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Estimating economic damage to cocoa bean production with changes in the spatial distribution of *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae) in response to climate change

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ABSTRACT

Cocoa is a crop that serves as a major source of income in some countries, but its production has been affected by red flour beetles, *Tribolium castaneum* (Herbst). In this study, we aimed to predict the global potential distribution of *T. castaneum* under the current climate and in response to climate change (2050 and 2100). In addition, we attempted to use the results for estimating damage and economic losses in the major cocoa beans-producing countries. The CLIMEX model was used to evaluate the climatic suitability of regions for *T. castaneum*, and the economic damage was estimated by incorporating a series of published models and published data. The results showed that the potential distribution of *T. castaneum* was consistent with that of cocoa beans-producing countries, and as expected, at the local-level, *T. castaneum* was concentrated in cocoa cultivation areas. It was estimated that up to 50% damage to cocoa beans and economic loss of 3.16 billion US dollars due to production loss could occur. This study is the first attempt to estimate the economic damage to cocoa bean production by predicting the potential distribution of *T. castaneum*. Further, this study not only provides insight to combine the potential distribution of a species and an estimation of the related economics, but also provides basic data for establishing an effective monitoring/controlling strategy for preventing damage by *T. castaneum*.

1. Introduction

Insects cause severe damage to various crops, and along with climate change, have resulted in sustained agricultural losses (Rosenzweig et al., 2001; Anwar et al., 2013). For this reason, an effective way to predict changes in their habitats has been emphasized upon, and species distribution modeling (SDM) has been applied to evaluate the potential distribution of a pest insect and to extrapolate to show areas at risk of damage (Phillips et al., 2004; Miller, 2010; Barve et al., 2011; Kriticos et al., 2015). For example, CLIMEX, a species distribution modeling software, uses long-term meteorological data to evaluate the potential distribution of a species, considering the effect of climate on the biological characteristics of the target species (Kriticos et al., 2015; Jung et al., 2016). Due to its ability to predict potential distributions, SDM has been used in various countries worldwide in which pest invasion is a concern (Lanoiselet et al., 2002; Senaratne et al., 2006; Pattison and Mack, 2008; Jung et al., 2017; Byeon et al., 2018).

Cocoa is a globally traded agricultural product with a total worldwide production of approximately 5.2 million tons in 2017 (FAO, 2017). It grows well in warm-temperate climates in countries located between ±20° from the equator (Ofori-Boat and Insah, 2014). Consequently, a few African, South American, and South Asian countries are the largest producers of cocoa beans in the world (FAO, 2017). However, in most of these countries, a lack of systematic monitoring of insects and control strategies has caused severe pest damage to agricultural commodities, including cocoa (Dinham, 2003; Parsa et al., 2014). Among pests, stored-product insects lead to the economic loss of agriculture by reducing the quality of the commodities and causing dissatisfaction of consumers (Sinha, 1973; Mills, 1992). In storage facilities, it is estimated

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that, on an average, more than 2.5% weight loss occurs due to insect infestation, and as high as 13% losses have been reported in China (Ahmad et al., 1992, Jayas and White, 2002).

The red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae) is a common stored-product insect that feeds on grains in storage facilities. It causes both quantitative and qualitative loss of produce in storage areas that are not properly secured and are exposed to the outside or when there is insufficient storage space and produce is left in the open (Campbell and Arbogast, 2004). In fact, it is the most common pest that causes both qualitative and quantitative degradation of cocoa beans (Navarro et al., 2007; Jonfia-Essien and Navarro, 2012; Tettey et al., 2014; Adarkwah et al., 2017; Abdullahi, 2018). Although an earlier study has reported the correlation between damaged cocoa beans and weight loss with the population density of *T. castaneum* in cocoa bean storage, published information on the exact damage to cocoa beans due to infestation by *T. castaneum* is limited (Abdullahi, 2018).

Climatic conditions suitable for cocoa cultivation are similar to those required for the growth of *T. castaneum* (Ofori-Boat and Insah, 2014). In addition, even though *T. castaneum* mainly lives in storage facilities, it has also been found in truck entrances, indicating that it invades from areas that are climatically favorable located outside storage facilities (Trematerra and Sciarretta, 2004). For this reason, the application of SDM to determine the potential distribution of *T. castaneum* to help evaluate damage and economic loss in cocoa bean production is necessary. Moreover, climate change will cause changes in its potential distribution in the field. Unfortunately, none of the studies to date have attempted this kind of investigation because the practical application of SDM to stored-product insects is very limited (Lee et al., 2020). Hence, the objective of this study was to predict the current global distribution of *T. castaneum*, predict its future potential distribution in response to climate change, and quantitatively estimate the loss of cocoa bean production caused by it.

