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Global Prediction of Geographical Change of Yellow Crazy Ant (*Anoplolepis gracilipes*) Distribution in Response to Climate Change Scenario

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Yellow crazy ant (*Anoplolepis gracilipes*) is a notorious insect which has destroyed local ecosystems when invaded. According to changes in habitats of alien species caused by the recent climate change, the risk of introducing yellow crazy ant into new area has been increase. This study aimed to predict and compare future global distribution of yellow crazy ant simulated based on different climate change scenarios by using CLIMEX The simulation showed that Central Africa, South America, Oceania, and Southeast Asia might be exposed to the threat of invasion under the current climate. In addition, the type of climate scenarios resulted in quantitatively different climatic suitability, while qualitative patterns of predicted distribution were similar. In conclusion, this study illustrated the use of niche model provided by CLIMEX for predicting global yellow crazy ant distribution changing by climatic condition, suggesting its future application on risk assessment of invasive species and on analyzing climate change scenario.

Key words: Climate change scenario, CLIMEX, Potential distribution, Yellow crazy ant

INTRODUCTION

Climate change is due to industrial emissions of greenhouse gases (GHG) such as carbon dioxide, methane, and nitrogen dioxide. The volume of greenhouse gas emissions has increased since the 1970s, and grown significantly during the last 10 years in spite of the enforcing policy established in 2000 (IPCC, 2014). Accordingly, Intergovernmental Panel on Climate Change (IPCC) reported how future climate would change using Special Report on Emissions Scenarios (SRES) (Fourth Assessment report) and Representative Concentration Pathways (RCP) (Fifth Assessment report). SRES scenario considered GHG emissions due to social structure changes, while RCP scenario considered recent GHG concentration according to implement of climate change policy. RCP scenario covers a wider range than SRES scenario, because it also represents scenario with climate policy.

According to IPCC Fifth Assessment report used in RCP scenario, the current levels of greenhouse gases in the atmosphere are at a record 80–year high, accelerating the warming. Due to this trend, serious damage has been caused to the physical environment, such as glaciers, snow, drought, flooding, and sea level changes; the biological environment; and social systems such as food production and supply (IPCC, 2104). In particular, various species may become extinct because of the rapid pace of climate change and the invasion of alien species (IPCC, 2014). Moreover, invasive species may threaten local human activities, such as agriculture, forestry, and fishing, which can lead to serious social problems including food supply and water shortage (Lanoiselet *et al.*, 2002).

Yellow crazy ant has been designated as the 100 of the world's worst invasive alien species by International Union for Conservation of Nature (IUCN), and is one of the pests that destroy the ecosystem. Yellow crazy ant has been found mainly in tropical and sub–tropical regions, meaning that they can thrive in harsh, rocky, and dry areas (Csurhes and Hankamer, 2012). Yellow crazy ant builds 'supercolonies' with multiple queens in invasion site, and attack native invertebrates and endemic species (O'Dowd, 1999; Hill *et al.*, 2003; Wetterer, 2005). For example, it was reported that birds' nests and native invertebrates had been attacked by yellow crazy ant on islands in the Seychelles (Feare, 1999; Hill *et al.*, 2003; Mckenney *et al.*, 2003), and the endemic red crabs of Christmas Island were massively killed by yellow crazy ant (Green *et al.*, 1999; O'Dowd, 1999; O'Dowd, 2003; Wetterer, 2005).

Chen (2008) reported the potential distribution of yellow crazy ant using various models (BioClim, GARP and Environmental Distance models) and climate change scenario, but CLIMEX proposes different types of assessment, and confirms the potential distribution provided by BioClim, GARP, Environmental Distance models used previous research. Researches using Bioclim, Domain, GARP and Environmental Distance models attempt to characterize the environment which species occupied, while CLIMEX determines their seasonal phenology, and relative abundance based on simulations of the mechanisms that limit species' geographical distributions. Where most models focus on describing the relationship

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between the occurrences of the species with respect to static environmental covariate, CLIMEX describes how the species responds to climatic variables at appropriate temporal scales (daily or weekly) (Kriticos, *et al.*, 2005). In addition, currently provided climate change scenario has low resolution which is not suitable for simulating on small areas, requiring upgrade to high resolution. Therefore, current study conducted predictions of potential geographical distribution of yellow crazy ant using CLIMEX, and compared two different climate changes scenarios (SRES and RCP) with upgraded the spatial resolution on tendency of future dispersion of yellow crazy ant.

