



Article

The Potential Distribution of the Potato Tuber Moth (*Phthorimaea Operculella*) Based on Climate and Host Availability of Potato [†]

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Abstract: This study evaluated the potential distribution of the potato tuber moth. This species severely impacts global potato production, especially in China and India, which have the world's largest potato production. We developed two indices considering host plant availability and production in addition to climatic suitability, which was simulated using the CLIMEX model. Thus, three different indices were used to project potential distribution of the potato tuber moth under a climate change scenario: (1) climatic suitability (ecoclimatic index (EI)) (EI_M), (2) climatic suitability combined with host plant availability (EI_{N1}), and (3) climatic suitability combined with host plant production (EI_{N2}). Under the current climate, EI_M was high in southern India and central to southern China, while EI_{N1} and EI_{N2} were approximately 38% and 20% lower than EI_M , respectively. Under the Special Report on Emissions Scenario A1B, the potato tuber moth would probably not occur in India, but its distribution could be extended to the north, reaching N47°. The areas with the highest climatic suitability by potato tuber moth based on three indices were Sichuan and Karnataka in response to climate change. These areas require adequate pest control, such as prevention of spread through transport of potato seed or by using cold storage facilities.

Keywords: CLIMEX; climate change scenario; host availability; potato tuber moth; potential distribution

1. Introduction

The potato tuber moth (*Phthorimaea operculella*) is the world's most significant potato (*Solanum tuberosum*) pest, originating from the Andean regions in South America [1]. Current climate change has changed its range of distribution along with bad quarantine problems, resulting in its distribution in approximately 110 countries [2]. It has become a major threat to the potato production system around the world, including in China and India, where one third of the world's potato production occurs [3,4]. China is the world's largest potato producer, with an annual production of 99 million tons, 85% of which is produced in the northern part of the country because of the cool temperature and sunlight suitable for growing potatoes [5]. Approximately 70% of the potato production in India is carried out on the alluvial plain that includes the northern portion of the Ganges River. Uttar Pradesh is the largest producer of potatoes in India. Unfortunately, 4.7%–8.5% of losses

occur because of the potato tuber moth in Himachal Pradesh [6]. In China, the loss of yield resulting from Pea weevil (*Bruchus pisorum*) and potato tuber moth establishment is expected to be 10.03 million US dollars [7]. In addition, 30%–70% of stored potatoes are infested by the potato tuber moth in China and India [7,8].

Species invasion is favored by climate because climate directly influences insect life phases [9,10]. Global changes in pest distribution and pest establishment have damaged local agriculture, biodiversity, and environment [11]. The considerable damages caused by pest introduction result in the need for effective control methods and monitoring strategies. Species distribution modeling (SDM) has been widely used as a tool for more efficient time and geographical monitoring approaches [12–16]. The SDM method allows for the evaluation of potential risk for a specific area by simulating pest occurrence as a function of environmental factors [17,18]. In addition, it allows for the projection of changes in species distribution and dispersion patterns in climate change scenarios [19,20]. Rafoss and Saethre [21], for example, assessed the potential geographical distribution of the codling moth and Colorado potato beetle in Norway using CLIMEX software under three different climate scenarios. Ireland and Kriticos [22] recently reviewed published papers for pathogens and arthropod pests of plants using the CLIMEX model. They analyzed the reason why the niche model is more applied on insects than on pathology and suggested the interaction between entomologists and pathologists for developing infinite niche models. Another study proposed a new measure of suitability by combining the potential distribution of the bean leaf beetle with that of its host plant (soybean), both estimated using CLIMEX [23]. The application of SDM is not limited to insect distribution, it has also been used for projecting distributional changes of plants, such as the prickly acacia [14], common bean [24], and potato [25]. Hijmans [25] investigated the changes in global potato production and cultivation areas caused by climate change. Kroschel et al. [2] applied insect life cycle modeling (ILCYM) to study the distribution of the potato tuber moth. They evaluated the annual production of potato under climate change scenarios and revealed areas with high risk of exposure to the potato tuber moth.

The application of SDM to the distribution of the potato tuber moth has been very limited, even though this pest requires early monitoring because of its severe damages to potatoes [2]. Therefore, the aim of the present study was to project the potential distribution of the potato tuber moth in response to climate change using SDM. We first estimated the possible areas of potato tuber moth distribution as a function of climatic suitability under the current climate in countries that mainly produce and consume potato. Then, a Special Report on Emissions Scenario (SRES) was used for projecting the future distribution of potato tuber moth as well as changes in cultivation areas and the potential distribution of potato. Finally, we compared the potential distribution and seasonal growth of the potato and potato tuber moth and predicted the most vulnerable regions that should be monitored as a result of climate change.

2. Materials and Methods

2.1. Species Distribution Modeling Tool: CLIMEX

There are a few computational tools implementing SDM algorithms, such as BioClim, MaxEnt, and CLIMEX. Each tool has its own advantages and should be used according to the variables to be reflected in the research purpose and results. In this study, the main variable was climate, which is the most dominant factor in determining species distribution [26]. For this reason, we selected CLIMEX (version 4.0, Hearne software, Melbourne, Australia), which evaluates species distribution by relating regional climatic conditions to population dynamics [26]. CLIMEX constructs a niche model for a species by focusing on how the species responds to climatic variables; thus, various types of meteorological data can be used, which makes this algorithm suitable for the present study [16,26]. In CLIMEX, the occurrence possibility of a species is represented by the ecoclimatic index (EI), which defines a specific area's climatic suitability based on population growth and stress indices. The lowest value of EI is 0, which indicates that the area is unsuitable for a species, while the maximum value is

100, which indicates that the area is completely suitable. In this study, we categorized the EI values into four categories: EI = 0, unsuitable, $0 < EI \leq 10$, marginal, $10 < EI \leq 20$, suitable, and $EI > 30$, optimal. This is based on the fact that an EI larger than 30 means that the potential population growth of the species reaches 60% [26]. Details regarding CLIMEX functions and the algorithm used to calculate EI values are described elsewhere [16,26].