2. Materials and methods

To simulate the global distribution of *T. castaneum* under current climatic conditions and predict their future distribution for the SRES (Special Report on Emissions Scenarios) climate change scenario, we developed CLIMEX models. To evaluate economic loss caused by *T. castaneum*, we developed a series of models that connected the potential distribution of *T. castaneum* under climatic change in the major cocoa beans-producing countries to damage on cocoa beans.

2.1. CLIMEX models

Three types of data (described in detail below) are necessary to build the CLIMEX (version 4.0, Hearne software, Australia) model: distribution of target species, biology of the target species, and meteorological data. With these data sets, the parameters are first estimated from which a distribution model is predicted. This is then validated using actual occurrence data. Lastly, based on the model, the potential distribution is mapped (Jung et al., 2016). Detailed information regarding the CLIMEX software is described well elsewhere (Kriticos et al., 2015; Jung et al., 2016; Byeon et al., 2018). The main outcome of the CLIMEX model is the Ecoclimatic Index (EI) that quantitatively evaluates the climatic suitability of a specific region for the target species. EI is calculated by considering population growth under favorable climate and stress that limit growth under unfavorable conditions (Jung et al., 2016). The value of EI ranges from 0 to 100, with higher values indicating higher climatic suitability. In general, an EI greater than 20 indicates optimally favorable climates for the target species, while EI = 0 suggests that the area does not have a suitable climate (Kriticos et al., 2015).

Using ArcGIS (version 10.4.1, Redlands, CA, USA), the predicted EI values at every point location with meteorological data were converted into raster format to generate the EI gradient for the world. Then, the EI values for cocoa production countries were extracted and averaged to compare their changes in response to climate change by using SAS software package (version 9.4, SAS Institute Inc. Cary, NC, USA) with a significance level of 0.05.

2.2. Distribution data of T. castaneum

T. castaneum is thought to have originated from the Indo-Australian region (Smith and Whitman, 1992; Ridley et al., 2011), preferring habitats in temperate areas. It is a stored-product insect that inhabits protected places to overcome unfavorable climatic conditions. Grain transportation has allowed its dispersal (Haines, 1991; Tripathi et al., 2001; Nenaah, 2014), and currently, they are widely distributed throughout the world (Hill, 1990). Also, the effect of regional climate and geographic characteristics on their distribution is lower than that on other pests observed in the field (Hill, 1983). To develop the distribution model, data on occurrence of the species are required to estimate parameter values and to validate the predicted distribution (Kriticos et al., 2015; Jung et al., 2016). CLIMEX models evaluate the potential distribution based on the external climate. As the available current occurrence information includes observations from storage facilities, this is not reliable for use in our study. Hence, we considered the occurrence data near the origin to be more appropriate and extracted occurrence data for Australia from public species databases of the Global Biodiversity Information Facility (GBIF, 2020).

2.3. Biological characteristics of T. castaneum

Information on the effect of temperature and relative humidity on the developmental rate and mortality of *T. castaneum* is the basis of parameter estimation in the CLIMEX model. An earlier study has shown that both fecundity and developmental rate were lower at 24 °C than at 29 and 34 °C (Park and Frank, 1948). Another study (Howe, 1956) suggested that *T. castaneum* did not survive at temperatures lower than 17.5 °C or greater than 40 °C, and that mortality was low from 25 to 35 °C. Further, this study showed that developmental time was shorter at approximately 35 °C than at any other temperature. These results were supported by Chon et al. (1991), who showed that low mortality was observed from 25 to 36 °C, while 20 and 42 °C were reported to be the lower and upper threshold temperatures, respectively. Howe (1956) also reported that developmental time and mortality were low at high relative humidity compared to low relative humidity. Two other studies have suggested that a high moisture content of over 70% relative humidity would be optimal for *T. castaneum* growth (Park and Frank, 1948; Chon, 1991). Mahroof et al. (2003a) investigated the effect of heat treatment at temperatures higher than 40 °C and showed that mortality increased with an increase in temperature. In another study, it was shown that mortality was very low when the treatment temperature was between 31.5 and 46 °C (Mahroof et al., 2003b). In summary, the optimal temperature for *T. castaneum* growth is thought to be 25–35 °C, while its population growth can be highly limited either below 17.5 °C or over 40 °C. Moreover, *T. castaneum* prefers high moisture conditions, while low humidity may limit its growth.

Based on these reports, the degree days (PDD) representing the effective cumulative temperature and limiting low temperature (DV0) were estimated to be 588 days and 14 °C, respectively. The optimal temperature range was considered to be between 25 °C (lower optimal temperature, DV1) and 35 °C (upper optimal temperature, DV2), while limiting high temperature (DV3) was set to 40 °C. Other parameters related to soil moisture and stress under unfavorable climatic conditions were set up to allow for the best simulation of the potential distribution of *T. castaneum*, which fit the current distribution data over tropical, temperate, and Mediterranean climate zones in Australia. For instance, the final parameter showed that, in Australia, *T. castaneum* was distributed mainly in Queensland, New South Wales, and along the coastal regions, which was consistent with the actual distribution. All parameters and their values are listed in Table 1.

