

Potential pest status of the Formosan subterranean termite, *Coptotermes formosanus* Shiraki (Blattodea: Isoptera: Rhinotermitidae), in response to climate change in the Korean Peninsula

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Abstract

Climate change impacts the current and potential distribution of many insects, since temperature is often a limiting factor to where the insects can survive. The Formosan subterranean termite, *Coptotermes formosanus* Shiraki (Blattodea: Rhinotermitidae), has never been reported in South Korea despite its close proximity to 2 countries (China and Japan) where this economically important pest has been reported. This may be due to the average winter temperature in South Korea which is below 4 °C, the lower limit of the current distribution range of Formosan subterranean termite. However, with climate change leading to increased temperatures, South Korea may be susceptible to successful invasion by Formosan subterranean termite. The objective of this study is to estimate the future possible distribution of Formosan subterranean termite in Korea based on temperature. Climate data from Korea showed a significant increase of 2.19 °C per 100 yr in average annual temperature from 1910 to 2018. Previous and current average winter temperatures were higher than 4 °C only in Jeju, and most provinces did not exceed 4 °C, except for some southern cities such as Busan in 2000 to 2019. With the estimated rate of temperature rises, winter temperatures in Gyeongsangnam-do will exceed 4 °C starting from 2020, and Jeollanam-do will exceed 4 °C from 2060. Coupled with the statistically significant, increased annual trade between Korea and other countries (China, Japan, Taiwan, and the USA) where *C. formosanus* is currently distributed, we predict that Formosan subterranean termite will become established in South Korea, probably starting from a southern trade port such as Busan.

Key Words: global warming, invasive species, species distribution, urban pest

Resumen

El cambio climático tiene un impacto sobre la distribución actual y potencial de muchos insectos, ya que la temperatura es a menudo un factor limitante a donde los insectos pueden sobrevivir. La termita subterránea de Formosa, *Coptotermes formosanus* Shiraki (Blattodea: Rhinotermitidae), nunca ha sido reportada en Corea del Sur a pesar de su proximidad a 2 países (China y Japón) donde se ha reportado esta plaga de importancia económica. Esto puede ser debido a la temperatura media de invierno en Corea del Sur, que está por debajo de 4 °C, el límite inferior del rango de distribución actual de la termita subterránea de Formosa. Sin embargo, con el cambio climático que conduce a un aumento de las temperaturas, Corea del Sur puede ser susceptible a una invasión exitosa de la termita subterránea de Formosa. El objetivo de este estudio es estimar la posible distribución futura de la termita subterránea de Formosa en Corea en función a la temperatura. Los datos climáticos de Corea mostraron un aumento significativo de 2,19 °C por 100 años en la temperatura media anual desde el 1910 hasta el 2018. Las temperaturas medias invernales anteriores y actuales fueron superiores a 4 °C solo en Jeju, y la mayoría de las provincias no superaron los 4 °C, excepto en algunas ciudades del sur como Busan en el 2000 hasta el 2019. Con la tasa estimada de aumento de temperatura, las temperaturas invernales en Gyeongsangnam-do superarán los 4 °C a partir del 2020, y Jeollanam-do superará los 4 °C a partir del 2060. Basado en estadísticamente significativo, además de mayor comercio anual entre Corea y otros países (China, Japón, Taiwán, y EE.UU.) donde se distribuye actualmente *C. formosanus*, predecimos que la termita subterránea de Formosa se establecerá en Corea del Sur, probablemente a partir de un puerto comercial del sur como Busan.

Palabras Clave: calentamiento global; especies invasoras; distribución de especies; plaga urbana

Climate change is an inevitable phenomenon and has had a significant impact on species extinction and the introduction of invasive species. Invasions by alien species in non-native areas due to climate change are important driving factors that affect ecosystems and biodiversity (Vitousek 1994; Dukes & Mooney 1999). These invasive spe-

cies often have an enormous economic impact on agriculture, the environment, and structures, as well as losses from regulatory actions and trade restrictions (Holmes et al. 2009). The total economic loss by invasive species in the USA, for example, is estimated around USD \$120 billion (Pimentel et al. 2005).

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In addition to climate change, human activities translocate species beyond their native range, which has increased substantially during the last centuries. Hence, globalization and increase of trade are responsible for spreading alien species into non-native areas. This is related to propagule pressure, defined as a measure of the number of individuals released into a non-native region, and consists of the propagule size, number of individuals per release event and number, and number of discrete release events (Lockwood et al. 2005). Propagule pressure is not easy to measure directly, but can be estimated by using international trade as a proxy (Westphal et al. 2008).