2.2. Meteorological Data and Climate Change Scenario

CLIMEX uses long-term average monthly climate data, such as the average maximum and minimum temperature, precipitation, and relative humidity, for calculating growth-related indices (GI) and stress indices (SI), and EI is calculated by multiplying GI and SI [16,26]. Climate data can be obtained from web databases such as CliMond (<https://www.climond.org>) [27]. In this study, 10'-gridded global terrestrial climate data from 1960 to 1990 were obtained from CliMond and used as the current climate dataset [27]. For future climate data, a 10'-gridded dataset was obtained from Special Report on Emissions Scenarios (SRES) A1B [28]. Carbon dioxide gas emission of SRES A1B was 720 ppm, and temperature was predicted to increase by approximately 2.9 °C by the year 2100. SRES A1B is an intermediate scenario between A2 (830 ppm) and B1 (550 ppm) and was chosen to exclude extreme climate change projections. Future climate change scenarios for 2030, 2050, and 2070 were used for projecting the future distribution of the potato tuber moth and potato.

2.3. Projection of Potato Tuber Moth and Potato Distributions

The distribution of the potato tuber moth has been reported for 110 countries by the Center for Agriculture and Bioscience International (CABI) [29], which listed 29, 26, 24, 13, 10, and 8 countries in Europe, Africa, Asia, North America, South America, and Oceania, respectively. In China, the potato tuber moth was first reported in Guangxi in 1937, and it is currently distributed in Yunnan, Guizhou, and Sichuan provinces [7,29,30]. In India, the potato tuber moth is recorded for Assam, Bihar, Gujarat, Himachal Pradesh, Punjab, Karnataka, Madhya Pradesh, Maharashtra, Meghalaya, Odisha, Tamil Nadu, Uttar Pradesh, and West Bengal [29]. It is currently densely distributed in the northern part of the country, where high amounts of potato are produced. Based on the information from the CABI, the Global Biodiversity Information Facility (GBIF) [30], and previous studies [7,30,31], we mapped the distribution of the potato tuber moth in China and India, and marked the name of their states (or provinces) using ArcGIS (version 10.4.1, Redlands, CA, USA) (Figure 1).

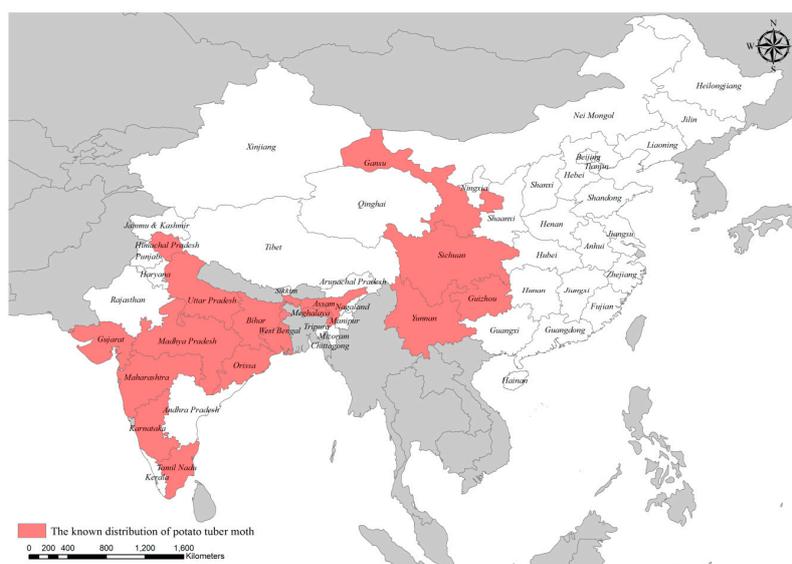


Figure 1. The name of states (or provinces) and location in China and India with areas where the potato tuber moth is known to occur.

2.4. Host Plant Availability for Potato Tuber Moth

A pest species' distribution is highly influenced by its host's distribution; therefore, considering the host plant distribution together with climate data enhances the model's projection ability [23]. Because potato is the main host plant of the potato tuber moth and its cultivation is directly affected by climate, this study evaluated the effect of host plant distribution on the distribution of the potato tuber moth. Even though tomato and eggplant are other hosts damaged by the potato tuber moth, previous studies used for estimating CLIMEX parameters in this study used potato as a food source. In addition, host suitability of potato is higher than tomato with higher preference, survival, and development rates [32]. The production of potato could not be directly connected to the EI of the potato tuber moth, but areas of large yields suggested a high potential distribution of the potato tuber moth due to abundant available hosts. For this reason, the EI of the potato tuber moth is necessary to be considered with potato cultivation and production. However, it was difficult to apply potato availability into the EI of the potato tuber moth because sowing methods and times are different by regions and some areas cultivate it through irrigation. Because of this difficulty, we attempted to assess the effect of climates only by climatic suitability of the host and apply the amount of regional potato production in India and China to include the artificial cultivation of potato.

We developed two indices to calculate host availability and the effect of host plant distribution: (1) Climate suitability of potato (EI_P), using CLIMEX, and (2) potato production. To determine the production of potato in China and India, the production (in tons) from 2008 to 2016 was obtained from National Bureau of Statistics of China (NBS) [33] and Crop Production Statistics Information System (CPSIS) [34]. To indicate the significant differences in potato production per province and state, these data were scaled from 0 to 1 by dividing the regional potato production by the highest amount of potato production in both China and India (Table 1). EI_P was converted into host plant availability (θ) using the method reported by Berzitis et al. [23] (Equation (1)) and multiplied by the EI of the potato tuber moth (EI_M) to produce the first new index, namely EI_{N1} (Equation (2)). Meanwhile, the normalized production of potato was multiplied by EI_M to produce the second new index, namely EI_{N2} (Equation (3)). Then, we only extracted areas where EI_{N2} was greater than 0 from the potato growing area obtained from MapSpaM [35]. Future potato production was predicted using regression analysis as function of years (from 2008 to 2016) when data was available. However, if the available data was not enough to perform the regression analysis or if the R^2 value of the regression equation was under 0.5 (i.e., estimated potato production was not reliable), we assumed that the current potato production was retained (Table 1). When a negative regression coefficient was obtained, future potato production was set as zero.

$$\theta = \frac{(EI_P/h)^q}{1 + (EI_P/h)^q} \quad (1)$$

where q is the speed of curve rise, and h is the value of EI_P for θ to be 0.5. Both values, q and h , were set to 5 and 15 based on Berzitis et al. [19].

$$EI_{N1} = EI_M \times \theta \quad (2)$$

where EI_M is climatic suitability of the potato tuber moth and θ is host plant availability in Equation (1).

$$EI_{N2} = EI_M \times \frac{\ln(PP)}{\ln(LPP)} \quad (3)$$

where EI_M is climatic suitability of the potato tuber moth, potato production (PP) is production of potato in specific state (or province), and largest potato production (LPP) is production of potato in the Sichuan province, which has the highest production in both China and India.