MATERIALS AND METHODS

CLIMEX software and Geographical Information Systems (GIS)

CLIMEX (version 3.0, Hearne software, Australia) is dynamic model for exploring the relationship between the fundamental and realized niche of any species (Vera, *et al.*, 2002; Wharton and Kriticos, 2004; Kriticos *et al.*, 2005; Khormi and Kumar, 2014). The result of the CLIMEX Model is represented as an Ecoclimatic Index (EI), representing the possibility of survival and growth for a species in specific locations. The EI scaled between 0 and 100 is calculated by growth (Growth Index, GI), stress (Stress Index, SI) and interactions of stress (Interaction Stress Index, SX), which are caused by climate (Sutherst *et al.*, 2007a; 2007b; Jung *et al.*, 2016). GI was calculated by seven sub–indices (temperature, moisture, radiation, substrate, diapause, light, and biotic index), and SI contain four types of stress which is Cold Stress (CS), Heat Stress (HS), Dry Stress (DS) and Wet Stress (WS) (Sutherst *et al.*, 2007a; 2007b). In short, GI represents the potential for population growth during the favorable season, while SI addresses the criteria for population reduction during the unfavorable season. In the result, EI close to 0 means that the location is not suitable for survival of the species during long–term season. An EI from 1 to 10 represents marginal climate for species survival, while an EI more than 30 indicates an optimal climate for a species in the given area (Shabani *et al.*, 2013; Sutherst *et al.*, 2007a; 2007b). The indices are described in detail elsewhere (Sutherst *et al.*, 2007a; 2007b; 2007c; Jung *et al.*, 2016).

In this study, as we focus on only yellow crazy ant (*Anoplolepis gracilipes*), CLIMEX model was applied for predicting the potential geographical distribution in the world. Also, we transferred the EI values to GIS using Arcmap 10.5 (ESRI, Redland, USA) for more efficient visualization by converting point of EI to a raster surface. Finally, we mapped the potential geographical distribution of yellow crazy ant in response to climate change scenarios.

Distribution of yellow crazy ant (*A. gracilipes*)

Yellow crazy ant are distributed wet tropical regions such as oceanic islands in the Caribbean (McGlynn, 1999), Indian Ocean (Agalega, Cocos Islands, Christmas Island, Madagascar, Mauritius, Rodrigues, Réunion, and Seychelles), and the Pacific, including Japan (Amami Oshima, Bonin, Okinawa, and Minami–Daito islands), Polynesia (Austral Islands, Cook Islands, Gambier Islands, Hawaii, Line Islands, Marquesas Islands, Niue, Samoa, Society Islands, Tokelau Islands, Tonga, Tuamotu Islands, Tuvalu, and Wallis and Futuna), Micronesia (Caroline Islands, Gilbert Islands, Mariana Islands, Marshall Islands, Palau, Rotuma, and Santa Cruz Islands), Melanesia (Fiji, New Caledonia, Solomon Islands, Tokelau, Vanuatu, and the Galapagos archipelago) (Abbott *et al.*, 2005; Haines and Haines, 1978; Holway *et al.*, 2002; Lewis *et al.*, 1976; Matsui *et al.*, 2009; McGlynn, 1999; O'Dowd *et al.*, 1999; Veeresh, 1984; Wetterer, 2005). For reliability of the result, we also present the reported distribution of yellow crazy ant on the map by receiving coordinates system from antmaps.org (Janicki *et al.*, 2016).

Meteorological data and climate change scenario

We obtained historical climatic data (period 1960–1990) which is composed of five factors (minimum and maximum temperatures, precipitation, and relative humidity at 9 am and 3 pm) from Climond (Kriticos *et al.*, 2012), and it was used to assess the current potential geographical distribution of yellow crazy ant. The future climate change scenarios were based on SRES A2 and RCP 8.5. SRES scenarios developed by MIROC–H (Centre for Climate Research, Japan) were provided by Climond (Kriticos *et al.*, 2012), while RCP scenarios were developed by Hadgem2–AO (Hadley Centre Global Environmental Model version 2, England), and provided by Climate Change, Agriculture and Food Security (CCAFS, 2016). Also we upgraded the spatial resolution of potential distribution map by about 15 times to $0.17^0 \times 0.17^0$ (latitude by longitude) from $2.5^0 \times 3.75^0$ (latitude by longitude) of previous map.

