implemented between 2005 and 2009 in 16 Korean districts that had newly PWD-infected stands. Preventative clear-cutting of neighboring asymptomatic pine trees (within a 10–50-m radius of wilt trees) and the removal of felled logs or branches suppressed spread of PWD. Occurrences of PWD wilt pines in districts (city or county) subjected to this silvicultural control method were significantly reduced compared with those in districts using conventional controls (physical or chemical treatment of wilt pine trees). Through silvicultural control, PWD was successfully suppressed in 11 of 16 districts investigated. In contrast, successful control was achieved in only 1 among 18 districts subjected to conventional control. Our results will be of considerable interest to those engaged in the very difficult battle against the global spread of PWD.

1. Introduction

Pine wilt disease (PWD) is caused by the pinewood nematode (PWN), *Bursaphelenchus xylophilus* whose vector is the pine sawyers (*Monochamus* spp.). PWD was ranked first on the 1986 quarantine list published by the European Plant Protection Organization; quarantining has caused international disputes in the lumber trade (Sathyapala, 2004). The first epidemic of PWD was documented in 1905 in Japan, and by the 1970s, with the exception of the northern districts, PWD had spread throughout the country (Kishi, 1995; Yoshimura et al., 1999). By the 1980s, the PWD epidemic had spread to many other Asian countries, including China, Taiwan, Hong Kong, and Korea. It subsequently entered Europe (Portugal) in 1999 (Futai, 2008; Mota and Vieira, 2008; Shin, 2008; Zhao, 2008). Various pine species that are common in Europe (*Pinus sylvestris*, *Pinus pinaster*, and *Pinus nigra*) are susceptible to PWN (Wingfield, 1987). Interestingly, *Pinus rigida*, a species native to North America, is resistant to PWD infection and, to date, has not been damaged by PWD in Korea (Shin, 2008). These ecological phenomena indicate that pine forests around the world, particularly those in Eurasia, are at high risk of PWD damage (Evans et al., 1996).

PWD wilt pines were first diagnosed in Busan, Korea in 1988 (Fig. 1). Because of strict control efforts in the early period of infection, numbers of PWD wilt pines declined abruptly from 345 in 1988 to 20 in 1990 (Korea Forest Service, unpublished). As public interest in PWD became weakened, however, the number of PWD wilt pines began to increase in Busan. In 1997, PWD wilt pines were found in pine forests bordering the junction of the Namhae and Guma highways in Haman, which is located 55 km from the first infection site in Busan (Fig. 1). In the next year, there were PWD wilt pines in 5 ha of pine forests bordering main roads within downtown in Jinju. The PWD epidemics had spread over 50% of the districts of Gyongnam Province by 2002, and through all districts by 2007.

In 2001, PWD wilt pines were found in Mokpo (Jeonnam Province) and in Gumi (Gyongbook Province). The PWD-infected forests in Mokpo and Gumi are located 245 km and 115 km from the first infection site in Busan, respectively. The infected forest in Gumi borders the Gyongbu highway. In 2003, PWD epidemics spread to Sinan and Youngam in Jeonnam Province and to Chilgok in Gyongbook Province. In Gyongbook Province, PWD wilt pines were newly found in Pohang, Gyongju, Andong, Gyongsan, and Youngcheon during 2004–2005. Almost all wilt pines fringed highways and main provincial roads. In 2004, PWD wilt pines were found among Japanese black pines (*Pinus thunbergii* Parlatore) stand near a golf course on Jeju Island, the biggest island in Korea and famous for tourism.

In 2005, PWD wilt pines were found in the northernmost districts of Gangreung and Donghae (Gwangwon Province). Nine PWD wilt pines in Gangreung were found at the end of Youngdong high-

* Corresponding author. Tel.: +82 2 880 6673; fax: +82 2 883 1254.
E-mail address: ejlee@snu.ac.kr (E.J. Lee).

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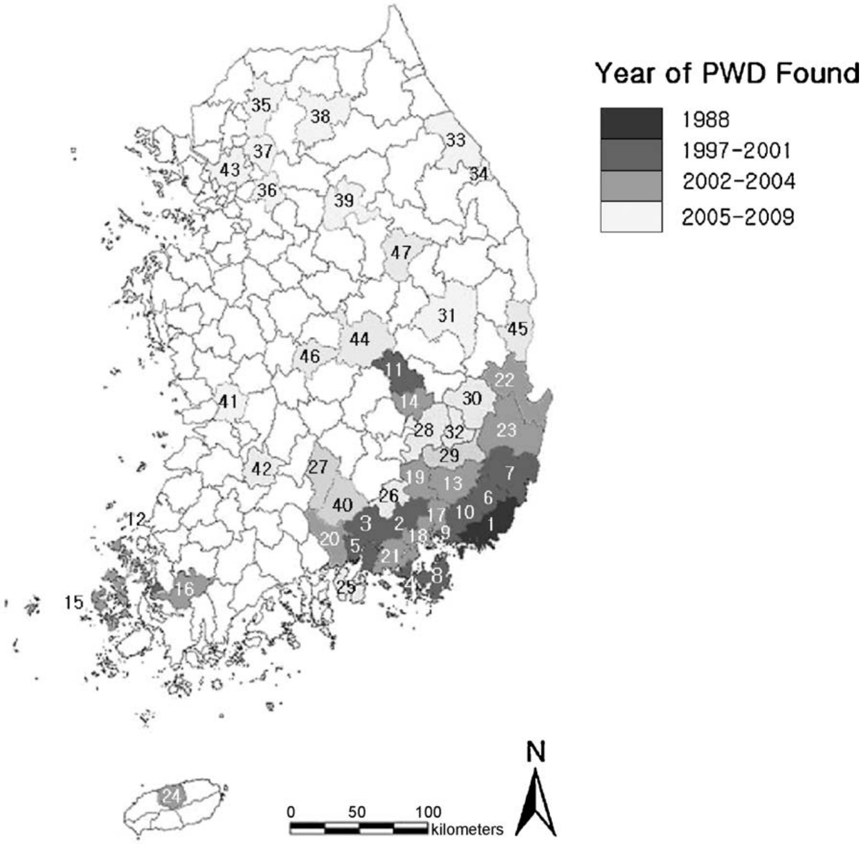