Table 1. Normalized potato production in the current and the future scenarios.

Country	State	Current	2030	2050	2070	Country	State	Current	2030	2050	2070
India	Andhra Pradesh	0.66	0.00	0.00	0.00	China	Inner Mongolia ²	0.98	0.93	0.68	0.67
India	Arunachal Pradesh	0.64	0.65	0.65	0.65	China	Liaoning ²	0.88	0.84	0.59	0.58
India	Assam	0.80	0.81	0.81	0.81	China	Jilin ²	0.90	0.85	0.61	0.60
India	Bihar ¹	0.84	0.80	0.78	0.76	China	Heilongjiang ²	0.95	0.90	0.65	0.64
India	Chandigarh	0.32	0.24	0.00	0.00	China	Shanghai	0.00	0.00	0.00	0.00
India	Chhattisgarh	0.66	0.70	0.71	0.72	China	Jiangsu	0.00	0.00	0.00	0.00
India	Gujarat	0.85	0.91	0.92	0.92	China	Zhejiang	0.85	0.87	0.87	0.87
India	Haryana ²	0.76	0.72	0.70	0.69	China	Anhui ²	0.75	0.70	0.68	0.67
India	Himachal Pradesh ²	0.64	0.60	0.58	0.57	China	Fujian	0.87	0.86	0.86	0.86
India	Jammu and Kashmir	0.57	0.61	0.62	0.62	China	Jiangxi ²	0.75	0.73	0.71	0.69
India	Jharkhand ¹	0.71	0.67	0.65	0.64	China	Shandong ³	-	-	-	-
India	Karnataka ²	0.76	0.73	0.71	0.70	China	Henan ³	-	-	-	-
India	Kerala ²	0.57	0.55	0.53	0.52	China	Hubei	0.92	0.91	0.92	0.92
India	Madhya Pradesh	0.82	0.87	0.87	0.88	China	Hunan ²	0.88	0.84	0.81	0.80
India	Meghalaya	0.73	0.72	0.72	0.72	China	Guangdong	0.85	0.84	0.83	0.83
India	Mizoram ¹	0.45	0.44	0.43	0.42	China	Guangxi	0.85	0.89	0.90	0.90
India	Nagaland ²	0.68	0.65	0.63	0.62	China	Hainan	0.40	0.00	0.00	0.00
India	Odisha ²	0.69	0.65	0.64	0.62	China	Chongqing	0.95	0.93	0.92	0.92
India	Rajasthan ²	0.70	0.68	0.66	0.65	China	Sichuan	1.00	1.00	1.00	1.00
India	Tamil Nadu ²	0.69	0.67	0.65	0.64	China	Guizhou	0.98	0.98	0.98	0.98
India	Telangana	0.64	0.00	0.00	0.00	China	Yunnan	0.97	0.95	0.94	0.93
India	Uttar Pradesh ²	0.99	0.95	0.93	0.91	China	Tibet	0.62	0.63	0.64	0.65
India	Uttarakhand	0.72	0.63	0.00	0.00	China	Shaanxi	0.92	0.91	0.91	0.90
India	West Bengal ²	0.93	0.94	0.91	0.90	China	Gansu ²	0.99	0.94	0.92	0.90
China	Beijing ³	-	-	-	-	China	Qinghai ²	0.88	0.84	0.81	0.80
China	Tianjin ³	-	-	-	-	China	Ningxia ²	0.89	0.85	0.82	0.81
China	Hebei	0.90	0.91	0.91	0.91	China	Xinjiang	0.83	0.80	0.77	0.76
China	Shanxi ²	0.87	0.82	0.58	0.57						

¹ Data is not enough to perform regression analysis as it only includes less than two years of the potato production; thus, the current amount of potato production is assumed to be constant for the future. ² R² of the regression equation is less than 0.5, suggesting the prediction is not reliable; thus, the current amount of potato production is assumed to be constant for the future.

³ Data is not available, and mark by a dash.

2.5. Parameter Estimation for Simulating Potato Tuber Moth and Potato Distributions

CLIMEX requires climate- and target species-specific parameters, which ultimately determine species distribution [20,26]. It uses, for instance, parameters such as temperature index (TI), moisture index (MI), light index (LI), and degree-days per generation (PDD), which affect growth and limit populations. In this study, the parameters used for evaluating potato and potato tuber moth distribution were estimated from previous studies. The low threshold temperature was varied by countries; thus, we used a study performed in China [36] based on the fact that PDD and DV0 were thermal accumulation and development threshold required by species to complete a generation [26]. Hence, the limiting low temperature (DV0) and degree-days per generation (PDD) were set to 9 °C and 497 degree-days respectively, based on Jin et al. [36], in China by considering the total developmental stage of the potato tuber moth. The DV1 (lower optimum temperature) and DV2 (upper optimum temperature) were temperature-estimated to be 20 and 30 °C respectively, because previous studies reported that the optimal temperatures for growth were in the range between them [37,38]. In addition, as the thermal limits of potato tuber moth reported by Briese [37] was 38 °C, we used the temperature for DV3 (limiting high temperature). Regarding parameters of soil moisture (SM), limiting low soil moisture (SM0) and lower optimal soil moisture (SM1) were calibrated to produce climatic suitability in California in the United States, where the potato tuber moth has survived in most parts. For SM2 (upper optimal soil moisture) and SM3 (limiting high soil moisture), they were adjusted so that the simulation could represent the distribution boundaries in South Korea, China, and Japan. For example, SM3 was set to be 1.5 for having the climate suitability of potato tuber moth in southern China. Consequently, SM0, SM1, SM2, and SM3 were set at 0.1, 0.15, 1, and 1.5, respectively. There are some available studies for estimating cold stress. Saour et al. reported that the survival rates of the potato tuber moth increased at 3 and 7 °C, but it inhibited the reproduction capacity [39]. In addition, Andreadis et al. reported that acclimation at low temperature did not affect supercooling points [40]. Based on information from the above study, the cold stress was calibrated so that the potato tuber moth was able to survive in most of the United States. Furthermore, the north limit of the potential distribution of the potato tuber moth was adjusted to the United States–Canada border lines because there were no reports of the potato tuber moth in Canada. As a result, the cold stress temperature threshold (TTCS) was estimated to be 5 °C. Heat stress temperature threshold (TTHS), dry stress threshold (SMDS), and wet stress threshold (SMWS) used the value of DV3, SM0, and SM3 respectively, and the rate of each stress was calibrated to have the known distribution of the potato tuber moth (Figure 2).