Parameter estimation

Yellow crazy ant mainly inhabits in tropical regions, and is found partly sub–tropical regions (Hoffmann and Saul, 2010; Worner, 1988). Accordingly, parameters were initially set by tropical template in the CLIMEX software, and then calibrated based on previous studies and reported distribution.

The limiting low temperature (DV0) and the optimum temperature thresholds (DV1 and DV2) in TI parameter were specified based on previous studies (Suwabe *et al.*, 2009; Haines and Haines, 1978; Abbott *et al.*, 2005). The limiting high temperature (DV3) was calibrated based on the highest temperature among the regions where yellow crazy ant was found (Baja California and Arab Emirates). SI was set by the precipitation of the regions where the yellow crazy ant occurred because no data clearly identify the relationship between soil moisture and yellow crazy ant. The values for SM0 (the lower soil moisture threshold) and SM1 (the lower optimum soil moisture) were very low because yellow crazy ant occurred in arid area such as Baja California and Arab Emirates. SM2 (the upper optimum soil moisture) and SM3 (the upper soil moisture threshold) were kept the same as the template, because there was no relevant data to adjust SM2 and SM3.

The stress parameters consider the environment that inhabits the yellow crazy ant; thus stress accumulation rate was calibrated to set the survival limit of the yellow crazy ant. The TTCS (cold stress temperature threshold) was estimated based on average monthly minimum temperature of Punjab, India where the region has the lowest temperature among the areas of actual distribution of the yellow crazy ant (monthly temperature was downloaded from Climate–data.org) (Janicki *et al.*, 2016). The cold stress accumulation rate (THCS) was determined by the survival limit of the yellow crazy ant in China and south–east Asia because these were one of the main regions of yellow crazy ant distribution, providing the clear survival limit in China. Also, the TTHS was set as a maximum temperature, which prevents foraging activity of the yellow crazy ant (Chong and Lee, 2009), and the heat stress accumulation rate (THHS) was used default value of wet tropical template in CLIMEX. The yellow crazy ant can survive in harsh, rocky, and dry areas (Csurhes and Hankamer, 2012), and has been found in areas where the average monthly rainfall is 10–50 mm. For these reason, DS was not used in this study. To show clearly, we described the detail parameter values and quantitative evidence for setting parameters in Table 1.

RESULTS

Potential distribution under current climate

In Africa, the central region (N13.5°–S12°) showed the highest possibility for habitation of yellow crazy ant, but they may not survive in the northern and southwestern regions (Fig. 1). The climatic suitable regions were generally the humid tropical areas, and Southeast Asia. On the other hand, marginal areas for yellow crazy ant were mainly deserts or cold locations. Specifically, countries including the Democratic Republic of the Congo, the Republic of Congo, Gabon, Cameroon, the Central African Republic, Ghana, Togo, and Ivory Coast had a high risk of potential distribution of yellow crazy ant, because their climate was very suitable. Central Africa around the Congo Basin had the highest potential distribution. Northern parts of Angola and Zambia also showed a suitable climate for inhabitation of yellow crazy ant. In contrast, Sudan showed a risk of yellow crazy ant distribution in the south, while the northern area was marginal.