Fig. 1. PWD-infected districts in the Republic of Korea. Numbering of districts is arranged by infection times, and matches information in Table 1. The districts are as follows; 1: Busan, 2: Haman, 3: Jinju, 4: Tongyoung, 5: Sacheon, 6: Yangsan, 7: Ulsan, 8: Geojae, 9: Jinhae, 10: Gimhae, 11: Gumi, 12: Mokpo, 13: Milyang, 14: Chilgok, 15: Shinan, 16: Youngam, 17: Changwon, 18: Masan, 19: Changyoung, 20: Hadong, 21: Goseong, 22: Pohang, 23: Gyongju, 24: Jeju, 25: Namhae, 26: Uiryeong, 27: Hamyang, 28: Daegu, 29: Cheongdo, 30: Youngcheon, 31: Andong, 32: Gyoungsan, 33: Gangreung, 34: Donghae, 35: Gwangju, 36: Pocheon, 37: Namyangju, 38: Chuncheon, 39: Weonju, 40: Sancheong, 41: Iksan, 42: Imsil, 43: Seoul, 44: Sangju, 45: Youngdeok, 46: Danyang, and 47: Okcheon.

way, and 9 more in Donghae occurred high on a mountainside (Kwon, 2006b). During 2006–2007, PWD wilt pines were found in other northern districts such as Seoul, Gwangju, Namyangju, Pocheon, Wonju, and Chuncheon. In 2009, PWD wilt pines were newly found in Youngdeok (Gyongbook Province), and Okcheon and Danyang (Chungbook Province). PWD occurs along highway in districts of Chungbook province. By 2009, 47 districts in Korea had experienced PWD epidemics, but 13 of them succeeded in suppressing the disease (Korea Forest Service, unpublished).

To date, PWD control has focused mainly on elimination of pine sawyer larvae inhabiting wilt pine trees, either by winter fumigation or by controlling the adult sawyers with aerial insecticide spray in summer. However, conventional control (C) has certain flaws. First, approximately 18–61% of PWD wilt trees have no wilt symptoms until the growing season in following year, and these trees are left untreated during the winter control season (Kishi, 1995). Secondly, even branches as small as 2 cm in diameter contain pine sawyers (Yoshimura et al., 1999) and require treatment. Small branches are often overlooked because it is a time-consuming task to collect them for fumigation from the scatter around felled logs. Furthermore, transportation of fumigated logs or wilt trees for lumber has been a main vector of long-distance spread of PWD in Korea, accounting for approximately 38% of the PWD invasion (Shin and Han, 2006). For these reasons, despite intensive control efforts, PWD wilt trees appear in the same pine stands every year or occur at new sites distant from previously infected stands. Therefore, it is likely that preventative clear-cutting of wilt trees, including adjacent asymptomatic pines and healthy pines followed by physical elimination of felled logs and branches by burning or chipping (for example) will significantly suppress the reoccurrence of PWD wilt trees within pine stands (Kwon, 2002, 2005a,b, 2006a,b; Kwon et al., 2008).

Between 1988 and 2001, burning of wilt pines or chipping were usual procedures for controlling pine sawyer larvae and PWN in Korean forests; the larvae inhabit logs during winter. After 1989, aerial pesticide spraying was undertaken in each June to control pine sawyer adults. Since 2002, wilt pine logs have been fumigated with metam-sodium (Kwon, 2005a). Despite the application of new control methods, the PWD-infected area grew exponentially until 2005. A specific law for the control of PWD epidemics became effective in September 2005; it includes strong penalties against illegal movement of pine logs from PWD infested regions. A control fund was greatly increased from US $7,600,000 in 2004 to $35,800,000 in 2005 and to $55,200,000 in 2006 (Korea Forest Service, unpublished).

Silvicultural control (S) involving clear-cutting around PWD wilt pines was newly applied to heavily infested pine forests spread over ca. 20 ha in Pohang in 2004 and to 0.5 ha in Jinju in 2005. The procedures have been used in newly PWD-infected districts since 2005 (Kwon et al., 2008). Tree-injection of a nematicide containing abamectin and emamectin benzoate may prevent wilting of pines by PWN (Lee et al., 2009), and this control method has been in use since 2005. From that point in time onward, the spread of PWD epidemics has been significantly inhibited in the Republic of Korea. In this study, we tested the effectiveness of preventative silvicultural control on PWD in the wild and compared the effectiveness of different control measures for PWD.