2.4. Meteorological data

Because CLIMEX requires meteorological data for its operation, current climate data and climate change scenarios were obtained from CliMond (https://www.climond.org) (Kriticos et al., 2012). The current climate data are long-term average data from 1960 to 1990 with 10'-grids (18 km × 18 km resolution). SRES A1B with the same resolution was used as a climate change scenario to predict the potential distribution of *T. castaneum* in 2050 and 2100 (IPCC, 2001).

2.5. Developing a model for estimating economic damage to cocoa bean production

To estimate the economic damage to cocoa bean production, 13 countries that produced more than 5 million tons (approximately 96% of world cocoa bean production) were selected (FAO, 2017) (Fig. 1). A previous study reported that damage and weight loss of cocoa beans were correlated with the population density of *T. castaneum* during storage of cocoa beans (Abdullahi et al., 2018). Using their published data, we developed a model for estimating percent damage and weight loss of cocoa beans as a function of *T. castaneum* population density (Eqs. (1) and (2)).

$$\text{Damaged bean}(\%) = 52.4 \times \left(1 - e^{-0.026 \times T}\right) \tag{Eq.1}$$

Table 1
CLIMEX parameters and estimated values for *Tribolium castaneum*.

Parameters	Code	Optimal value
Temperature		
Limiting low temperature (°*C*)	DV0	14
Lower optimal temperature (°*C*)	DV1	25
Upper optimal temperature (°*C*)	DV2	35
Limiting high temperature (°*C*)	DV3	40
PDD		588
Moisture		
Limiting low soil moisture	SM0	0.1
Lower optimal soil moisture	SM1	0.25
Upper optimal soil moisture	SM2	1.0
Limiting high soil moisture	SM3	1.5
Cold stress		
CS temperature threshold (°*C*)	TTCS	2
CS temperature rate	THCS	−0.005
Heat stress		
HS temperature threshold (°*C*)	TTHS	40
HS temperature rate	THHS	0.0002
Dry stress		
DS threshold	SMDS	0.05
DS rate	HDS	−0.02
Wet stress		
WS threshold	SMWS	1.5
WS rate	HWS	0.007

$$\text{Weight loss }(\%) = 35 \times \left(1 - e^{-0.0175 \times T}\right) \tag{Eq.2}$$

where T indicates the population density (number of adults) of *T. castaneum*.

Because one of the main outcomes of this study is climatic suitability represented by EI, it was necessary to relate climatic suitability with population density. Unfortunately, even though there is a report suggesting that high climatic suitability was found to support substantial population densities (Sutherst, 2003; Poutsma et al., 2008), no study to date has investigated the quantitative relationship between them. For this reason, we decided to employ the equation of host availability that calculates the abundance of host plants based on its climatic suitability because it relates density with EI (Berzitis et al., 2014; Jung et al., 2020) (Eq. (3)).

$$\text{Population density }(\%) = \frac{(\mathrm{EI}/\mathrm{h})^{\mathrm{q}}}{1 + (\mathrm{EI}/\mathrm{h})^{\mathrm{q}}} \times 100 \tag{Eq.3}$$

where q represents the speed of the curve rise, and h is the value of EI for T to be 0.5. Herein, we set 5 and 15 for q and h, respectively, based on Berzitis et al. (2014).

Consequently, by integrating equations (1) and (2), a model for evaluating percent damage and weight loss as a function of population density of *T. castaneum* was developed (Eqs. (4) and (5)). Because EI was determined for every point with climatic data and climate change scenario, the number of points with EI values for a cocoa beans-producing country varied from 148 to 25,444, depending on the area of the country. For this reason, we averaged the EI values for each country so that the average EI value can be used in the developed economic model.

$$\text{Damaged bean}(\%) = 52.4 \times \left(1 - e^{-0.026 \times \frac{(\mathrm{EI}/15)^5}{1+(\mathrm{EI}/15)^5}}\right) \tag{Eq.4}$$

$$\text{Weight loss}(\%) = 35 \times \left(1 - e^{-0.0175 \times \frac{(\mathrm{EI}/15)^5}{1+(\mathrm{EI}/15)^5}}\right) \tag{Eq.5}$$

where the averaged EI value for each cocoa beans-producing country in response to climate change was used for EI.

In addition, by considering the price and the amount of production, we estimated the economic loss due to quantity loss of cocoa beans because of *T. castaneum* (Eqs. (6) and (7)).

$$\text{Production loss (ton)} = \text{Production amount} \times \text{weight loss}(\%) \tag{Eq.6}$$

$$\text{Economic loss due to quantity (\$)} = \text{Production amount} \times \text{weight loss (\%)} \times \text{Price/ton} \tag{Eq.7}$$

where the sources of production amount and price/ton were Food and Agriculture Organization (FAO), and International Cocoa Organization (ICCO, 2018), respectively.