Table 1. Parameter values used for yellow crazy ant in CLIMEX

Parameters	Calibrated value	Description	Reference
Temperature			
DV0	15	1) An unfavorable temperature for the yellow crazy ant : 10°C 2) General foraging temperature: 21°C–35°C 3) Maximum temperature of Baja California and Arab Emirates on July : about 36–40°C	1) Suwabe *et al.*, 2009 2) Haines and Haines, 1978; Abbott *et al.*, 2005 3) Climate–data.org
DV1	21		
DV2	35		
DV3	38		
Moisture			
SM0	0.01	1) Annual average rainfall of Baja California and Arab Emirates: 10–50 mm 2) Wet tropical template in CLIMEX	1) Climate–data.org 2) Sutherst *et al.*, 2007c
SM1	0.2		
SM2	1.5		
SM3	2.5		
Cold stress			
TTCS	5	1) Concerning the lowest temperature in Punjab, India: 5°C 2) Calibrating the survival limit of the yellow crazy ant in north–east China and south–east Asia	1) Climate–data.org
THCS	–0.003		
DTCS	0		
DHCS	0		
Heat stress			
TTHS	40	1) A maximum temperature, which prevents foraging activity: 40°C 2) Wet tropical template in CLIMEX	1) Chong and Lee, 2009 2) Sutherst *et al.*, 2007c
THHS	0.0002		
Dry stress			
SMDS	–	–	–
HDS	–		
Wet stress			
SMWS	2.5	1) Wet tropical template in CLIMEX	1) Sutherst *et al.*, 2007c
HWS	0.002		

Most parts of Southeast Asia, in particular, were shown to be suitable for the survival of yellow crazy ant (Fig. 1). Counties including Bangladesh, China (the southern regions of Guangdong and Fujian), Malaysia,

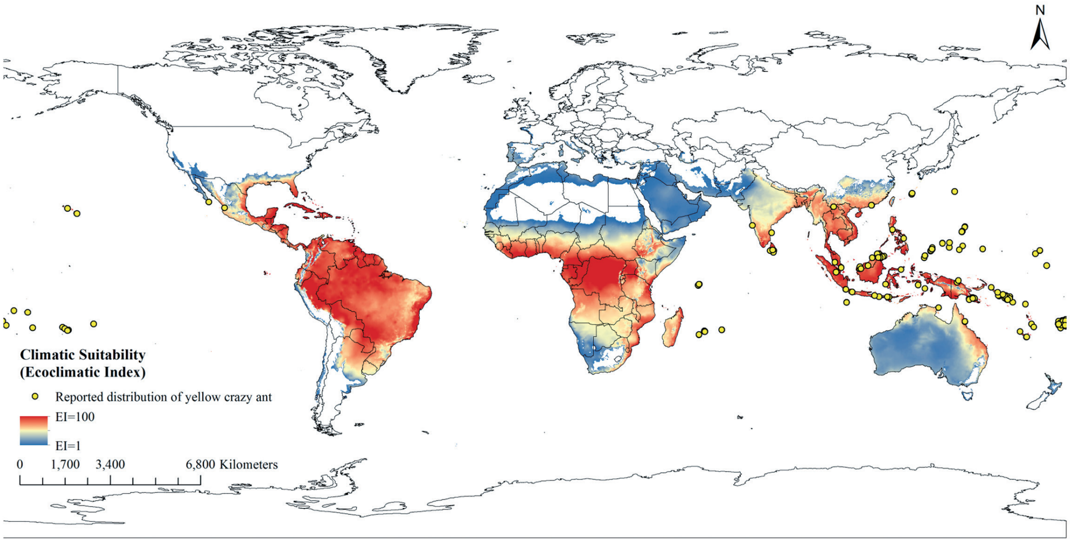

Fig. 1. Predicted potential global distribution of yellow crazy ant using CLIMEX under current climate.