2. Methods

2.1. Topography, climate, and vegetation of the Republic of Korea

Many coniferous and deciduous tree species occur on the Korean peninsula, which has a long north-south oriented topographic complexity. Seventy percent of the terrain is dominated by hills and mountains; there are many high peaks with east-west slopes. Relative warm temperatures prevail through the year in South Korea (annual mean temperature 10–16 °C, Korea Meteorological Administration). Annual mean precipitation is ca. 1000–1800 mm, and more than a half of precipitation falls in summer (June to August). Winters are dry and cold, fitting a typical continental climate pattern.

Invasion of northeastern Chinese, eastern Siberian, Japanese, and subtropical floral elements contribute to the high tree diversity. Korea falls within the temperate zone, although broadleaved evergreen plants and bamboo grow in the south. The northern part of the country is at the same latitude as New England, and the southern part is at the latitude of South Carolina (USA). The Korean peninsula is about as large as mainland Britain.

Pinus densiflora and *Quercus* species are dominant trees in Korean forests. These pines and oaks form mixed stands in many parts of the country. *P. densiflora* naturally grows in relatively dry and nutrient-poor sites and can successfully regenerate with human intervention. This photophilous pine has an extraordinary capability for natural regeneration by seeds. Over the last millennium, *P. densiflora* has been considered the only tree available in sufficient quantities to supply timber for building palaces, temples, public buildings, and farm cottages. With special government protection, the species has flourished in most lower-elevation forests. In addition to PWD damages, *P. densiflora* stands in urban forests have been negatively affected by fast-growing, introduced species such as *Robinia pseudoacacia*. These two species compete with one another in common environments, with *R. pseudoacacia* taking over sites formerly occupied by *P. densiflora* (Lee, 2001). Pine forests (*P. densiflora* and *P. thunbergii*) make up 23.5% of the forest area in Korea and provide distinctive landscape throughout the terrain (Kwon, 2006).

2.2. Control methods

2.2.1. Conventional control (C) and nematicide-injection (N)

Control procedures for PWD epidemics included aerial spraying of pesticide to kill pine sawyer adults, and physical or chemical treatment of wilt pines to kill their larvae. Aerial pesticide spraying began in 1989 following the first PWD detection. Fenitrothion, a broad-spectrum organophosphate (EXTONET, 2004), was the main agent in the sprays (Kwon, 2008). Because of fenitrothion damage on bee farms and other negative environmental impacts, it was replaced with thiacloprid in 2006. Aerial spraying was conducted on 3–5 occasions each year (from early June to mid July) over PWD infected forests and neighboring stands in all PWD-infected districts. In 2009, pine forests covering 15,000 ha were subjected to aerial spraying (Korea Forest Service, 2009), although the area of PWD infected forests in that year was estimated to be only 5633 ha (Korea Forest Service, unpublished). Information on aerial spraying is presented by Kwon et al. (2005b) and Kwon (2008).

The methods of conventional control, in which only wilt pines were physically or chemically treated, have been altered several times since 1988. Until 1995, physical controls such as chipping and burning (CP) were the usual treatment for wilt pines. Chemical control with aluminium phosphide was developed in 1995 (Moon et al., 1995), and used for a short period in the treatment of wilt pines. However, effects of this chemical treatment were very weak (Lee et al., 2003), and physical control was the main treatment until 2001. After the effectiveness of metam-sodium (previously used in Japan) in wilt pine fumigation became clear (Lee et al., 2003), it was adopted as a treatment agent over the period 2002–2005. Nevertheless, PWD epidemics spread rapidly (Figs. 1 and 5). Accordingly, the physical control has been employed once again for treating PWD wilt pines since 2005, and the metam-sodium treatment (CF) has been used only in the most difficult circumstances when physical treatment is impractical. In addition, fumigated logs scattered in PWD-infested forests have been gradually removed by chipping or burning.

Nematicide (N) such as abamectin and emamectin benzoate is highly efficient in the prevention of pine wilt caused by PWN. PWN mortality is high for both abamectin (1.8% EC) and emamectin benzoate (2.15% EC) treatments (Lee et al., 2009). Nemacides were tree-injected from December to February (Korea Forest Research Institute, 2007). Injection procedures have been in place since 2005. About one-fifth of PWD-infested forests in long-infected districts, and all the PWD-infested forests in newly infected districts have been injected annually. Injection has become the main preventative control method.

2.2.2. Silvicultural control (S)

Fig. 2 schematically presents our protocols for the elimination of PWD epidemics by preventative control of PWN-infected pines with no wilt symptom using silvicultural control, which entails clear-cutting and the physical elimination of logs and branches. Pine trees surrounding (i.e. within a radius of 10–50 m) PWD wilt trees were cut along with the wilt trees, and the felled logs or branches were burnt or chipped to sawdust. Silvicultural control was conducted from December to April in the following year with the exception of Daegu and Sanju, where control procedures were implemented in May and June, respectively. The remaining rooted trunks of PWD wilt trees were fumigated with metam-sodium and covered with vinyl sheets.

In 2004, silvicultural control was firstly applied to a 20 ha stand of ca. 90 ha of PWD-infested forest in Pohang. Felled logs were burnt. In 2005, silvicultural control was also applied experimentally in 0.5 ha of PWD-infested forest in Jinju, where all felled logs were fumigated with metam-sodium (Kwon, 2006b). After 2005, silvicultural control was the main procedure for combating PWD epidemics in newly infested districts. Silvicultural control was applied in 16 out of 27 districts (city or county) experiencing new PWD infections between 2005 and 2009 (Table 1). Silvicultural control was also applied to heavily infested stands with >30% mortality in long-infested districts (Forest Human Resources Development Institute, 2008). Pine forests surrounding clear-cut zones formed during silvicultural control were subjected to nematicide-injection (N).