3. Results

The current simulation of the field distribution of *T. castaneum* was mapped, showing that it could potentially be distributed in

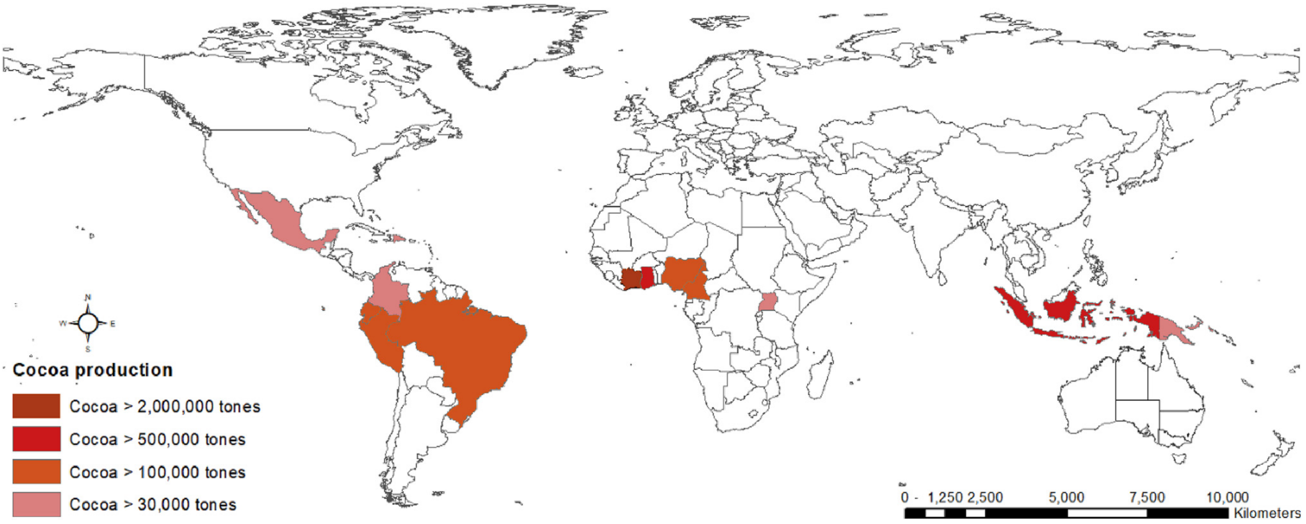

Fig. 1. Map of major countries producing cocoa beans and the amount of production.

temperate and tropical regions, including South America and Africa (Fig. 2a). In 2050, the global potential habitat of *T. castaneum* does not significantly change, but a notable reduction in suitable areas was observed in Asia (Fig. 2b). Its distribution range near the equator tended to decrease with continuous climate change, but the northern and southern limits shifted slightly to the north and south, respectively, suggesting climate change forced the species to move to new areas that had been unsuitable for it under the lower temperatures (Fig. 2c). Africa, where approximately 70% of the world's cocoa beans is currently being produced, showed the largest potential population for the current scenario as well as for 2050 and 2100. To investigate the changes in the climatic suitability in cocoa production countries with climate change, we extracted the EI values for the selected 13 countries shown in Fig. 1. For each country, the average EI value showed variations, which differed between countries and showed different tendencies of change due to climate change (Table 2). In general, most countries in Africa showed relatively higher EI values throughout the simulated years than other regions. The highest EI value was simulated for the Dominican Republic under the current and 2050-year climate scenarios, but Uganda showed the highest EI value in 2100. The lowest value was observed for Papua New Guinea in all three years. The pattern of change depended on the country. Four countries showed continuous decreases and three showed continuous increases, while the remaining countries showed the peak EI value in 2050. However, it should be noted that not all the changes across years were statistically significant. For example, Ivory Coast, the largest producer of cocoa beans in the world, showed a significant decrease in EI value, while the EI value in Cameroon increased significantly as climate change progressed. In contrast, although there was a change in EI values in Papua New Guinea, it was not statistically significant.