Table 2. Risk assessment of yellow crazy ant in 3 continents by climate change

Climate change scenarios	Continent	Climatic suitable areas rate (increase rate)[1]	Potential limit line[2]	Potentially Dangerous areas (Country or State)[3]
Current	America	9%	About N 32.58	California, Arizona, Texas, Louisiana, Mississippi, Alabama, Georgia, Florida, South Carolina
	Europe	8%	About N 45.58	Italy, Greece, Portugal, Spain, Albania
	Northeast Asia	13%	About N 34.7	China (Yunnan, Sichuan, Guizhou, Guangxi, Hunan,Guangdong, Hainan, Jiangxi, Fujian, Zhejiang, Hubei, Shanghai), South Korea (Jeju–do), Taiwan, Japan (Kyushu)
RCP	America	23% (+14%)	About N 2.83 (southeastern)	With dangerous sites in Current climate. Oklahoma, Arkansas, Tennessee, Kentucky, North Carolina, Washington, Oregon
	Europe	35.3% (+27%)	About N 8	With dangerous sites in Current climate. Montenegro, Macedonia, Serbia, Bulgaria, Romania, Hungary, Slovakia, France, Germany, Luxembourg, Belgium, Netherlands, Switzerland, United Kingdom (south), Ireland, Croatia, Slovenia
	Northeast Asia	20.6% (+8%)	About N 3.04	With dangerous sites in Current climate. China (Anhui, Henan, Shaanxi, Jiangsu, Sangdong), South Korea (Busan–si, Kwangju–si, Chollanam–do), Japan (Shikoku, Chungku, Kinki, Chubu, Kanto)
SRES (MR)	America	16% (+7%)	About N 1.5 (southeastern)	With dangerous sites in Current climate. Arkansas, North Carolina
	Europe	19.2% (+11%)	About N 4	With dangerous sites in Current climate. France, Belgium, Croatia (seaside), Ireland, United Kingdom (south)
	Northeast Asia	17.6% (+5%)	About N 1.22	1With dangerous sites in Current climate. China (Anhui, Jiangsu), Japan (Shikoku, Chugoku, Kinki, Kanto)

[1] Percentages of area ($EI\geq1$) in total area of each continent (America (total area: 9,826,675 km^2), Europe (total area: 6,212,591 km^2) except Russia and Turkey, Northeast Asia (total area: 11,762,377 km^2 except Russia)

[2] limit line of potential distribution through the maximum latitude of $EI\geq1$ in total area of each continent except America where calculated range was limited to the eastern part only.

[3] Area ($EI\geq1$) of the state or province in country belonging to each continent was more than 30 percentage about total area in there state or province.

and Vietnam also showed high potential for yellow crazy ant distribution. Indonesia and the Philippines were especially suitable countries for inhabitation of yellow crazy ant. In contrast, Iraq, Oman, and Pakistan were predicted to have restricted survivability due to dry climatic characteristics, while yellow crazy ant cannot live in Russia, Kazakhstan, and northern parts of China because of the extreme cold. Furthermore, mainland Japan had a low risk of potential distribution for yellow crazy ant. As for Korea, only Jeju island was predicted to show potential distribution probabilities under the current climate. This is due the fact that that Korea has cold weather in the most regions except during summer.

Under the current climate conditions, Europe had a low risk of invasion by yellow crazy ant (Fig. 1). In the most regions, EI was 0 due to the low average temperature (lower than 25°C). Italy, Portugal, and Greek Mediterranean coast had a slight risk of invasion by yellow crazy ant, but it might not indicate that the risk is high enough because EI was less than 10 for all over Europe.

Yellow crazy ant favored coastal areas in Queensland and New South Wales in Australia, Papua New Guinea, and Fiji under the current climate (Fig. 1). Most of the islands in Oceania such as New Caledonia, Vanuatu, and Fiji showed especially high EIs, suggesting the high potential distribution of yellow crazy ant. In addition, northern areas of New Zealand had a potential for inhabitation of yellow crazy ant because of EI>10.

Future distribution using climate change scenarios

The future climate suitability of yellow crazy ant in 2070 using the two climate change scenarios showed qualitatively similar results in the distribution, but some-