2.3. Data analysis

A systematic system for control of PWD epidemics was not in place in Korea until 2002 (Lee, D.L., in the Korea Forest Service, pers. comm.). Therefore, data for districts that had PWD wilt pines prior 2001 were not used in the analysis. Data from eight districts neighboring the heavily infested districts (e.g. Jinhae, Masan, Hadong, Chilgok, et al.) were also excluded because PWD wilt pines (infected by pine sawyers immigrating from neighboring districts) were very likely present. Data for Pohang was not included because silvicultural and conventional controls were applied simultaneously in 2004.

Hence, control effects were determined from data on PWD wilt pines (i.e. number of PWD wilt pines) in the period 2002–2009. During the period 2002–2004, when PWD wilt pines were fumigated with metam-sodium, we selected for analysis seven newly infested districts, including Mokpo, Shinan, Youngam, Gumi, Geoje,

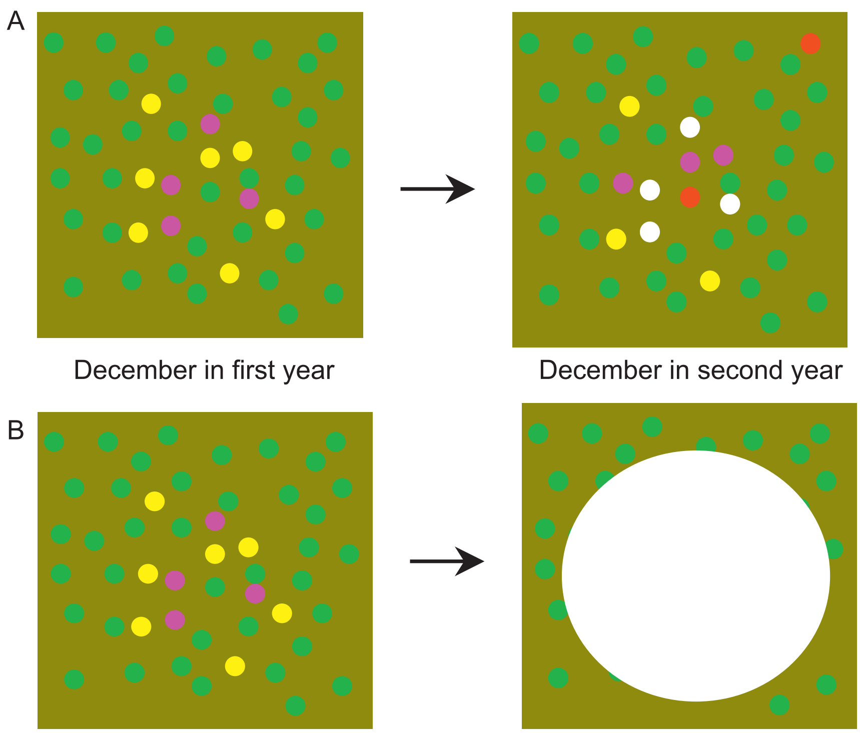

Fig. 2. Schematic process of the PWD infection under conventional (A) and silvicultural (B) control protocols. Green circle: normal pine trees, pink circle: first-year PWN-infected pines with wilt symptoms, yellow circles: first-year PWN-infected pines without wilt symptoms, red circles: second-year PWN-infected pines with wilt symptoms, white circles: chemically treated pines, and large white circle: preventative clear-cut area around PWD wilt pines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Milyang, and Jeju because in these areas there was a low probability of PWD infection through pine sawyer immigration from neighboring districts. After 2005, the fumigation control (CF) method was replaced with physical control (CP), and nematicide-injections (N) were applied to trees around wilt pines, and to trees in neighboring pine forests. From 2005 to 2009, 11 districts using these dual control methods were selected for analysis. These districts were also newly infested. Of the 11 districts, 7 had first occurrence of PWD wilt pines during this period; the remaining 4, Andong, Daegu, Namyangju, and Gwangju changed control methods from silvicultural to conventional control. Data from all of the 16 new districts utilizing silvicultural procedures with nematicide injection (S + N) as the main control method were used for comparison of control effects with conventional (CF and CP + N) controls. In addition, data from Gyongju where methods switched from conventional in 2005 to silvicultural control in 2006 were used to assess the silvicultural control effect.

Data for PWD wilt trees were obtained from the Korea Forest Service, and certain errors were corrected through communications with agents of the forest division in the districts. Damage scales in the district were categorized as large (i.e. >100 wilt trees in pre-treatment year) or as small (i.e. <100). The numbers of PWD wilt trees in the first and second years following treatment were converted into percentages of numbers in the pre-treatment stage. These values were used for ANOVA. Aerial spraying was applied to all the PWD-infected districts, precluding analysis of effects in PWD control.

ANOVA was used to determine the significances of difference in procedural effects among CF (2002–2004, chemical control of wilt pines, $n = 7$), CP plus nematicide-injection (CP + N) (2005–2009, physical control of wilt pines, $n = 11$), and S plus nematicide-injection (S + N) (2005–2009, $n = 16$) districts (Zar, 1999). Interaction effects of the control methods and the damage scales were also estimated by ANOVA. Because all silvicultural controls were conducted with nematicide injection, effect of nematicide injection could not be independently tested by ANOVA. It should be noted that data in the present study was obtained from the regional districts combating with PWD but not from the pre-designed study plots.