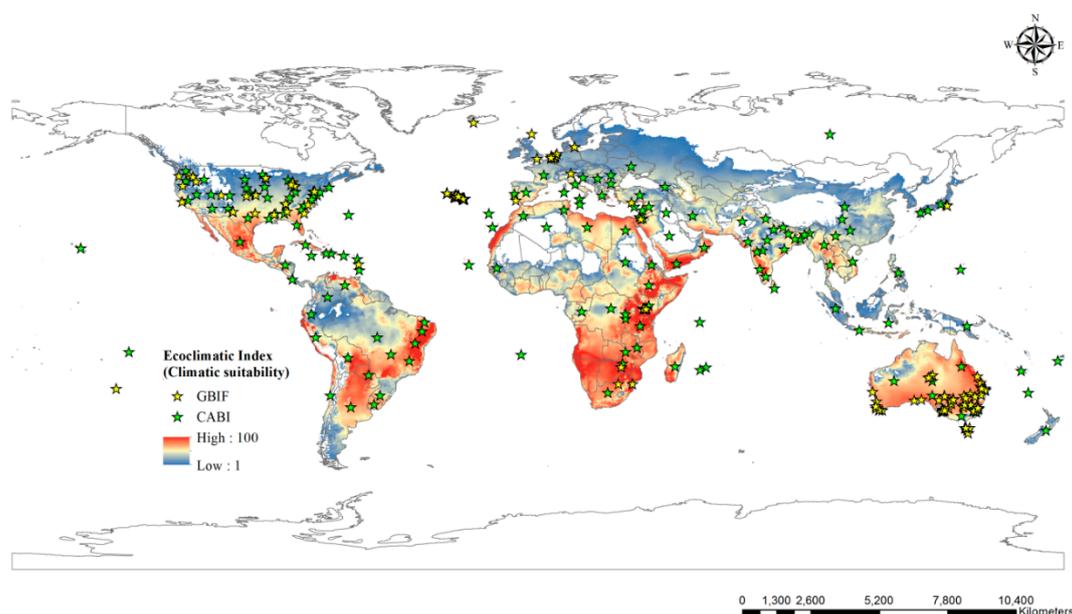


Figure 2. The potential distribution of the potato tuber moth in the world.

Potato requires 750–1128 day-degrees at 4 °C and germinates at 13 °C [41]. Thus, the parameters DV0 and PDD were set to be 4 °C and the median value of 950, respectively [42]. The optimum and maximum temperatures for potato cultivation widely vary depending on the stage of development [30]. Hence, we used the most efficient temperature and maximum temperatures for photosynthesis to estimate DV1, DV2, and DV3. In most previous studies, the optimum temperature for potato photosynthesis was reported to be within 16–25 °C, while the maximum temperature was 40 °C [42–46]. Therefore, DV1, DV2, and DV3 were estimated to be 16 °C, 25 °C, and 40 °C, respectively. In China, potato has been planted primarily in dry areas or in areas with low water availability [5]. In northwestern and western China, where large amounts of potato are produced, annual precipitation is approximately 200–400 mm. In contrast, precipitation in southern China is 1200–1800 mm, which is approximately five times higher than that in the north. Thus, MI was adjusted to have a value between 200 and 1500 mm and calibrated to fit to the actual distribution of areas cultivating potato. The optimum soil moisture for potato cultivation has been reported to vary from 12% to 60% [47], however, there was another study that potato production was inhibited by approximately 12% [48]. As a result, SM0, SM1, SM2, and SM3 were set to be 0.12, 0.2, 0.8, and 1.5, respectively. SM1 and SM2 were fit to the distribution of potato cultivation in the world, and SM3 was set up to show climate suitability in southern China. The parameters of LI affecting photosynthesis includes two sub-parameters: LT1 (day length at no growth) and LT0 (day length at maximum growth) [19,26]. Demagante and Van der Zaang [49] reported that the growth of potatoes increased with the shift of the photoperiod duration from 11.5 to 16 h. Hence, we set LT0 to be 16 h, while LT0 was estimated to be 10 h to meet the actual potato cultivation area values. Since potatoes are seeded and harvested during periods of moderate climate, they are rarely exposed to external stress, so all stress on the potato is not used in the present study [23]. In addition, the irrigation scenario (2.5 mm/day of top-up irrigation throughout the year) provided by CLIMEX was added for representing the current potato cultivation. Finally, the potential distribution of potato and the potato tuber moth was verified based on the results of Hijmans [25]. The CLIMEX parameters of the potato tuber moth and potato are summarized in Table 2.

Table 2. Parameter values used for the analysis of the potato tuber moth and potato distribution in CLIMEX.

Parameters	Code	Potato Tuber Moth	Potato
Temperature			
Limiting low temperature (°C)	DV0	9	4
Lower optimal temperature (°C)	DV1	20	16
Upper optimal temperature (°C)	DV2	30	25
Limiting high temperature (°C)	DV3	38	40
PDD ¹		497	950
Moisture			
Limiting low soil moisture	SM0	0.1	0.12
Lower optimal soil moisture	SM1	0.15	0.2
Upper optimal soil moisture	SM2	1.0	0.8
Limiting high soil moisture	SM3	1.5	1.5
Light			
Day-length at no growth	LT1	-	10
Day-length at maximum growth	LT0	-	16
Cold stress (CS)			
CS temperature threshold (°C)	TTCS	5	
CS temperature rate	THCS	-0.00013	

Table 2. Cont.

Parameters	Code	Potato Tuber Moth	Potato
Heat stress (HS)			
HS temperature threshold (°C)	TTHS	38	-
HS temperature rate	THHS	0.005	-
Dry stress (DS)			
DS threshold	SMDS	0.1	-
DS rate	HDS	−0.02	-
Wet stress (WS)			
WS threshold	SMWS	1.5	-
WS threshold	HWS	0.001	-

¹ Minimum degree-days above DV0 is required to complete a generation.