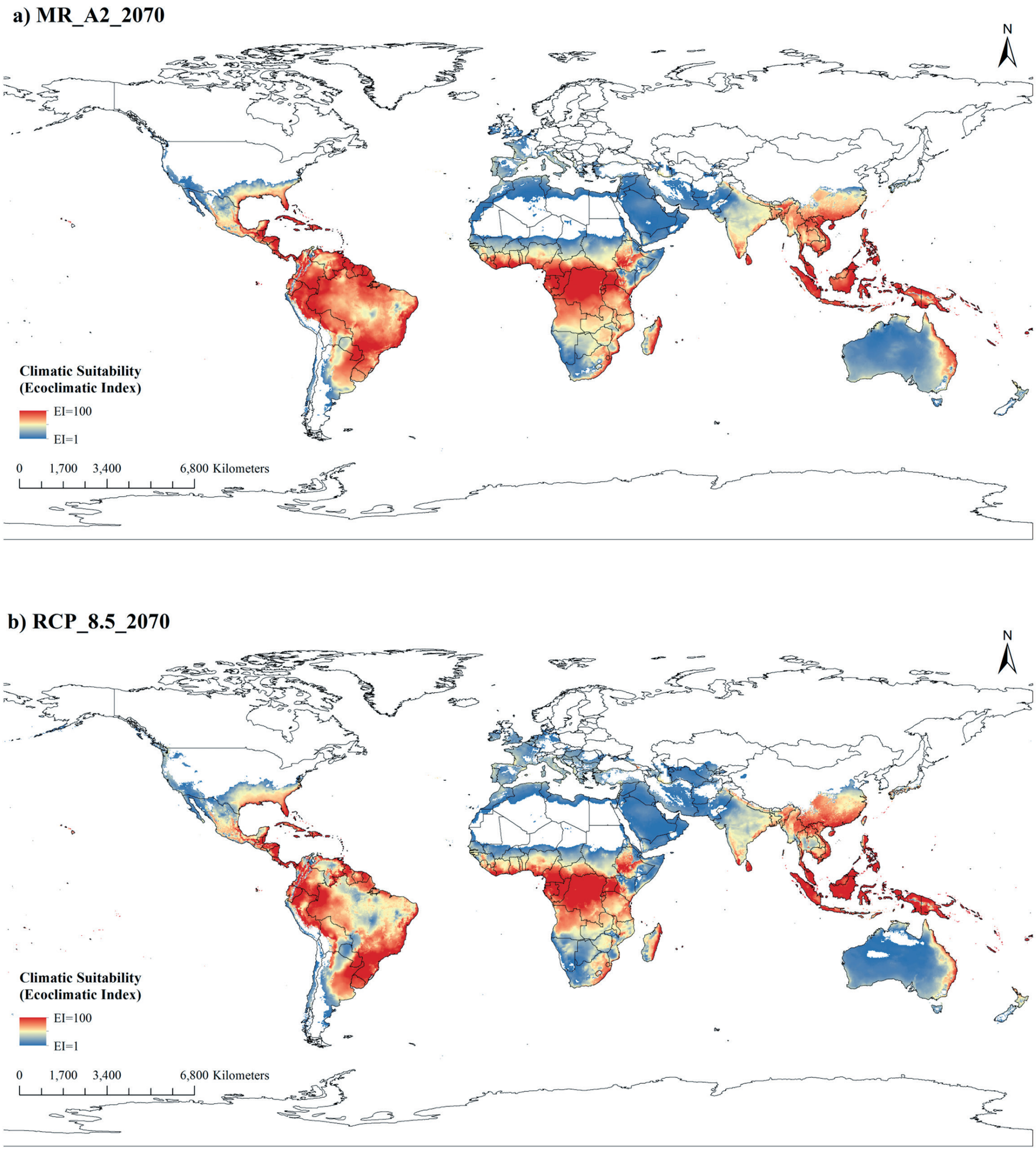

Fig. 2. Potential distribution of yellow crazy ant in 2070 with application of climate change scenarios using CLIMEX. (a) SRES A2 scenario by MIROC–H (Centre for Climate Research, Japan); and (b) RCP 8.5 scenario by Hadgem2–AO (Hadley Centre Global Environmental Model version 2, England).

what differed in specific survivable areas and quantitative climate suitability (Table 2). Both scenarios expected that the climate suitability of yellow crazy ant would be consistently high in Southeast Asia and Central Africa around the equator, while it would decrease in the equatorial region of South America. However, the potential geographical distribution of yellow crazy ant of RCP scenario was wider than that of SRES (Fig. 2, Table 2). Specifically, climate suitability in South America simulated by RCP scenario showed shaper decrease than by SRES scenarios. In southeastern areas of United States, Europe, and Northeast Asia, the expected climatic condition would be more suitable as the latitude becomes higher with both scenarios, suggesting global warming increases the risk of introducing yellow crazy ant. In Europe, climate suitability would be expanded to wide regions in Spain, Italy, and Greece. Moreover, climate suitability would reach up to southern regions including islands in Korea and western Japan in Northeast Asia. Northwestern region of Australia showed higher climate suitability under the current climate conditions, but it would move along the western coast. Also, the southwestern region would have higher climate suitability for yellow crazy ant in 2070.