The Formosan subterranean termite, *Coptotermes formosanus* Shiraki (Blattodea: Rhinotermitidae), is one of the world's 100 worst invasive alien species (Lowe et al. 2000), and is the most-studied termite species due to its economic importance in temperate and subtropical regions. The nest of *C. formosanus* may be found either underground or inside trees, and the mature colony contains millions of individuals (King & Spink 1969; Su & Scheffrahn 1988). The foraging distance of *C. formosanus* may be up to 100 m using underground tunnels or above-ground shelter tubes (King & Spink 1969).

The global economic loss, including control and repair costs, caused by subterranean termites is USD \$32 billion annually (Rust & Su 2012). Formosan subterranean termite is endemic to southern China and Taiwan (Kistner 1985; Su & Tamashiro 1987; Li 2000; Su 2003; Li et al. 2009), and has been introduced to multiple locations, including Japan (Su & Tamashiro 1987), South Africa (Coaton & Sheasby 1976), Marshall Island, Midway Island, and the US (Su & Tamashiro 1987; Su 2003; Evans et al. 2013). Past and current distribution of *C. formosanus* in the world showed that it is restricted to an area about 35° north and south of the equator (Su & Tamashiro 1987).

Despite the fact that South Korea is located between ca. 33° to 38° north and between China and Japan, there is no official record of Formosan subterranean termite in South Korea. These 2 neighboring countries have known distributions of Formosan subterranean termite and have a long history of damage by this pest (Mori 1987; Wang et al. 2002). The distribution of *C. formosanus* in South Korea is controversial. Early work by Lee et al. (1998) reported finding *C. formosanus* from 3 southern locations: Busan, Jinju, and Geogje Island. However, a later extensive survey of the same areas failed to find *C. formosanus* in Korea (Lee et al. 2015). The reason it is controversial is that firstly, Lee et al. (1998) did not include any pictures of the specimens. Secondly, they stated that they confirmed the presence of *C. formosanus* based on damage, which is unreliable. Lastly, if it was present in 1998, the damage by *C. formosanus* also should have been reported elsewhere. However, there was no such reports yet. Officially, only 2 species of subterranean termites were found, *Reticulitermes speratus kyushuensis* Morimoto (Becker 1969) and *Reticulitermes kanmonensis* Takematsu (both Blattodea: Rhinotermitidae) (Lee et al. 2015).

Temperature is the crucial factor responsible for the distribution of *C. formosanus* (Kofoid 1934; Shimizu 1962; Coaton & Sheasby 1976; Su & Tamashiro 1987). The distribution of this species in Japan is limited to regions where the monthly mean temperature of winter is above 4 °C (Abe 1937; Mori 1987). However, *C. formosanus* also was discovered in Kanagawa Prefecture (Japan), where the temperature drops lower than 4 °C in the winter (Mori 1987).

Considering the geographical proximity of South Korea to China and Japan, we hypothesize that the temperature may not have been favorable to Formosan subterranean termite in the past, but is likely to become suitable in the future due to climate change, especially in the southern part of South Korea. To project the potential future areas that may be threatened by Formosan subterranean termite in South Korea, we surveyed the amount of imported wooden materials and the amount of trade between South Korea and other countries where

Formosan subterranean termite is currently distributed (i.e., Japan, China, Taiwan, and the US) as a proxy of propagule pressure. Further, we analyzed past and current temperatures to find the trend of temperature due to climate change and average winter temperatures to determine the possible distribution limits of Formosan subterranean termite in South Korea if it is introduced. Furthermore, the future distribution limit with the consideration of temperature increase rate was estimated.

Materials and Methods

STUDY AREA

Republic of Korea (South Korea) occupies the southern half of the Korean Peninsula, which was divided by the Korean Demilitarized Zone after the Korean War in 1953. The land mass of South Korea is approximately 100,000 km², and it has about 2,500 km of coastline (Fig. 1). There are 9 provinces, the first-level divisions within the Republic of Korea. In this study, we assigned letters to the provinces for simplicity (A to I, from south to north and from east to west) (Table 1).

South Korea has a temperate climate with 4 distinct seasons (winter: Dec–Feb; spring: Mar–May; summer: Jun–Aug; fall: Sep–Nov). The