3. Results and Discussion

3.1. Projection of Climatic Suitability of the Potato Tuber Moth

Climate suitability for the potato tuber moth (EI_M) in India was projected to be higher in the south than in the north (Figure 3a). The central region had EI_M under 10, but the climatic condition was estimated to still allow potato tuber moth establishment. Meghalaya, Assam, Nagaland, Tripura, Mizoram, and Arunachal Pradesh, located between China and India, had optimal temperature for the establishment of the potato tuber moth. In general, low EI_M values caused by high wet stress was observed in areas with approximately 1700 mm of annual precipitation. This finding is consistent with that of a previous study, which showed that rainfall and larval survival were inversely correlated (correlation coefficient of -0.52) [50]. The northern part of India recorded an average temperature of approximately 39 °C from April to June, which caused high heat stress on the development of the potato tuber moth, as the potato tuber moth cannot survive temperatures above 39 °C [38]. However, the potato tuber moth might not die by heat stress in their areas (Jammu and Kashmir, Himachal Pradesh, Uttar Pradesh, Bihar, and West Bengal), and after April to June, these areas are suitable for growth of the potato tuber moth. In the southern region (Karnataka, Andhra Pradesh, and Tamil Nadu), the average monthly minimum temperature did not drop below 10 °C, and the average monthly maximum temperature was maintained at approximately 34 °C [33]. For this reason, the southern region of India was projected to be more suitable for the potato tuber moth than the northern region. In addition, most states in India have stored potato in 90% of the installed agricultural storages, whereas only 12% of cold storages have been used to store potato in the Karnataka state. This suggests that the Karnataka state would have a high risk of potato tuber moth damages [51].

In China, the limit of EI_M for the potato tuber moth was clear. The western regions of China, which are generally covered with high-altitude mountains, showed high cold stress, suggesting their inadequacy for potato tuber moths. In addition, the northeastern region of China had an adequate precipitation for the survival of the potato tuber moth, but the cold stress caused by the low temperature during winter would not be suitable for the species. In contrast, the EI_M value was greater than zero in most of the central and the southern regions in China, indicating their suitability for the distribution of the potato tuber moth. Finally, the highest EI_M values were found for the mid- and southwestern regions, which generally had low precipitation and warm climate during the summer.

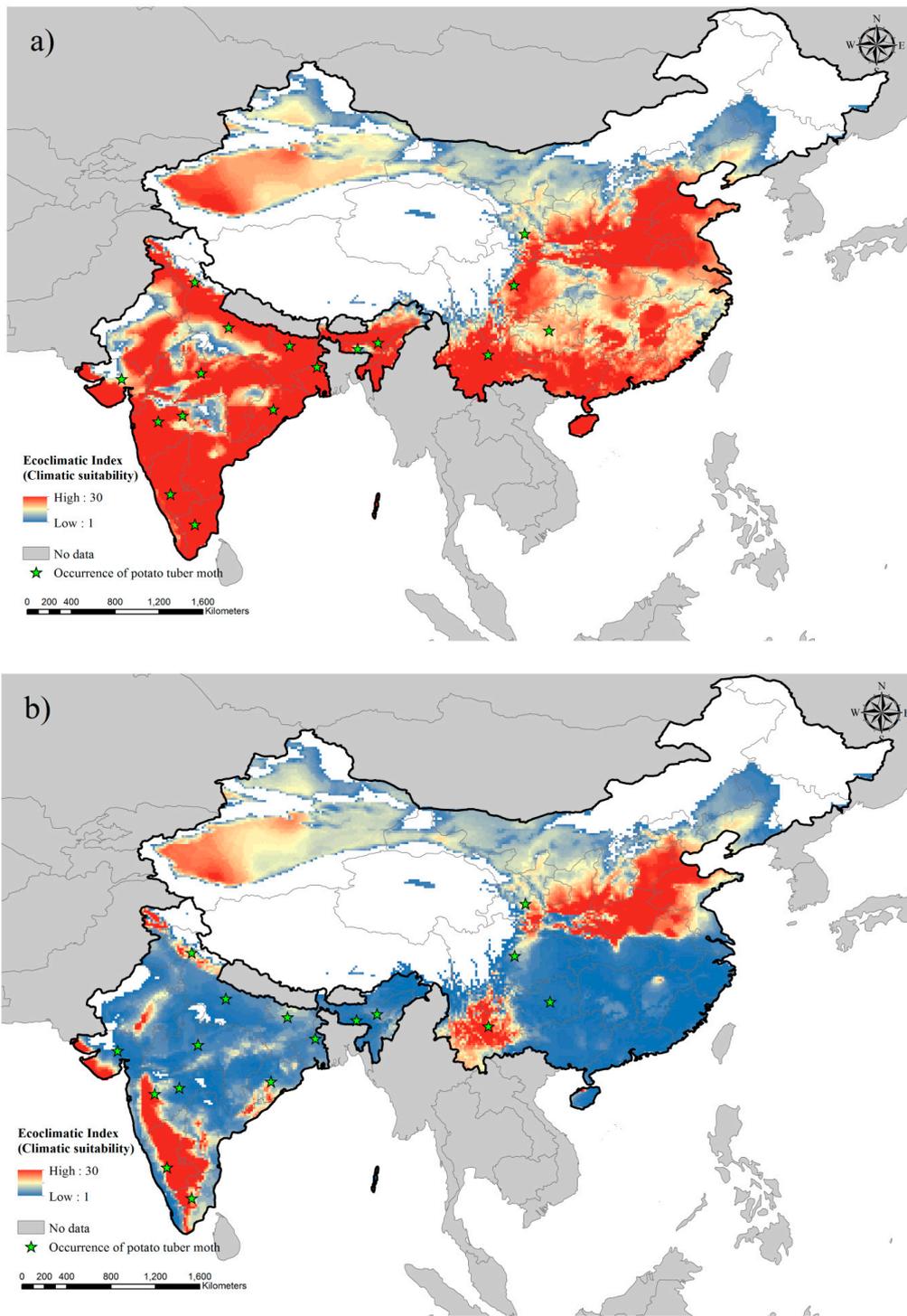


Figure 3. Cont.