The Korea Forest Service defined the suppression of PWD epidemics in a district as zero presence of PWD wilt pines in 2 consecutive years. When suppression was declared for a district, transportation of pine logs to other districts was permitted. Frequencies (i.e. number of districts) of suppression in 34 districts investigated were compared among the 3 control regimes using log-linear analysis of frequencies (StatSoft Inc., 2001; Zar, 1999).

3. Results

Table 1 and Fig. 3 present the occurrence of PWD wilt trees in the first (A) and second (B) years after the treatment in comparison with pre-treatment occurrences. The effect of silvicultural control was significantly different from the two conventional procedures (first year, $F_{2,31} = 11.3$, $p < 0.0001$; second year, $F_{2,25} = 4.7$, $p < 0.05$) but effects were not significantly different between the two conventional procedures (Fig. 3, $p > 0.05$). There was no significant interaction between control method and damage scale (first year, $F_{2,31} = 0.67$, $p = 0.52$; second year, $F_{2,25} = 2.3$, df = 2, $p = 0.12$). Hence, control effects of three control procedures did not be changed according to damage scale of PWD. This shows that S + N control significantly depressed occurrence of PWD wilt pines compared with CF and CP + N. However, the treatment methods (i.e. physical or chemical) on wilt pines in conventional procedure or/and the nematicide-injection on non-wilt pines did not have a significant impact on the depression of PWD epidemics.

After the implementation of S + N procedures, trees in 11 of 16 districts investigated had no symptoms of PWD over 2 years, indicating suppression of the PWD epidemic (Fig. 4). The suppression

Table 1
Occurrences of PWD wilt pines, host pine species, control methods and climate data by the district (county or city). District numbers match those in Fig. 1. CF: conventional control (C) using fumigation of wilt pines with metam-sodium, CP: conventional control using physical treatment, N: tree injection of nematicide into non-wilt pines, and S: silvicultural control. Year indicates that of pretreatment. Damage scale is defined in the running text. Host pine species; Pd: *Pinus densiflora*, Pt: *P. thunbergii*, and Pk: *P. koraiensis*. Climate data were obtained from district weather stations, and are presented as annual mean temperature (°C) and mean precipitation (mm) in the 10 years after 2000 (Korea Meterological Administration, 2000–2009).

Number	District	Method	Year	Scale	Number of PWD wilt pines			Host pine	Climate	
					Pretreatment	1st year	2nd year		Temp.	Precipitation
12	Mokpo	CF	2002	Large	360	895	372	Pd, Pt	14.0	2475
8	Geoje	CF	2002	Large	18,700	11,950	12,143	Pt	14.1	1986
11	Gumi	CF	2002	Large	10,983	7,846	3,842	Pd	12.0	1194
13	Milyang	CF	2002	Large	500	357	534	Pd	13.4	1274
15	Shinan	CF	2003	Small	61	44	225	Pt	14.0	2475
24	Jeju	CF	2004	Small	14	44	–	Pt	16.1	1599
16	Youngam	CF	2004	Small	22	0	0	Pt	14.0	2475
24	Jeju	CP + N	2005	Small	44	52	29	Pt	16.1	1599
23	Gyongju	CP + N	2005	Large	227	309	–	Pd, Pt	12.7	1136
19	Changyoung	CP + N	2005	Large	271	962	917	Pd	13.4	1274
25	Namhae	CP + N	2005	Large	782	600	695	Pt	14.1	1940
29	Cheongdo	CP + N	2005	Large	4,076	3,731	3,480	Pd	14.4	1131
28	Daegu	CP + N	2006	Small	23	19	7	Pd	14.4	1131
40	Sancheong	CP + N	2007	Small	9	0	2	Pd	13.1	1635
42	Imsil	CP + N	2007	Small	10	10	1	Pd	11.3	1384
31	Andong	CP + N	2007	Small	14	27	34	Pd	12.0	1127
37	Namyangju	CP + N	2008	Small	10	15	–	Pk	12.9	1481
35	Gwangju	CP + N	2008	small	17	20	–	Pk	11.8	1423
31	Andong	S + N	2005	Large	2,799	14	–	Pd	12.0	1127
27	Hamyang	S + N	2005	Small	11	0	0	Pd	13.1	1635
28	Daegu	S + N	2005	Large	150	23	–	Pd	14.4	1131
30	Youngcheon	S + N	2005	Small	24	0	0	Pd	12.7	1136
26	Uiryeong	S + N	2005	Small	3	0	0	Pd	13.6	1573
33	Gangreung	S + N	2005	Small	9	0	0	Pd	13.5	1611
34	Donghae	S + N	2005	Small	9	0	0	Pd	12.6	1460
32	Gyoungsan	S + N	2005	Small	9	0	0	Pd	14.4	1131
39	Weonju	S + N	2006	Small	1	0	0	Pk	11.9	1398
38	Chuncheon	S + N	2006	Small	3	0	0	Pk	11.4	1411
36	Pocheon	S + N	2006	Small	12	0	0	Pk	10.2	1397
37	Namyangju	S + N	2006	Small	16	0	10	Pk	12.9	1481
23	Gyongju	S + N	2006	Large	309	13	14	Pd, Pt	12.7	1136
35	Gwangjoo	S + N	2006	Large	313	0	17	Pk	11.8	1423
41	Iksan	S + N	2007	Small	10	0	0	Pd	13.1	1313
43	Seoul	S + N	2007	Small	37	0	0	Pd	12.9	1481