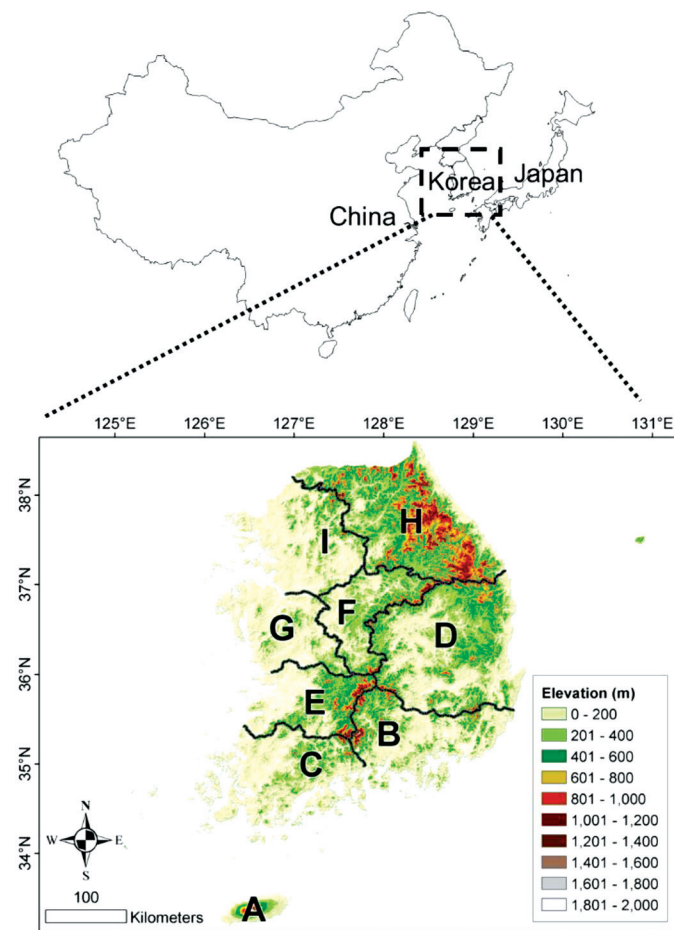


Fig. 1. Geographic location of the Republic of Korea, South Korea, in Far East Asia. The name of the provinces is presented on the map as A to I, from south to north and from east to west. The map was produced using data from GADM and USGS (Projection: WGS1984 (horizontal) and EGM96 (vertical)) in ArcMap 10.5.1.

Table 1. Information of climate data stations including latitude, longitude, and elevation used in this study. For simplicity, we assigned provinces letters from A to I.

Name used in this study	Provinces	City	Latitude (°N)	Longitude (°E)	Elevation (m)
A	Jeju-do	Seogwipo	33.2461	126.5653	49.03
		Seongsan	33.3868	126.8802	20.34
		Jeju	33.5141	126.5297	20.45
B	Gyeongsangnam-do	Busan	35.1047	129.032	69.56
		Ulsan	35.5826	129.3344	82
		Geoje	34.8882	128.6045	45.4
		Namhae	34.8166	127.9264	45.71
		Miryang	35.4915	128.7441	11.21
		Tongyeong	34.8455	128.4356	32.3
C	Jeollanam-do	Gwangju	35.1729	126.8916	72.38
		Mokpo	34.8169	126.3812	38
		Yeosu	34.7393	127.7406	64.64
		Wando	34.3959	126.7018	35.24
		Jangheung	34.6888	126.9195	45.02
D	Gyeongsangbuk-do	Daegu	35.8852	128.619	64.08
		Gumi	36.13	128.32	48.88
		Andong	36.5729	128.7073	140.1
		Yeongcheon	35.9774	128.9514	93.8
		Ulleung	36.3561	128.688	81.81
		Pohang	36.032	129.38	3.94
E	Jeollabuk-do	Gunsan	36.0053	126.7614	23.2
		Buan	35.7295	126.7166	11.96
		Imsil	35.612	127.2856	247.04
		Jeonju	35.8215	127.155	53.4
		Jeongeup	35.5631	126.8392	69.84
F	Chungcheongnam-do	Daejeon	36.372	127.3721	68.9
		Boryeong	36.3272	126.5574	9.98
		Buyeo	36.2724	126.9208	11.79
		Seosan	36.7766	126.4939	25.86
		Cheonan	36.7624	127.2927	81.5
G	Chungcheongbuk-do	Boeun	36.4876	127.7341	174.99
		Jecheon	37.1593	128.1943	259.8
		Cheongju	36.6392	127.4407	58.7
		Chupungnyeong	36.2202	127.9946	243.7
		Chungju	36.9704	127.9527	116.3
H	Gyeonggi-do	Seoul	37.5714	126.9658	85.8
		Ganghwa	37.7074	126.4463	47.84
		Incheon	37.4777	126.6249	68.99
		Suwon	37.2723	126.9853	34.84
		Yangpyeong	37.4886	127.4945	47.26
		Icheon	37.264	127.4842	80.09
I	Gangwon-do	Gangneung	37.7515	128.891	26.04
		Daegwallyeong	37.6771	128.7183	772.57
		Sokcho	38.2509	128.5647	18.06
		Wonju	37.3376	127.9466	148.6
		Inje	38.0599	128.1671	200.16
		Chuncheon	37.9026	127.7357	76.47
		Hongcheon	37.6836	127.8804	139.95

annual precipitation of South Korea varies yr to yr; usually, it is about 1,200 mm. During the summer, there are summer monsoons with occasional typhoons.