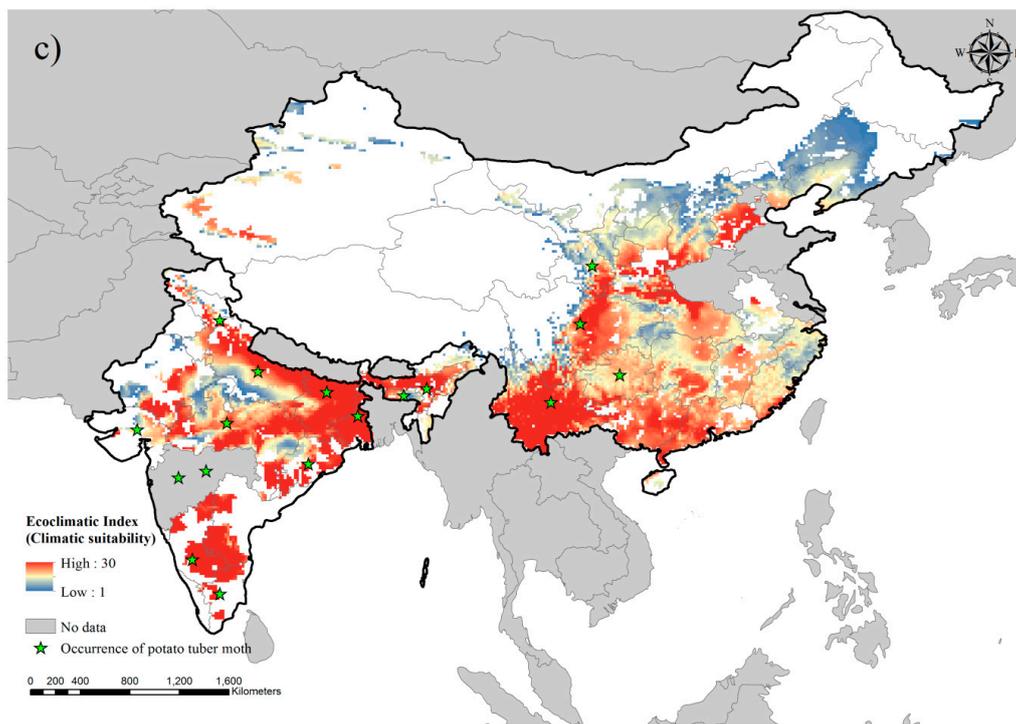


Figure 3. Potential distribution of the potato tuber moth under the current climate in China and India. (a) Potential distribution of potato tuber moth based on climatic suitability (ecoclimatic index (EI) (EI_M), (b) EI_M * host plant availability (EI_{N1}), and (c) EI_M * potato production (EI_{N2}).

3.2. Potential Distribution of the Potato Tuber Moth by Incorporating Potato Distribution and Production in the Analysis

The potential distribution of the potato tuber moth is related to the host plant's distribution and production as well as to climatic factors [23]. A high climatic suitability of potato was projected in central and northeastern China, with EI_P values between 25 and 30, suggesting that the regions would be climatically optimal for yielding potato (host plant availability was over 0.8) (Figure 3b). In contrast, the central and northern regions of India were not suitable for cultivating potatoes because of an average maximum temperature of 40 °C from May to June. In both China and India, there were no areas where EI_P was zero, i.e., impossible to cultivate potato, except for the western and southwestern provinces in China (Tibet and Qinghai provinces). In contrast, no region (except central China, northern China, and southern India) showed an EI_P larger than 25 and most of EI_P was actually less than 10. Approximately 56% of areas in China or in India had an EI_P under 15 (host plant availability under 0.5). Consequently, EI_{N1} was reduced to approximately 59% of the EI_M value in the total area (Figure 3b). In most parts of India and in southern China, the overall EI_{N1} was low because of the low EI_P value. Nevertheless, it may be possible to grow potato in artificial facilities in India from October to March even though the annual climate is not as suitable as necessary to be an adequate natural habitat for potato [25]. Finally, the Karnataka, Hubei, Shaanxi, Henan, and Anhui provinces were the regions with the highest EI_{N1} (over 30) in China and India, indicating that the potato tuber moth might favor these regions for establishing its distribution.

Alternatively, the area of potato production was used to estimate the distribution of the potato tuber moth and to establish its risk index [2]. By employing this idea, we incorporated potato production into the EI_M value to generate a new index, EI_{N2} , because EI_{N1} only considers field cultivation. The overall EI_{N2} was not much different from EI_M (Figure 3c). In general, EI_{N2} had a 20% average decrease in 95% of regions compared to EI_M (considering only potato cultivation area), but this change was relatively smaller than that observed in the EI_{N1} . In China, potato production was higher than that in India; thus, EI_{N2} did not largely differ with EI_M as production was multiplied by EI_M to generate

EI_{N_2} . Nevertheless, the overall EI_{N_2} was decreased by approximately 14% compared to EI_M and the highest decrease was observed in the central areas of China (25% decrease). The difference between EI_{N_2} and EI_M in Sichuan and Gansu provinces, which produce more than 10 million tons of potato, was under 1%. In contrast, Hainan province recorded the lowest production (2167 tons); thus, this province showed an approximately 60% reduction compared to EI_M (Figure 4a). However, most of Tibet had an EI_M equal to zero, suggesting that it might be impossible for potato tuber moths to survive in these locations regardless of potato production. EI_{N_2} in Uttar Pradesh and West Bengal states, were the smallest compared to EI_M because these areas had the largest potato production in India [28] (Figure 4b). The northern part of the Uttar Pradesh state towards the Nepalese border had an EI_{N_2} between 10 and 30, and the West Bengal state generally had an EI_{N_2} of over 20, suggesting that these regions were the best for the establishment of the potato tuber moth. In addition, the potato tuber moth was likely to occur in the southern parts of India (Andhra Pradesh, Karnataka, and Tamil Nadu). The EI_{N_2} of these areas were over 30 even though their EI_{N_2} decreased by 24%–34% compared to EI_M . In summary, Sichuan, Yunnan, and Guizhou had the highest potato production and EI_M . In addition, Hubei, Shaanxi, Henan, and Anhui provinces showed the highest EI_{N_2} resulting from high EI_M , even though potato production was relatively low.