The areas where showed the largest change in climate suitability in 2070 compared to the current were the United States, Europe, and Northeast Asia. To quantitatively compare the changes, we performs following process, resulting numbers in the Table 2; 1) we firstly calculated the current and future (year 2070) percentage ratio of area whose EI≥1 to the total area of each continent (America, Europe, Northeast Asia), and then 2) determined the percent increase by the difference between current and future percentages. We additionally determined the limit line of potential distribution through the maximum latitude of areas having EI≥1 except US where was limited to the eastern part only. In addition, we considered that a country was exposed to invasion risk when more than 30% state or province area compared to total area of the country had EI≥1. This calculation permitted a quantitative illustration of the changes in possible areas of yellow crazy ant distribution by time and by different climate change scenarios. According to RCP scenario, the survivable area for yellow crazy ant in 2070 would increase by 14% in United Stated with extending the potential limit line up to about N 2.83 in the east. SRES scenario showed qualitatively similar results. However, the rate of areal increase was expected to be 7%, and the expansion of limit line was to be N 1.5. Europe predicted to have the largest changes in potential yellow crazy ant distribution in both RCP and SRES scenarios, showing suitable area would be increased by 27% and 11%, respectively, in 2070. It was predicted that most countries near the Mediterranean changed into suitable regions for yellow crazy ant, and the potentiality was even reached in the southern part of England. Also, the latitudinal limit for yellow crazy ant survival was extended, ranging from N 8 at maximum (RCP scenario) to N 4 at minimum (SREES scenario). In Northeast Asia, another region of drastic changes in potential distribution by climate change, the suitable region was increased by 8% with extending limit line northwards up to 3 degrees according to RCP scenario in 2070. For example, RCP scenario expected that climate suitability in 2070 would increase in Far East Asian countries, such as South Korea, Japan, and China. In contrast, SRES scenario expected Japan and China would be partially at risk caused by the potential geographical distribution of yellow crazy ant, but the future distribution was not much changed in South Korea.

In short, Europe was expected that the most countries would be exposed to additional danger of yellow crazy ant invasion due to climate changes. Also, the potential geographical distribution of yellow crazy ant will change in the United States and Northeast Asia, but not as much as Europe. RCP scenario overall expected that 17 European countries, 2 states in United States, 5 provinces in China and Japan, 3 provinces in South Korea would be in danger of introducing yellow crazy ant. On the other hand, SRES scenario predicted that 5 European countries, 2 states in United States, some of China and Japan would be at risk of yellow crazy ant dispersion due to the increased climate suitability. All the results including the dangerous locations are illustrated in Table 2.

DISCUSSION

Major regions in potential geographical distribution of yellow crazy ant

The current potential geographical distribution of yellow crazy ant is usually the tropical and subtropical regions, and it is significantly high in the Southeast Asia, Oceania, Central Africa, and South America. However, the regions where yellow crazy ant was actually found were mainly countries in Southeast Asia and Oceania (Green *et al*., 1999; O'Dowd *et al*., 1999; O'Dowd *et al*., 2003; Wetterer, 2005), and there was not any report regarding discovery of yellow crazy ant in Central Africa and the inland areas of South America excluding Chile. Interestingly, yellow crazy ant has been mainly found in vacation spots or islands such as Okinawa (Suwabe *et al*., 2009), Hawaii (Kirschenbaum and Grace, 2007), and Christmas Island (O' Dowd *et al*., 1999), while it is rarely observed in inland regions. Based on our simulation and the above reports, we can infer that yellow crazy ant likely to be found in the areas where 1) the lowest monthly temperature never goes down below 5°C (EI>10), 2) have large floating population, 3) does not have adequate quarantine facilities, and 4) exists fluent shipping. This inference is supported by some reports that yellow crazy ant usually spreads into a new region when a queen ant or an egg transferred by means of transportation for commerce or tourism (Csurhes and Hankamer, 2012, Wetterer, 2005). Also, the fact that high density of yellow crazy ant was especially found in Southeast Asia suggests that unsystematic quarantine facilities compared to those in developed countries may be one of reasons for its spread besides its climatic suitability.