INDIRECT MEASUREMENT OF PROPAGULE PRESSURE

We surveyed the amount of imported wooden materials, including raw logs, lumber, and timber, and possible transportation sources of

termites, from 1995 to 2017 (Korea Forest Service, Statistical Yearbook of Forestry [<https://www.forest.go.kr/>]). We were not able to acquire the exact amounts of imported wooden materials from China, Japan, Taiwan, and the US. Instead, we examined the amount of annual trade from 2000 to 2018 between Korea and these other countries where *C. formosanus* is currently distributed, because they are potential sources of future introduction events into the Korean Peninsula (Korea Customs Service trade statistics [<https://unipass.customs.go.kr/>]).

TEMPERATURE DATA

There are 95 land-based stations for climate measurement in South Korea. All data are accessible and available on the internet (<https://data.kma.go.kr/>). Using the climate data from 3 stations, we calculated the average, minimum, and maximum annual temperatures from 1910 to 2018. We also analyzed the average winter temperature, defined as the average temperature in Dec through Feb from 1960 to 2019 using data from 3 to 7 stations for each province (Table 1).

We estimated future temperatures based on the increase rate of the average annual temperatures. On average, the temperature increased 2.19 °C per 100 yr; therefore, the increase rate for 20 yr was determined to be 0.44 °C. Therefore, the future temperature was calculated by adding 0.44 °C to previous temperatures.

MAPPING AND STATISTICAL ANALYSIS

Country/province shapefiles from GADM (https://gadm.org/download_country_v3.html) and elevation raster imagery from the USGS EROS Archive - Digital Elevation - Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global (https://dds.cr.usgs.gov/srtm/version2_1/SRTM3/Eurasia/) were used to create the map (ArcMap 10.5.1, Environmental Systems Research Institute, Redlands, California, USA).

Pearson's correlation coefficient test was used to determine the statistical correlations between the amount of imported wooden materials, amount of trade between the Republic of Korea and other countries, average annual temperatures, average annual minimum temperatures, average annual maximum temperatures, and yr. All statistical analyses were carried out using SPSS v19.0 (IBM Corp. 2010).

Results

The amount of imported wooden materials significantly increased between 1995 and 2017 (Pearson's correlation coefficient $r = 0.764$; $P < 0.001$; Fig. 2A). In addition, the amount of trade between South Korea and China ($r = 0.964$; $P < 0.001$), Japan ($r = 0.629$; $P = 0.004$), Taiwan ($r = 0.982$; $P < 0.001$), and the US ($r = 0.922$; $P < 0.001$) statistically increased over time (Fig. 2B).

Overall, there were significant increases in average annual ($r = 0.804$; $P < 0.0001$), minimum ($r = 0.859$; $P < 0.0001$), and maximum ($r = 0.658$; $P < 0.0001$) temperatures from 1910 to 2018 (Fig. 3). In South Korea, previous and current average winter temperatures were higher than 4 °C, which is the northern temperature limit of *C. formo-*

sanus only in location A. Most locations (i.e., B to I) do not exceed 4 °C, except some cities in location B, such as Busan, Namhae, Geoje, and Tongyeong between 2000 and 2019 (Fig. 4). Future estimated winter temperatures of location B, however, exceed 4 °C after 2020, and those of location C will exceed 4 °C by 2060 (Fig. 5).

Discussion

In this study, we revealed that the Formosan subterranean termite, which is the most economically important termite, possibly will be found in southern regions of the Korean Peninsula due to climate change. *Coptotermes formosanus* is known as an urban pest due to its propensity to be found in man-made wooden structures such as houses and historical properties (Lowe et al. 2000; Rust & Su 2012; Evans et al. 2013). This invasive termite has never been completely eradicated once it becomes established in an area (Su 2003).

To predict the distribution of species, several climate variables have been used (Guisan & Zimmermann 2000; Beaumont et al. 2005). The variables, minimum, mean, and maximum temperatures are some of the basic components to project future distribution. Accordingly, most studies that predict the distribution of subterranean termites also applied air temperatures, although subterranean termites are soil-dwelling insects (Li et al. 2013; Tonini et al. 2014; Buczkowski & Bertelsmeier 2017). This is because soil temperatures are closely related to air temperatures, and may be predicted from air temperatures (Toy et al. 1978; Zheng et al. 1993).