was achieved only in Youngam among the 18 conventional control (CF, CP + N) districts investigated (Table 1). It was significantly different among the three control regimes ($\chi^2 = 12.7$, df = 2, $p < 0.01$). Suppression was recently declared in Mokpo, where no PWD wilt pines had not been found in the 2 years since 2008. However, suppression was achieved in Mokpo 7 years after first detection of PWD wilt pines. During the early years (2001–2003) of the infection period, PWD from Mokpo may have spread to neighboring districts, such as Shian and Youngam (Fig. 1).

Fig. 5 presents the annual change in PWD damage extent (number of PWD infected districts, and area of PWD-infected forests) in the Republic of Korea. The two estimators of annual change were congruent except in 2009, when the area of PWD-infected forests

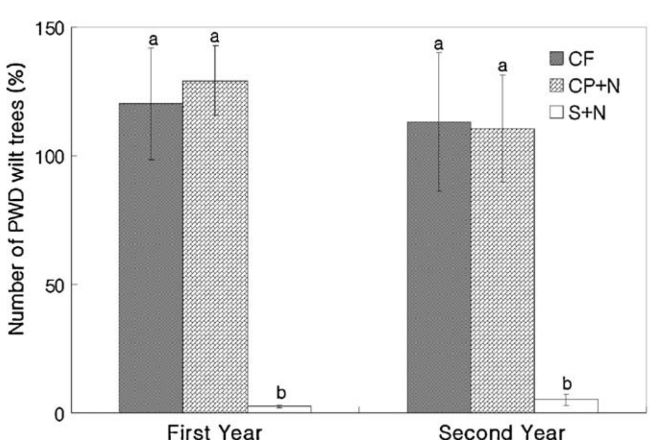

Fig. 3. Changes in occurrences of PWD wilt trees in the first (A) and second (B) year following application of three control methods. CF: conventional control (chemical treatment of wilt pines using metam-sodium, $n = 7$), CP + N: physical treatment plus nematicide-injection ($n = 11$), and S + N: silvicultural control (treatment of wilt pines and surrounding non-wilt pines, $n = 16$) plus nematicide-injection. Numbers indicate proportional changes (%) in PWD wilt trees occurrences after the treatment compared to pre-treatment values. The error bars indicate 1 SD. Different lower case letters above bars indicate significantly different means ($p < 0.05$).

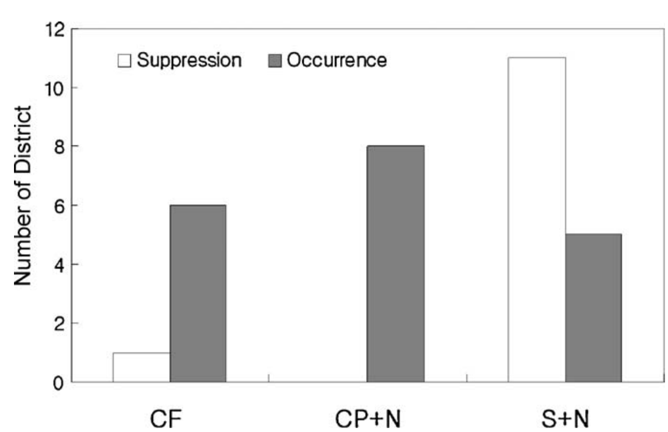

Fig. 4. Suppression of PWD epidemics in districts using three control methods. Suppression is defined as absence of PWD wilt pines in 2 consecutive years. Control method abbreviations are given in the legend to Fig. 3.

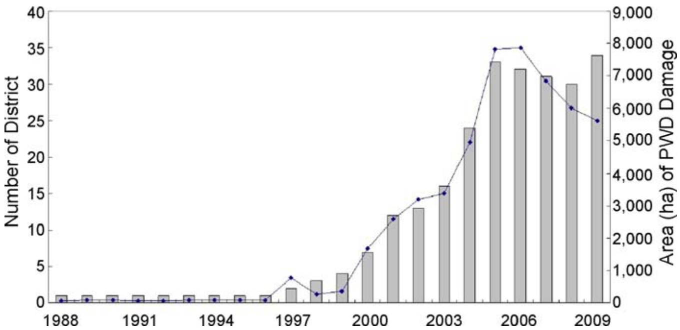

Fig. 5. Annual change in PWD damage extent (number of PWD infected districts and area covered by PWD infected trees). A PWD-infected district was one in which PWD wilt pines were present in each year. Annual PWD damage extent data was provided by Korea Forest Service (unpublished).

decreased but the number of PWD-infected districts increased. Spread of PWD epidemics accelerated until 2005 but significantly inhibited since 2006. In 2005, 10 districts were newly infected by PWD but 6 succeeded in suppression using silvicultural control (Table 1). In 2006, five districts newly experienced PWD, and subsequently applied silvicultural control. None of the districts had wilt pines in the next year, and three of them declared suppression. However, PWD wilt pines reappeared in Gwangju and Namyangju in 2008 (Table 1) when the procedure was changed to conventional from silvicultural control. Among three districts newly experiencing PWD in 2007, only Iksan using S + N succeeded in suppression. However, the other two districts using conventional control did not achieve suppression, even though the number of PWD wilt pines in the pretreatment was low (Table 1). Since 2008, four districts newly experienced PWD, and used S + N treatment. PWD wilt pines nearly disappeared (Okcheon, Danyang, and Sangju) or greatly declined (Youngdeok).