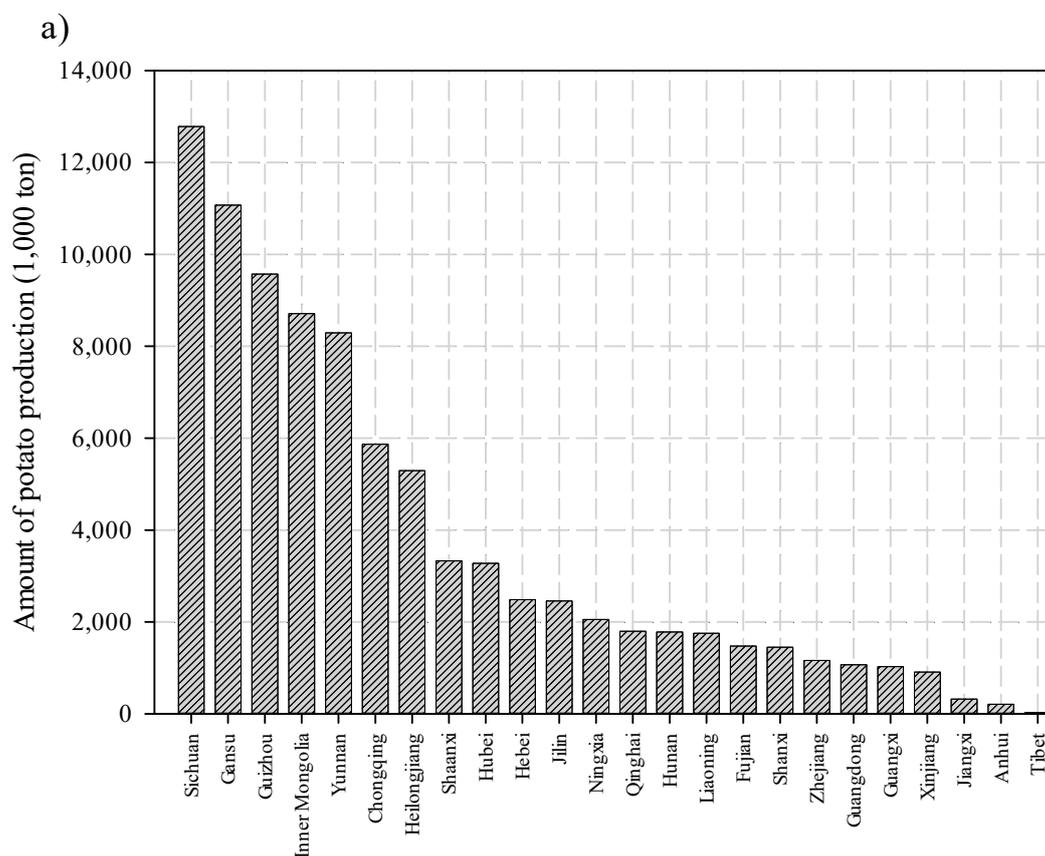


Figure 4. *Cont.*

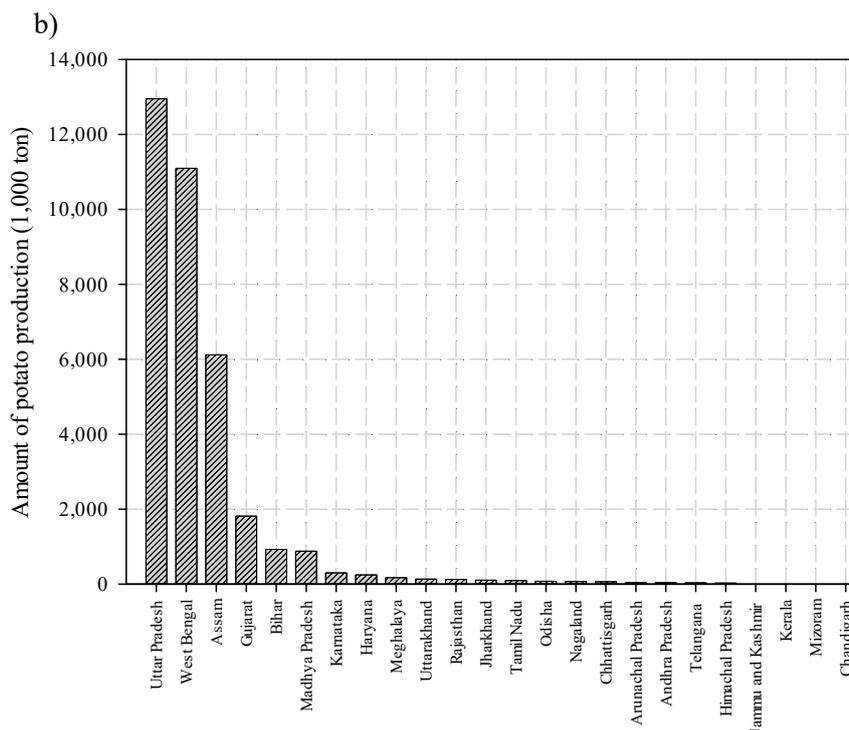


Figure 4. Potato production in provinces and states in 2008–2016 in (a) China and (b) India, obtained from National Bureau of Statistics of China (NBS) and Crop Production Statistics Information System (CPSIS).

3.3. Potential Distribution of the Potato Tuber Moth Under the 2050 Climate Change Scenario

Recently, climate change has altered the distribution of species, which in turn influences agricultural production [52]. Under the SRES A1B climate change scenario, we observed that EI_M was reduced in most areas of India. In particular, Madhya Pradesh state showed a very low climate suitability (EI_M) for the potato tuber moth (Figure 5a). In particular, the central areas in India had low climate suitability (EI_M under 10), whereas the most suitable habitats were Karnataka and Tamil Nadu states, where locations with an EI_M over 30 comprised approximately 70% of the total area. When considering the distribution of potato, the EI_{N1} value was projected to be under 10 throughout India, which suggests that a suitable region for the establishment of the potato tuber moth will not exist in the future (Figure 5b). Even though the projection showed an EI_{N1} value over 30 for some areas in Karnataka and Jammu and Kashmir, these areas were too narrow to affect the overall reduction of EI_{N1} in India. Regarding EI_{N2} , the largest change was observed in Tamil Nadu state, confirming that the distribution of the potato tuber moth may be reduced as a result of the decrease in potato production (Figure 5c).

The distribution of the potato tuber moth in China was projected to be extended to the north, reaching $N47^\circ$, including Liaoning province, which had a steadily increased EI_M . In particular, many areas in the southern part of China that showed a high potential for survival of the potato tuber moth ($EI_M > 30$). However, the EI_{N1} was projected to be lowered in southern China, while remained to showed marginal EI_{N1} larger than zero. Southern China has a relatively high precipitation (approximately 1500 mm/year) compared to northern regions and was not suitable for growing potatoes as the moisture index (MI) exceeded 1.5 from April to July. Particularly, Zhejiang province became an inadequate area for the potato tuber moth unless the region could artificially cultivate potato. EI_{N2} has a similar distribution to that of EI_M , but it was projected to be lower in northern China. In terms of decrease of quantitative EI_{N2} in China and India, the EI_{N2} value under the current climate in China was reduced by approximately 14% compared to EI_M , while it was approximately 20% in 2050. Finally, potato production and increase rate were lower in India than in China, indicating that future potato tuber moth distribution will be more restricted in India than in China.