Country-wise results for the percent damaged beans, percent weight loss, production loss, and the corresponding economic loss due to quantity are presented in Table 3. In general, an EI value larger than 20 was expected to damage 45% of the total produced cocoa, while only 15% would be damaged by *T. castaneum* when the EI value was approximately 10. The total quantity loss in the 13 countries combined did not significantly change across the years, but the change within countries across years was significant. Our results showed that in African countries, half of the produced cocoa beans would be damaged, while Asian countries would have damaged less than 20%. For example, for Ivory Coast, the estimated damage and weight loss could be approximately 50% and 29%, respectively, causing quantity loss of more than 1.3 billion US Dollars. Losses in countries in South America except Brazil were estimated to be moderate, but damages in Central America were predicted to be as serious as those in Africa. Even though climate change caused variations in the EI value, it did not significantly affect the economic loss in African countries because their EI values over the years remained higher than 20. In other words, African countries would continue to experience cocoa production loss due to *T. castaneum*. In contrast, South American countries showed fluctuations, except Brazil where it was predicted that a high EI value, enough to cause weight loss of cocoa beans to more than 28%, would be retained across the years. The economic loss was predicted to peak in 2050 in Peru and Colombia with more than 20% of weight lost, and economic losses were expected to increase to more than 12 and 6.5 million dollars, respectively. The economic loss was predicted to be more than 41 million dollars in 2100 in Ecuador, which is an increase of more than 14 million dollars over current losses. The countries in Central America were predicted to retain weight losses through 2100, whereas in Asia, Indonesia showed a drastic increase in damaged cocoa beans from 18% to 46% and increase in economic loss of more than 13 million US dollars in 2100 compared to the current loss.

4. Discussion

Estimation of economic losses in agricultural production by connecting climatic suitability has rarely been performed in pest studies. In this study, a series of models were conceived to evaluate the economic loss in cocoa bean production based on climatic suitability predicted for *T. castaneum* by the CLIMEX model. Because *T. castaneum* is a stored product insect, its occurrence has been recorded in most parts of the world, making the use of species distribution modeling difficult. A previous study applied species distribution modeling to predict *Plodia interpunctella* (Hübner) distribution in South Korea (Lee et al., 2020), but it has rarely been used for global scale. Nevertheless, since the climates for cocoa cultivation and *T. castaneum* distribution are similar and there is a high possibility of infiltration of a pest into the storage area in a climatically favorable region (Shiha and Utida, 1967; Tigar et al., 1994; Palyvos et al., 2008), we thought that the climate suitability