In temperate latitudes, low temperature has a significant impact on range expansion, and affects insect survival and development (Robinet & Roques 2010). For instance, the northern distribution limit of the southern pine beetle, *Dendroctonus frontalis* Zimmermann (Coleoptera: Curculionidae), is determined by lower winter temperature (Ungerer et al. 1999). Studies on the distribution of Formosan subterranean termite indicate that the lower limit in winter temperature (about 4 °C) is the most important factor responsible for its distribution (Kofoid 1934; Abe 1937; Shimizu 1962; Coaton & Sheasby 1976; Mori 1987; Su & Tamashiro 1987; Su 2003). In the past (i.e., 1960 to 1999), there was no area with suitable temperature in Korea except Jeju Island (location A, Fig. 4). The rise in winter temperatures in southern parts of Korea, such as coastal areas in southern regions (locations B and C), may allow Formosan subterranean termite to become established in the future (Fig. 5). Additionally, we speculate that if the temperature rises at the same rates that we observed for the past 100 yr, Formosan subter-

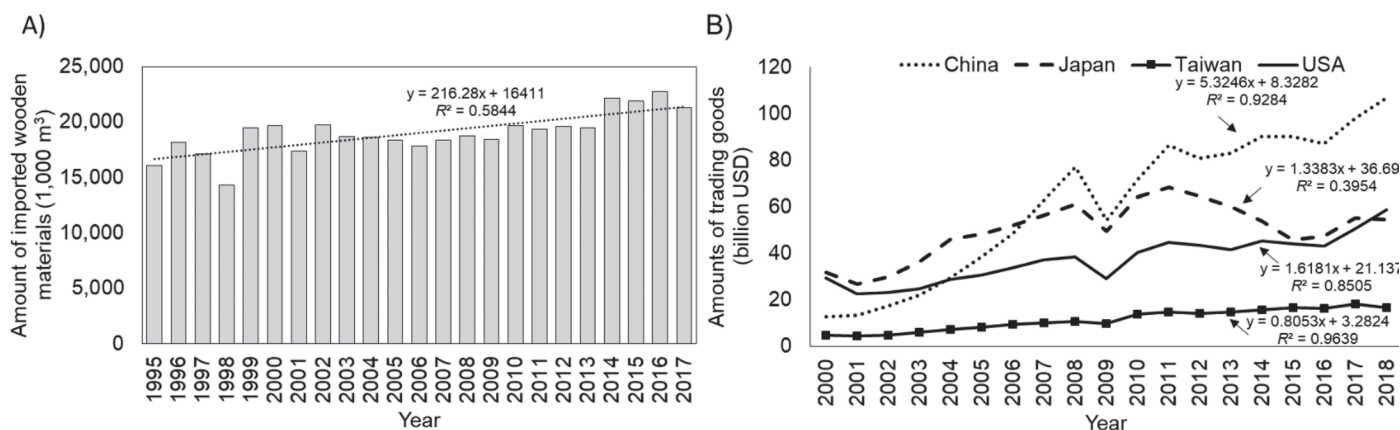


Fig. 2. (A) Bars indicate amounts of imported wooden materials into Korea from 1995 to 2017, and the dotted line on top of the bars represents the trend line for imported wooden materials. The data were obtained from the Statistical Yearbook of Forestry, Korea Forest Service. (B) Amounts of trade goods (USD billions) between South Korea and China (dotted), Japan (dashed), Taiwan (solid with square) and US (solid). Arrows indicate a linear equation and R-square of the trend line.