4. Discussion and conclusions

In the Republic of Korea, spread of PWD epidemics has been significantly inhibited since 2006 through successful control effected in newly infected districts by application of the silvicultural method. The effectiveness of silvicultural control was astonishing. However, its use is restricted to control of PWD epidemics in newly infested districts or in heavily damaged pine forests in long-infested districts (Korea Forest Service, 2007, 2009). In 2009, silvicultural control was used as the main treatment for PWD epidemics in newly infested districts, including Okcheon, Danyang, and Youngdeok, but conventional control with the nematicide-injection was still the major treatment in most PWD infected districts despite its limited effectiveness and inherent flaws that are apparent in the present study. Nematicide-injection was a preferred procedure for preventative control in pines. Injection was even thought to be a good alternative to silvicultural control in treatment of asymptomatic pine trees. In 2009, injections were applied in 1530 ha of long-infested districts, and silvicultural control was applied in 100 ha (Korea Forest Service, 2009). However, injections did not improve *in situ* results for conventional control.

On Jeju island, where only 15 PWD wilt pines were identified within a 1 ha area in 2004, conventional procedures and injection had been used together since 2005. Japanese black pines are dominant trees in seaside forests on the island and the wide spread of PWD epidemics is serious problem for forest management and conservation of the beautiful landscape for tourism, the main industry of the island. Therefore, forest managers in local government did their best to eliminate PWD epidemics using adequate funding under the guidance of PWD specialists in the Korea Forest Service. Despite sincere efforts toward suppression of PWD epidemics, several tens of PWD wilt pines occurred annually, and PWD epidemics spread 8 km out from the origin of infection in 2008 (Forest Human Resources Development Institute, 2008). As documented above, however, silvicultural control succeeded in suppressing PWD epidemics in 11 of 13 new districts with low infection levels (i.e. less than 100 PWD wilt trees). Since 2005, silvicultural control has been used as a main control method in all newly infested districts except Sancheong, Imsil and Cheongdo. The dual control procedure of conventional control and injection was also used there. Despite low number of PWD wilt pine in pretreatment (i.e. less than 10), PWD wilt pines reoccurred in Sancheong and Imsil in the following years. In Cheongdo, number of wilt pines slightly decreased from 4076 in 2005 to 3480 in 2007. However, the area of PWD infection increased tenfold from 30 ha in 2005 to 296 ha in 2008 (Kwon et al., 2008). Suppression of wilting of pine trees by the injection procedure may induce pine sawyers to move on to weak or wilting pine trees in neighboring pine forests for oviposition.

The decline in PWD damage within heavily infested regions such as Busan and Gyongnam provinces is not explained solely by the application of silvicultural procedures, because treatment was restricted to heavily infested pine forests. Numbers of PWD wilt pines in Busan and Gyongnam provinces greatly decreased from 518,349 in 2005 to 96,558 in 2009 (Korea Forest Service, unpublished). Removal of the heavily infested forest by silvicultural control might eliminate the largest populations of pine sawyers and PWN in the regions, perhaps the biggest sauce populations for accelerated spread of PWD epidemics until 2005. In addition, numerous PWD wilt pines occurred annually in these heavily infested forests; these trees made up the largest proportion of wilt pines in our data. Since 2005, PWD wilt pines have been physically treated by chipping or burning rather than by fumigation with metam-sodium. Fumigation was restricted to a few PWD infested pine forests where chipping or burning were impractical as noted above. In addition, old fumigated logs were removed by chipping. Vinyl sheets covering fumigated logs were sometimes opened by mistake during the treatment or broken by branches on logs (Kwon, 2005a). These exposed logs would be potential sources of repetitive PWD damage.

Most of PWD wilt pines newly found in occurred districts such as Jinju, Haman, Gumi, Pohang, Andong, Youngdeok, Danyang, Okcheon, Weonju, Chuncheon, Seoul, Gangreung, Gwangju, and Youngcheon bordering highways or motorways, indicating that PWD is spread by vehicle vectors. The movement by vehicle of just 1 pine sawyer with abundant PWN to a distant forest can lead to the infection of several pines, from which the population of PWN may be spread by pine sawyers already present in the forests before PWN arrival. Adults of *Monochsamus saltuarius* have been collected from PWD wilt pines in northern districts such as Gwangju (Kwon, Y.D., Go, S.H., pers. comm.). Kwon et al. (2005a) reported that *M. alternatus* occurs in Korean regions with an annual mean temperature >13 °C, whereas *M. saltuarius* occurs preferentially in regions with annual means <13 °C. In the southern sector of Korea, *M. alternatus* is the exclusive PWN carrier (Moon et al., 1995), indicating a PWN carrier transition from *M. alternatus* to *M. saltuarius* in the northern parts of the country. In contrast, *M. alternatus* with PWN has migrated to the northern parts of Japan, where it functions as the main PWN carrier (Kishi, 1995). This suggests that the size of migrating populations of *M. alternatus* might be insufficient for persistence in isolated PWD-infested pine forests in the northern sector of the Republic of Korea. Thus, new PWD epidemics in northern districts may have been caused through distant transport by unknown carriers of a few pine sawyers carrying PWN.