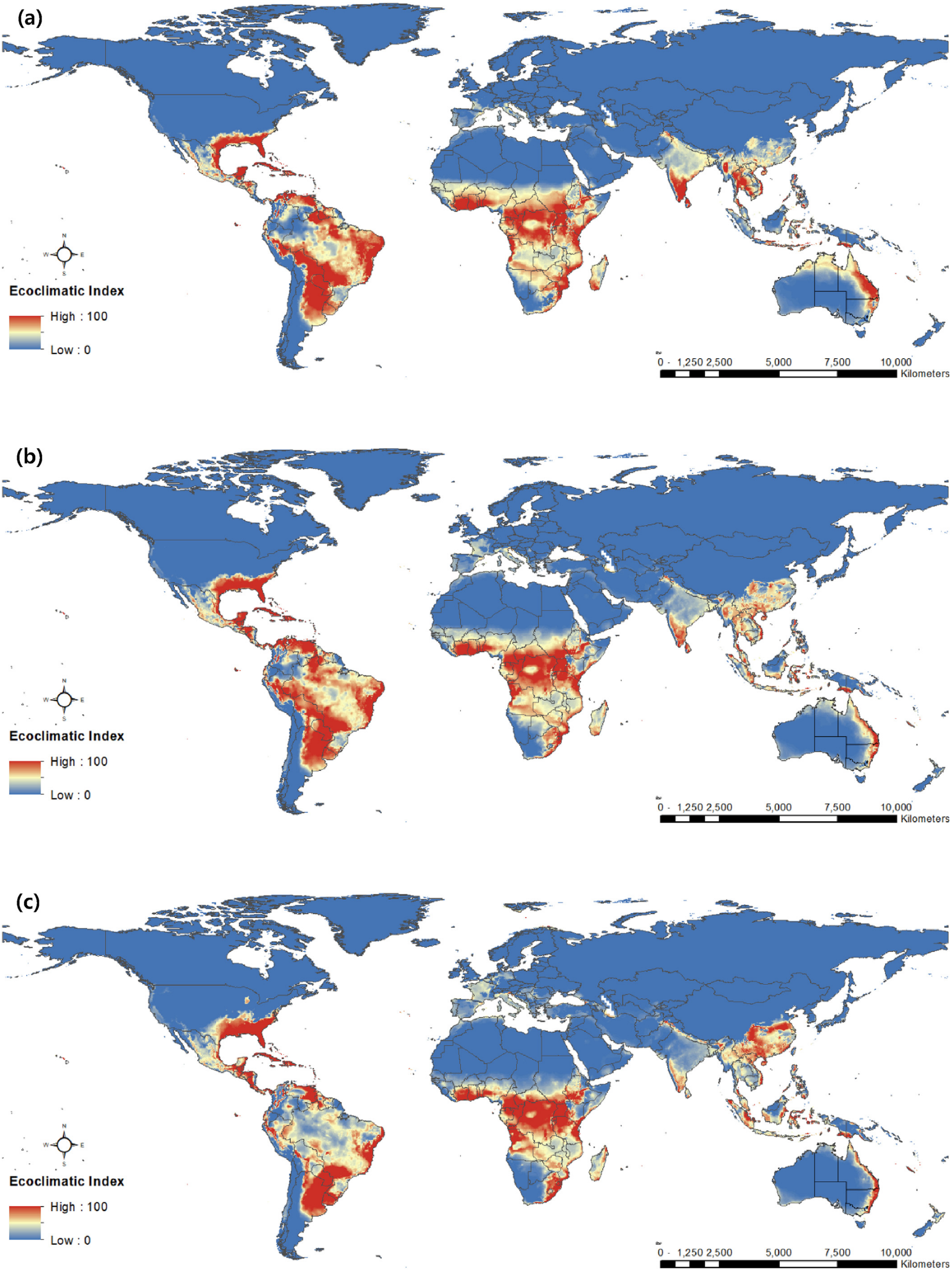

Fig. 2. Predicted potential distribution of *Tribolium castaneum* in response to (a) current climate, (b) climate in 2050, and (c) climate in 2100.

of *T. castaneum* through specific distribution modeling might be correlated with losses in cocoa bean production. In addition, because the total production includes both field cultivation and storage after harvesting, the estimated loss based on it is the whole loss caused by both field occurrence and storage infiltration of *T. castaneum*. In the case of *Phthorimaea operculella* (Zeller) (Lepidoptera: Gelechiidae), total production data were used to account for the amount of stored potato and field production in predicting its potential distribution (Jung et al., 2020). Population growth has been modeled by using a specific function that shows a plateau after transient changes (e.g., logistic model) because it tends to be saturated against available resources (Roughgarden, 1975; Tsoularis and Wallace, 2002; Sibly et al., 2005). Biologically, limited resource availability and competition between inter/intra species may limit the infinite population growth (Lawton and Strong Jr. 1981; Dempster, 1983; Debouzie et al., 2002). In this study, the model employed to connect climatic suitability and population density showed sigmoidal patterns of population density, weight loss, and damaged beans and revealed a slowing down in the rate of population increase at the EI value of approximately 20. In general, EI values larger than 20 mean that the climate is favorable for the population growth of a species (Kriticos et al., 2015). Therefore, the developed model showing the saturated loss of cocoa beans against climatic suitability seems to be adequate as a previous study that we used as a basis of the current model shows a maximum damage saturated at 50% of stored cocoa beans by *T. castaneum* depending on the population (Abdullahi et al., 2018). Unfortunately, exact information regarding economic losses on cocoa bean production is limited (Abdullahi et al., 2018); thus, we compared our predictions with published global damages. The average damage predicted by this study is 38.9% compared to the actual report regarding global annual loss ranging from 10% to 30% (Singh et al., 2009; Obeng-Ofori, 2010). This discrepancy is due to the fact that we used total production only from major cocoa beans-producing countries, (Lale, 2002; Abdullahi et al., 2018). In these less developed countries, it is reported that the maximum loss can reach 50%, which is consistent with the maximum loss from our predictions; thus, not surprisingly, our predicted value taking into account such countries is higher than the global loss (Lale, 2002; Obeng-Ofori, 2010). In addition, the model incorporates recently published data relating to population density (Abdullahi et al., 2018), damaged cocoa beans, and models explaining population density and climatic suitability (Berzitis et al., 2014; Jung et al., 2020). Therefore, this study can provide a long-term estimation of the economic loss associated with the potential distribution of *T. castaneum* with minimum reliability from publications. We additionally want to note that the economic evaluation in this study focuses on quantity loss, but does not consider quality loss which can be roughly estimated by the amount of damaged bean. However, decrease in quality does not mean the entire value of the cocoa beans is lost, and there may be markets that can make use of lower quality beans. For this reason, the primary and secondary market prices are required for the accurate estimation of quality loss (Bellemare et al., 2017). In addition, there is possibility that cocoa beans are calculated in the quantity loss may have also been counted as having reduced quality, suggesting double counting can occur. This double counting would result in estimates of losses biased higher than they should be, requiring a calculation for solving the source of double counting. Unfortunately, due to limited available data for primary and secondary market prices of cocoa beans and for considering the source of double counting, this study did not include the estimation of economic loss by damaged quality. This could be a future study.