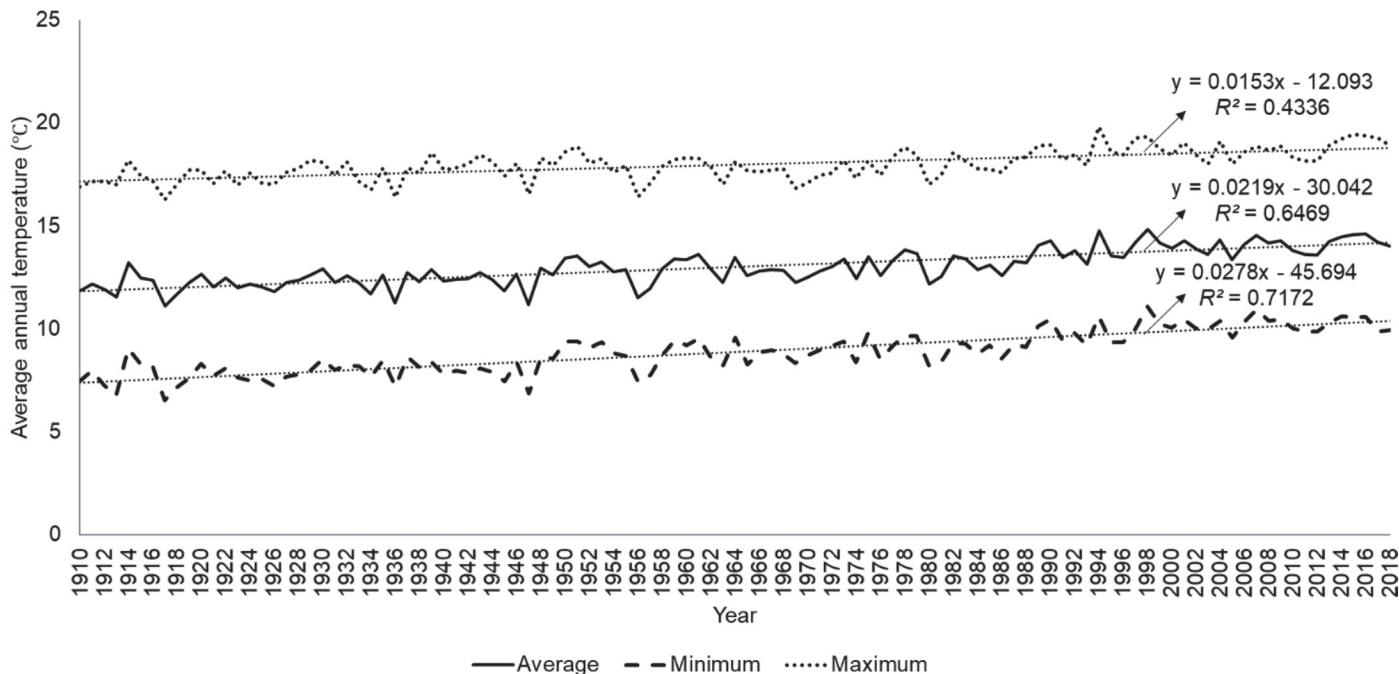


Fig. 3. Annual temperature of Korea based on 3 stations (Busan, Daegu, and Seoul) from 1910 to 2018. Solid, dashed, and dotted lines are the average, minimum, and maximum, respectively. Arrows indicate the linear equation and R-square.

anean termite also may expand its distribution farther north in the future (Figs. 5, 6), with the possible exception of mountainous sections of the central and northeast regions (Fig. 6), due to the relatively low temperatures at high elevations.

Aside from rising temperatures, anthropogenic activities may provide favorable conditions for establishment of Formosan subterranean termite colonies in urban areas. For instance, heating systems in structures, as well as moisture-related conditions around structures, such as rain seepage, plumbing leaks, condensation, and poor ventilation,

may supply enough heat and moisture for termites to survive (Mallis & Story 2003). Accordingly, it is possible that these kinds of favorable conditions may alter our projections.

The natural rate of spread of termites is relatively slow because of the time required for colony maturity (Chouvenc & Su 2014) and low distance of the dispersal flights (about 0.2 to 1 km) by alates (winged reproductives) (Messenger & Mullins 2005; Mullins et al. 2015). The minimum distances from areas in China and Japan where Formosan subterranean termite is known to occur to South Korea are 543 km