During the adult period of about 100 days (Kobayashi, 1988), very young adult pine sawyers are active, but become stationary thereafter (Kobayashi et al., 1984). The adults move a mean of 10.6–12.3 m during their lifetimes in pine stands heavily infested with pine wilt disease (Shibata, 1986). Therefore, maturation feeding and oviposition of individual pine sawflies, which are the primary infection routes of PWN (Mamiya and Enda, 1972; Arakawa and Togashi, 2002), may be restricted to a few pine trees located within a restricted area. As a result, most pine trees that wilt in 1 year are located close to pine trees that wilted in the previous year. Variations in the wilting season of nematode-infected pine trees inoculated by individual pine sawflies arise from differences in time of infection, number of inoculated pinewood nematodes, and temperature at the time of nematode inoculation (Kishi, 1995). In Weonju, asymptomatic Korean pines wilted up to 3 years after infection (Jeong, Y.J., in Korea Forest Research Institute, pers. comm.). Treatment of PWD wilt pines has generally been carried out from November to April, when the pinewood nematode and its vectors inhabit wilt pine trees. Hence, asymptomatic pine trees are not treated until they wilt. In May 2003 when chemical treatment of wilt pines finished, new wilt pines were found around ca. 10% of treated wilt logs, and small untreated branches with more than 2.5 cm of diameter were detected around ca. 7% of the treated logs (Korea Forest Service, 2003); these may be major habitats for surviving pine sawflies and PWN even when control programs are repeated annually. New wilt pines can be last year's asymptomatic pines. Furthermore, the asymptomatic pines attract pine sawyers, forming a chain infection in PWD epidemics (Futai and Takeuchi, 2008).

PWD wilt pines tend to be highly clumped because of the steady movements of pine sawyers and their aggregation around wilt pines (Togashi, 1991), resulting in an initially very slow PWD epidemic spread rate. In the Republic of Korea, PWD wilt pines were first found on Mt. Geumjeong in Busan in 1983, and remained within a restricted area of about 72 ha for 6 years with no proper treatment until 1988 when PWN was diagnosed from wilt pines (Enda, 1989). Complete removal of wilt pines did not successfully control PWD because of after effects from the previous-year's infection (Togashi, 1991). Therefore, asymptomatic pines (infected in a previous year) around PWD wilt pines must be treated along with the PWD wilt pines. Selection of the asymptomatic pines from healthy pines needs laborious procedures such as a test of resin exudation and recognition of PWN in wood (Futai and Takeuchi, 2008), making this an impractical method for control of PWD epidemics. Instead, all non-wilt pines around wilt pines should be designated asymptomatic and treated. Accordingly, control efforts for PWD epidemics must be focused on the PWD-infested patch (PWDP), which is a PWD infested forest area that includes PWD wilt pines and the designated asymptomatic pines, rather than on PWD wilt pines alone. If 1 PWD wilt pine is found, an area of about 0.03–0.1 ha surrounding it (i.e. a circle with a radius of about 10–20 m) could be considered as 1 PWDP. Numerous PWDPs, the total of which amounted 5633 ha in 2009 (Korea Forest Service, unpublished), are scattered across the ca. 9,960,000 ha of South Korea. Each year, most PWD wilt pines occur within existing PWDPs. Therefore, preventative elimination of pines in each PWDP using SC would significantly suppress the annual occurrence of PWD wilt trees. The majority of PWDP increases occurred in C + N treatment areas, and most pine trees in PWDP succumb to wilt within 10–20 years of the initial infection, despite repeated control efforts. The PWDP is an island for the collaborative system comprising PWN and its vectors, which emigrate and reproduce new PWDP; the pine sawyer vectors can fly up to 3.3 km during the early adult stage (Kishi, 1995) or be moved >100 km by human activities. The rarity of PWDP death may be the major contributory cause of the worldwide spread of PWD epidemics. Hence, we recommend clear-cutting of PWDPs rather than attempting other repetitive procedures.

In China, a band of pine 100-km long by 4-km wide was felled to prevent natural dispersal of PWD epidemics into the pine forest around Huangshan, a World Natural and Cultural Heritage site, but this could not stop the movement of PWN by human activity (Zhao, 2008). In 2006, a phytosanitary strip 3-km wide and devoid of *P. pinaster* was established in Portugal to prevent spread of PWD epidemics (Rodrigues, 2008; Mota and Vieira, 2008); this too was a failure (Han, H.L., in Korea Forest Research Institute, pers. comm.). Considering the frequent long dispersal of PWD epidemics due to human activities, a phytosanitary-belt in pine stands would not prevent the spread of PWD epidemics. If large-scale clear-cuts in the phytosanitory belts were separately applied on numerous PWDPs in China and Portugal, PWD damage in those nations would be greatly reduced. Pines in most regions except North America are highly susceptible to PWD epidemics because of long-distance lumber trading. If PWD wilt pines newly occur in a nation, export of pine woods from this nation should be prohibited (Evans et al., 1996). This disease has become a serious economic disaster for major pine lumber producers such as Australia and New Zealand (Lawson and Sathyapala, 2008). However, if silvicultural controls were applied in newly infested nations, suppression of PWD epidemics may not be difficult.

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