Our results show that the current field distribution of *T. castaneum* is mostly predicted to be in Africa, South America, and South Asia, where more than 95% of the world's cocoa beans is being produced (FAO, 2017). In other words, *T. castaneum* is distributed in areas with a suitable climate and where their host plant, namely cocoa beans is available (Navarro et al., 2007; Jonfia-Essien and Navarro, 2012). In addition, even though there is a slight change in its distribution in response to climate change, the overall range of potential field occurrence of *T. castaneum* is concentrated in countries producing cocoa beans, suggesting that these areas remain under high risk. For example, most cocoa beans-producing countries would maintain an EI value greater than 10, which indicates moderate climatic suitability and a high potential distribution of *T. castaneum* in these countries. However, it should be noted that it has been found in most parts of the world because it feeds on various stored crops. While the change in climate suitability varied by country and time along with climate change, the standard deviation of EI tended to increase. Except for the Dominican Republic, for most countries the standard deviation of EI increased in 2050 and 2100 compared to the present value. The large standard deviation of climate suitability means that the deviation of suitability between local areas within the country is large, suggesting that the distribution of *T. castaneum* is more likely to be concentrated and causes severe damage to specific areas. The developed model predicts an average weight loss of 22.4% in cocoa bean production in 13 major countries, resulting in predictive quantity losses of up to 3.2 billion US dollars. In addition, depending on climate change, 24.9% and 23.6% of weight losses are expected in 2050 and 2100, corresponding to economic losses of up to 3.2 billion US dollars. However, if the population density of *T. castaneum* reaches the value of $EI = 20$ due to the concentration of its population in a specific region, losses in Latin America and Asia where relatively low losses are expected can increase, and overall losses can be much larger. Overall, there is an area where the EI value changes significantly, but the EI values of countries except Papua New Guinea are maintained at 15 or higher, indicating that most countries producing cocoa beans would have favorable climatic conditions. In addition, changes in temperature and precipitation due to climate change will cause a local change in the distribution of *T. castaneum*, thereby concentrating the distribution to specific areas. Because the actual distribution of insects is influenced not only by the climate but also by host plants (Araújo and Luoto, 2007; Berzitis et al., 2014; Wang et al., 2017; Jung et al., 2020), the concentration phenomenon due to climate change may cause movement of *T. castaneum* to areas producing host plants. Cocoa cultivation requires a mean temperature of 27 °C and a daily variation of less than 8 °C; thus, cultivation areas are confined within 20° north or south of the equator (Ofori-Boat and Insah, 2014). The climatic conditions suitable for cocoa cultivation are favorable for the occurrence of *T. castaneum*, suggesting that the cocoa cultivation area and the distribution of *T. castaneum* will continue to overlap with climate change. Consequently, there is a high risk of causing continuous damage to cocoa bean production. To make matters worse, the loss can increase with increased exposure time to *T. castaneum* attack (Abdullahi et al., 2018) and infestation by other insects, such as, *Cryptolestes ferrugineus* (Stephens), and *Ephestia cautella* (Walker) (Finkelman et al., 2003; Singh et al., 2009). Therefore, it is necessary to develop an intensive control strategy in countries producing cocoa beans to prevent damage by *T. castaneum*. For example, various methods to eradicate it have been studied, such as LED traps (Song et al., 2016), heat treatment (Fields, 1992; Dowdy, 1999; Mahroof et al., 2003b), and fumigation (Wang et al., 2006; Sahaf et al., 2008; Abdelgaleil et al., 2009). Thus, these controls can be used in countries that have been predicted to be under high risk of potential distribution and economic loss.

This study evaluated the economic loss to cocoa bean production by using the potential distribution of *T. castaneum* predicted by species distribution modeling in response to climate change. The results suggest that sustained damage might be expected as climatically favorable conditions are similar between cocoa cultivation and population growth of *T. castaneum*. Consequently, an effective control strategy for *T. castaneum* is highly recommended for countries where profit from cocoa bean production is likely to be affected. Even though this study is limited by the lack of data for global field occurrence and actual economic loss of cocoa bean, it provides a novel approach for evaluating long-term economic losses based on the potential distribution of a specific pest as a response to climate change, and the results are useful for establishing a monitoring and controlling strategy for *T. castaneum*

Table 2
Predicted climatic suitability in response to climate change in cocoa beans-producing countries.

Country	No of points	Current EI	EI in 2050	EI in 2100
Ivory Coast	948	49.3 ± 10.2^{a}	46.4 ± 10.1^{b}	38.3 ± 10.8^{c}
Ghana	707	45.5 ± 10.7^{a}	44.6 ± 12.2^{a}	37.5 ± 13.6^{b}
Nigeria	2698	25.3 ± 9.1^{a}	24.9 ± 10.9^{a}	19.3 ± 11.2^{b}
Cameroon	1365	29.6 ± 13.5^{a}	34.7 ± 16.7^{b}	37.2 ± 21.0^{c}
Uganda	708	54.1 ± 12.8^{a}	69.4 ± 13.5^{b}	70.0 ± 13.8^{b}
Brazil	25,444	29.8 ± 15.0^{a}	32.7 ± 15.0^{b}	23.0 ± 15.8^{c}
Peru	3836	14.4 ± 18.5^{a}	18.6 ± 21.1^{b}	15.4 ± 16.1^{c}
Colombia	3337	13.4 ± 16.1^{a}	16.7 ± 19.1^{b}	12.6 ± 15.2^{a}
Ecuador	734	12.5 ± 16.4^{a}	14.1 ± 18.7^{ab}	15.3 ± 19.3^{b}
Dominican Republic	148	55.0 ± 22.2^{a}	76.1 ± 17.2^{b}	54.8 ± 18.2^{a}
Mexico	6258	23.0 ± 17.5^{a}	20.1 ± 17.3^{a}	15.7 ± 20.0^{b}
Indonesia	5364	10.8 ± 12.8^{a}	17.4 ± 15.0^{b}	15.2 ± 9.1^{c}
Papua New Guinea	1329	8.9 ± 15.2^{a}	9.3 ± 16.3^{a}	9.1 ± 15.8^{a}

*The EI values with different letters in the same country are significantly different by year at a significance level of 0.05 ($P < 0.05$).