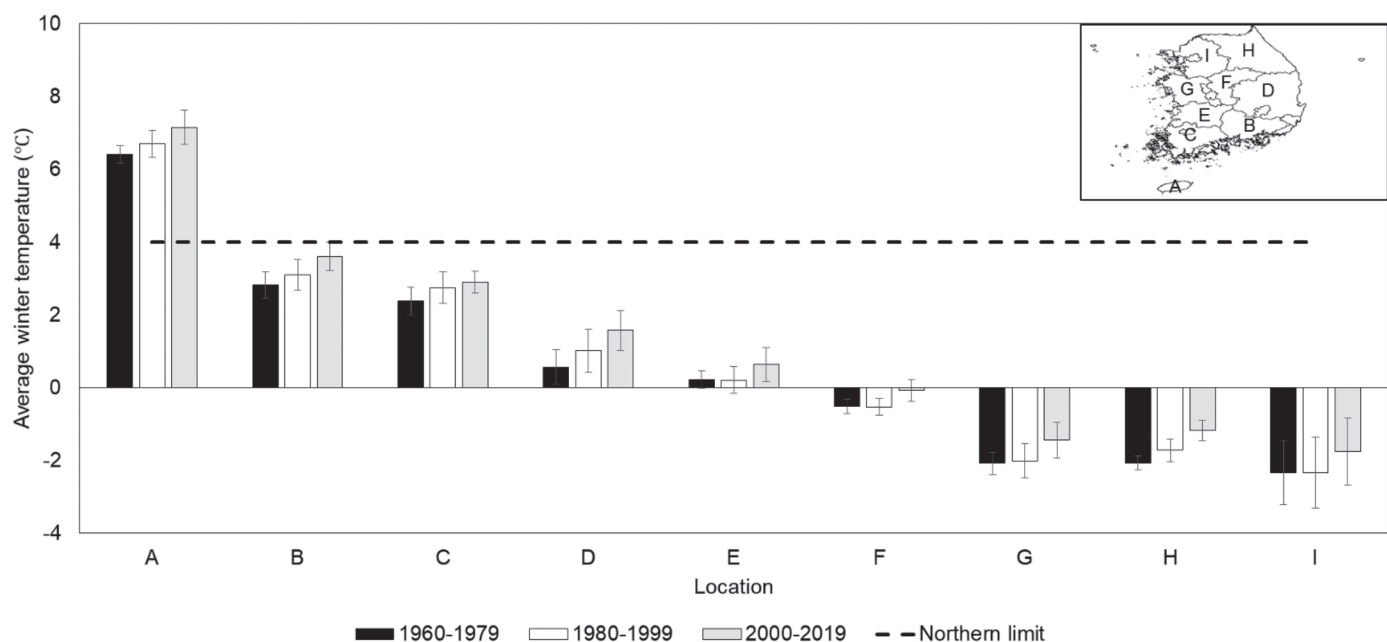


Fig. 4. Average winter temperature of each province (A to I). Black, white, and gray bars indicate the average winter temperature of each time period, and the dashed line indicates the northern distribution temperature (4 °C) limit of *Coptotermes formosanus*. The map in the figure shows the location of A to I.

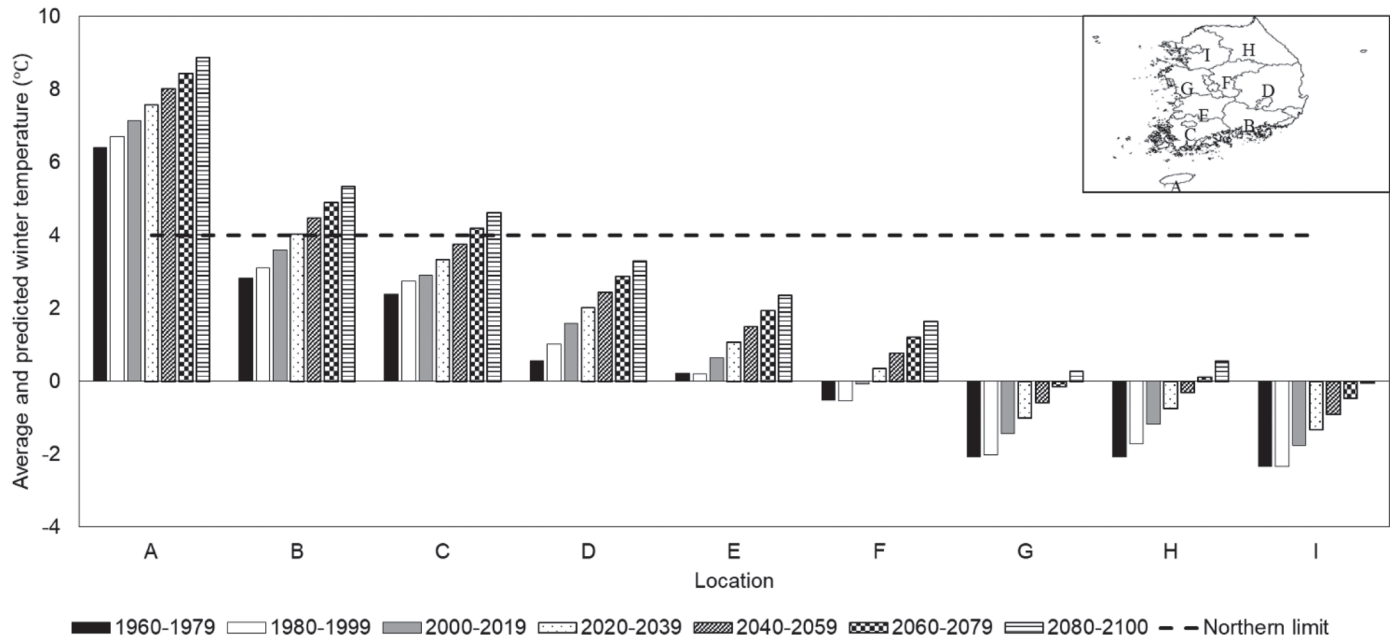


Fig. 5. Past and estimated average winter temperature of each province (A to I) according to the temperature increase trend of Korea. Each bar indicates the average winter temperature of each time period. The dashed line in the figure shows the northern distribution temperature limit of *Coptotermes formosanus*.