There have been reports that yellow crazy ant was found in Africa and South America (Wetterer, 2005). However, Wetterer (2005) reported that the occurrence of yellow crazy ant in Chile is error or died out, and occurrence record of yellow crazy ant has not been reported in Durban, South Africa for more than 20 years (Wetterer, 2005). In addition, the record in Tanzania has been reported by Wetterer (2005) except Arnold (1922). Based on the above controversies, it is not obvious yet why the yellow crazy ant has never been established in high density in Africa and South America, although the climate suitability for yellow crazy ant in these regions is significantly high. This may be due to the exchange of commerce which has been considered as a main way for yellow crazy ant transfer. When simply considering the exchange of commerce of Africa and South America which has the highest potential distribution of yellow crazy ant most of the major importing partners of them are from the regions where yellow crazy ant has never been found, and their regions are considerably far away from its major place. This reason holds true for Central Africa as well, suggesting one of the reasons that these regions are not suitable for yellow crazy ant's invasion. However, high climatic suitability suggests that the dispersion of yellow crazy ant may significantly rapid once it succeeds in settling down in these two regions. Also, it is expected to be much faster in South America where the rate of floating population is higher than Central Africa.

Exploring danger regions due to climate changes

The regions expected to have the highest potential distribution of yellow crazy ant according to the two climate changes scenarios are the southeastern area of United States, Europe, and Northeast Asia. Among three regions, Northeast Asia is the closest to the major origin of yellow crazy ant, proposing high risk of yellow crazy ant's invasion because the climate suitability of this region is predicted to increase continuously. Especially, the main island of Japan and the major islands in the southern coast of South Korea are exposed to a significant danger of invasion. This is consistent with previous study by Chen (2008) which specifies most regions in South Korea and Japan as median affected risk under the current climate and reported South Korea as high invasive risk due to the accelerated climate change. However, South Korea is far from the warm and humid regions where yellow crazy ant prefers since most regions in South Korea have below zero temperatures during winter season until 2050 even with RCP 8.5 scenario. In addition, if yellow crazy ant invades South Korea under the current temperatures, it would not survive due to harsh winter causing too high cold stress. Nevertheless, the southern coast area in South Korea including Jeju Island and many southern islands can have high invasion risk as its climate is gradually changing into subtropical. Moreover, Japan showed higher climate suitability for yellow crazy ant compared to South Korea and Kyushu, Shikoku, Chugoku, and Kinki regions had significantly high invasive risks.

Setting limit line of potential geographical distribution

CLIMEX model may have a shortage in that the potential geographical distribution limit line is clear since it matches the potential distribution based on the currently known distribution. For example, potential distribution for yellow crazy ant mainly living in wet–tropical regions of Southeast Asia and Pacific was limited in other wet–tropical regions around the world. This is because that it depends on strongly known site are chosen for matching. Wetter (2005) has mentioned on this issue by arguing that prediction including temperate sites (e.g., Auckland), high elevation sites (e.g., Zayul, and Tibet), and very arid sites (e.g., Baja California) would show a considerably distribution map. For this reason, this study this study calibrated the parameter values using repeated fine adjustment process (calibrating parameters with repeated changes in values by a small unit) with inclusion of Auckland, and Baja California for better prediction (Fig. 1). Zayul in Tibet was excluded from potential distribution because CLIMEX mainly considered climate but could not account high elevation. In addition, climates of Zayul, Tibet in terms of latitude and elevation are out of range for the apparent climatic tolerance of yellow crazy ant. Especially, the lowest average temperatures of Zayul during December, January, and February are about 0°C, which were obviously inadequate for the survival of yellow crazy ant (Suwabe *et al.*, 2009, Haines and Haines, 1978; Abbott *et al.*, 2005). Furthermore, we may deduce that yellow crazy ant can temporarily appear in this region from May to September, but its establishment is impossible.

AUTHOR CONTRIBUTIONS

Jae Min Jung designed the study, operated CLIMEX to construct a distribution map for the target species, analyzed the CLIMEX results and wrote the manuscript. Chisa Yasunaga–Aoki participated in the design of the study and discussed biological meanings of the results. Yong Man Yu provided biological information of the target species and involved in result discussions. Sung Hoon Jung supervised the work, provided biological information and edited the manuscript. Wang Hee Lee designed and supervised the work, analyzed and discussed the CLIMEX result and wrote manuscript.

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