Table 3
Estimated economic loss by *Tribolium castaneum* in major cocoa beans-producing countries in present, 2050, and 2100.

	Density (%)	Damaged bean (%)	Weight loss (%)	Production amount (ton)	Production loss (ton)	Economic loss (USD)
Current						
Ivory Coast	99.74	48.48	28.89	2,034,000	587,626	1,346,250,869
Ghana	99.61	48.47	28.88	883,652	255,168	584,589,264
Nigeria	93.11	47.74	28.14	659,776	185,652	425,327,603
Cameroon	96.74	48.16	28.56	328,263	93,754	214,791,018
Uganda	99.84	48.49	28.90	295,028	85,264	195,340,850
Brazil	96.88	48.18	28.58	235,809	67,386	154,381,268
Peru	44.63	35.98	18.97	205,955	39,074	89,518,337
Colombia	35.99	31.85	16.36	121,825	19,928	45,654,049
Ecuador	28.88	27.67	13.89	86,599	12,025	27,548,420
Dominican Republic	99.85	48.49	28.90	56,808	16,419	37,614,935
Mexico	80.91	46.01	26.51	44,504	11,796	27,025,054
Indonesia	16.04	17.86	8.56	31,312	2682	6,143,459
Papua New Guinea	6.81	8.50	3.93	27,287	1072	2,456,973
Average/total		38.91	22.24		1,377,845	3,156,642,098
2050						
Ivory Coast	99.65	48.47	28.88	2,034,000	587,428	1,345,798,161
Ghana	99.57	48.46	28.87	883,652	255,131	584,504,648
Nigeria	92.59	47.68	28.08	659,776	185,235	424,374,205
Cameroon	98.52	48.35	28.76	328,263	94,401	216,273,147
Uganda	99.95	48.50	28.91	295,028	85,301	195,424,831
Brazil	98.02	48.30	28.70	235,809	67,686	155,068,253
Peru	74.56	44.86	25.51	205,955	52,531	120,349,443
Colombia	62.84	42.17	23.35	121,825	28,442	65,160,644
Ecuador	42.70	35.13	18.42	86,599	15,953	36,547,777
Dominican Republic	99.97	48.51	28.91	56,808	16,426	37,631,711
Mexico	83.12	46.36	26.83	44,504	11,940	27,353,819
Indonesia	67.52	43.34	24.26	31,312	7597	17,404,611
Papua New Guinea	8.24	10.10	4.70	27,287	1282	2,937,802
Average/total		43.10	24.94		1,409,354	3,228,829,053
2100						
Ivory Coast	99.09	48.41	28.82	2,034,000	586,199	1,342,982,778
Ghana	98.99	48.40	28.81	883,652	254,573	583,226,005
Nigeria	77.73	45.45	26.02	659,776	171,665	393,284,588
Cameroon	98.95	48.40	28.80	328,263	94,556	216,627,975
Uganda	99.95	48.50	28.91	295,028	85,302	195,426,303
Brazil	89.41	47.27	27.68	235,809	65,271	149,536,635
Peru	53.25	39.28	21.22	205,955	43,696	100,106,514
Colombia	29.19	27.87	14.00	121,825	17,057	39,078,611
Ecuador	52.83	39.13	21.11	86,599	18,284	41,889,380
Dominican Republic	99.85	48.49	28.90	56,808	16,418	37,614,546
Mexico	55.70	40.09	21.80	44,504	9700	22,222,114
Indonesia	81.25	46.06	26.56	31,312	8315	19,050,214
Papua New Guinea	7.43	9.20	4.27	27,287	1164	2,667,717
Average/total		41.28	23.61		1,372,201	3,143,713,378

* In the average/total row, damaged bean and weight loss values shown are averages, while production loss, and economic loss are the total values.
**Economic loss is calculated by averaging the prices provided by International Cocoa Organization (ICCO) from January to December in 2018.

occurrence and subsequent agricultural losses.

CRediT authorship contribution statement

Jae-Min Jung: Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft, Visualization. **Dae-hyeon Byeon:** Software, Formal analysis, Investigation. **Se-Hyun Kim:** Validation, Investigation. **Sunghoon-Jung:** Investigation, Writing - review & editing. **Wang-Hee Lee:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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