(from Jiangsu, China, to Jeju, Korea) and 244 km (from Yamaguchi, Japan, to Busan, Korea), respectively. Considering these distances, we can exclude the possibility of natural dispersal from either China or Japan to South Korea. Therefore, Formosan subterranean termite most likely will be introduced either by trade of goods, such as in shipping containers, raw logs, timber, and lumber, or by boats to port cities (Su 2003), which is the same way Formosan subterranean termite has invaded other countries. Incipient colonies of Formosan subterranean termite are able to seal off the nest after tunneling into wet wood, allowing them to survive during transportation. We showed that the amount of imported wooden materials significantly increased over time, as well as the amount of trade between Korea and countries where Formosan subterranean termite is currently distributed (Fig. 1A, B).

Although environmental factors, such as temperature, are suitable, invasive species need to survive in interspecific competition with native species (Su 2013). Therefore, competition can be another limiting factor to the establishment of invasive species in non-native areas. However, it is believed that Formosan subterranean termite is more aggressive and usually out-competes different species such as *Reticulitermes* (Su 2003). Formosan subterranean termite has not shown antagonistic behavior towards colonies of other conspecific colonies in introduced areas, e.g., Florida, USA (Su & Haverty 1991), and *C. formosanus* may fuse with other colonies (Lee et al. 2019).

Busan, the second largest city in Korea, located in the southern tip of the Korean Peninsula, has the largest port in Korea and acts as a point of entry for invasive alien species. The pine wood nematode, *Bursaphelenchus xylophilus* (Steiner and Buhner) Nickle (Secernentea: Parasitaphelenchidae), which is the agent for pine wilt disease, was first found in Busan in 1988, and spread to most mountains in South Korea, resulting in an average USD \$8 million per yr in control programs (Shin 2008). A tropical/subtropical species of hornet, *Vespa velutina* Lepeletier (Hymenoptera: Vespidae) also was found first in Busan in 2003 (Kim et al. 2006), and is distributed in locations B and C (Fig. 1) as of 2010 (Choi et al. 2012). The hornet is now well-adapted to and has become a pest in urban environments (Choi et al. 2012). Another invasive species, the red imported fire ant, *Solenopsis invicta* Buren (Hymenoptera: Formicidae), native to central South America, has been

found recently in Busan Port in 2018 (Choi et al. 2018). Furthermore, 10 different macro-moths of subtropical origin were found in Korea in 2006 (Park et al. 2006).

Buczkowski and Bertelsmeier (2017) showed that under the RCP 4.5 scenario in 2050, the future distribution range of *C. formosanus* will expand north to North Korea. However, our study showed that *C. formosanus* may not survive if it is introduced in the northern region of South Korea due to low winter temperatures. Buczkowski and Bertelsmeier (2017) incorrectly assumed that *C. formosanus* is currently distributed in South Korea.

In conclusion, with the rise of temperature due to climate change and the increase of trade between South Korea and other countries where Formosan subterranean termite is currently distributed, Formosan subterra-

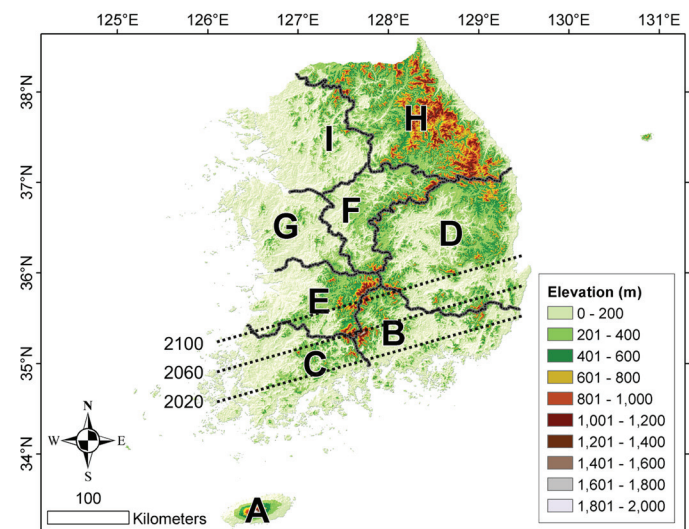


Fig. 6. Potential future distribution of *Coptotermes formosanus* based on the estimated winter temperature according to Figure 5. The dotted lines indicate the estimated northern distribution limits of 2020, 2060, and 2100, respectively.

nean termite may be introduced and be able to establish in the southern part of the Korean Peninsula if it survives during transportation.

A targeted quarantine inspection in the southern part of South Korea is required to prevent the introduction of Formosan subterranean termite in Korea, and baiting programs using chitin synthesis inhibitors may be needed to eradicate the initial small population. Otherwise, Formosan subterranean termite will cause damage in the southern region of South Korea as they already have done in other countries.

Acknowledgments

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