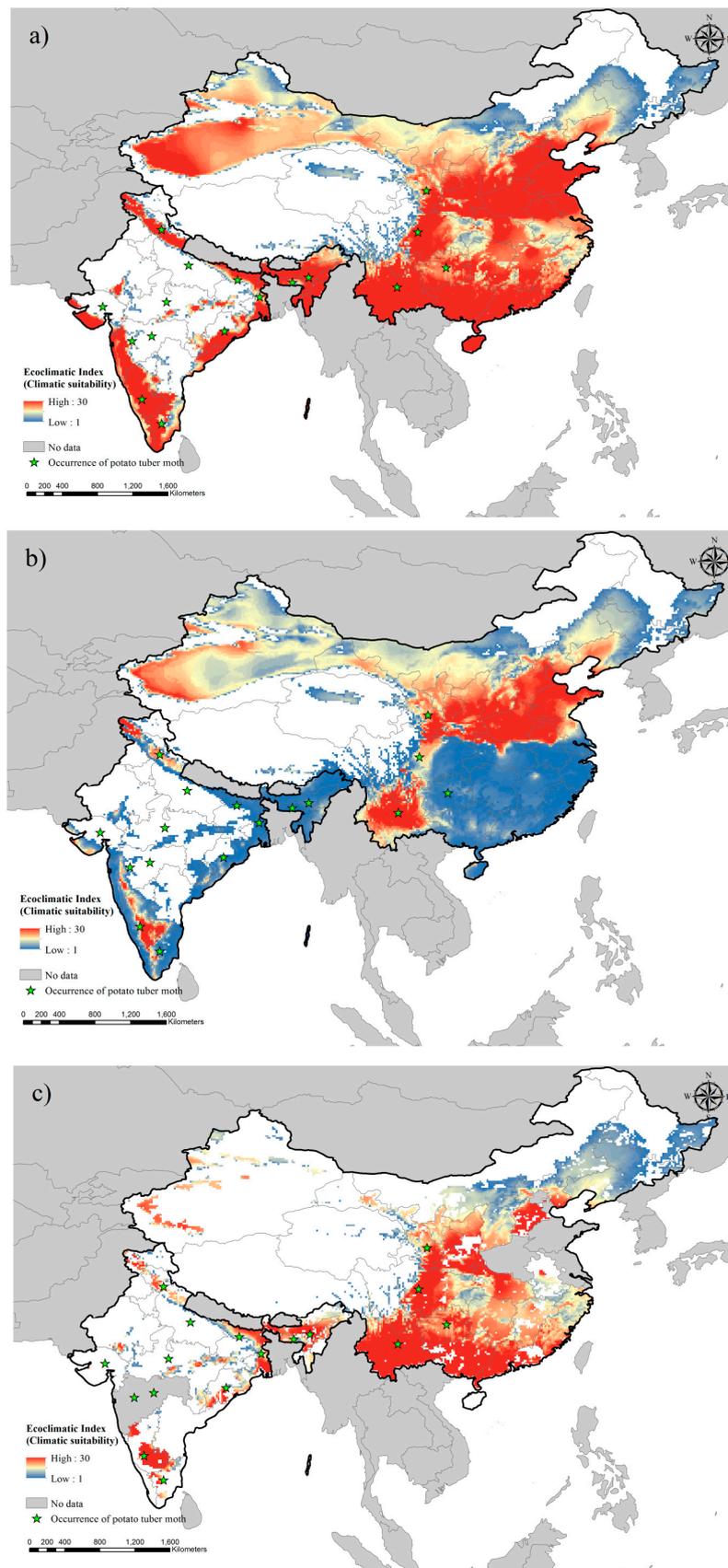


Figure 5. Potential distribution of the potato tuber moth in 2050 in China and India. (a) Potential distribution of the potato tuber moth based on climatic suitability (EI_M), (b) EI_M * host plant availability (EI_{N1}), and (c) EI_M * the potato production (EI_{N2}).

3.4. Risk Analysis of the Potato Tuber Moth Distribution Based on Changes in Potato Production

China and India account for approximately 38% of the world's potato production [4]. Because the potato tuber moth is one of the potato-specific pests that exist in both India and China, it is necessary to select areas where its potential distribution is likely to be high to determine the strategy for monitoring and controlling it [19,26]. In addition, it is necessary to establish adequate control strategies for each region by focusing on the regions where the climate suitability is rapidly increasing due to climate change. The efficient use of limited resources and budgets by prioritizing regions with high climate suitability can minimize damage from pests. Kroschel et al. [2] used the ILCYM model to assess the climate impacts of the potato tuber moth and suggested the essential data for planning pest management. Their result showed a little difference in predicting North and South America and this might be due to the fact that the distribution by Kroschel et al. was a regulated simulation under the control, while this study showed potential distribution based on climate and host plant. Actually, the prediction in this study could include the current areas of potato tuber moth occurrence in North America. Similarly, there are many examples of fundamental data on the potential distribution of pests according to climate [53–57]. However, studies that directly combine potential distribution and availability of the host plant are limited [23].

In this study, the potential distribution of potato was used to produce the EI_{N1} , which evaluated the natural possibility of the occurrence of the potato tuber moth. EI_{N2} was calculated by weighting EI_M by the potato production in provinces or states of China and India. As larger potato production means higher resource availability for the development of the potato tuber moth, and as potato can be cultivated in artificial facilities (EI_{N1} only considers field cultivation), EI_{N2} was added to our analysis. When comprehensively considering the three types of EIs, central China and southern India had values of over 30 in all three EIs, suggesting that these regions were favored for potato tuber moth establishment because of suitable climate, host distribution, and potato production. As a result of climate change, the number of suitable regions for the potato tuber moth in India has steadily declined, and only a few parts of the southern India showed more than zero values in all three types of EIs (Figure 5). In contrast, the three EI values continuously increased in China and projected the expansion of the species' habitat to the north. Particularly, southern and central China would be the best regions for the establishment of the potato tuber moth. The regions with relatively higher potential for the establishment of the potato tuber moth in India were Uttar Pradesh, West Bengal, Andhra Pradesh, Karnataka, Tamil Nadu, and Hebei. In China, the regions were Hubei, Gansu, Yunnan, Shaanxi, Shanxi, and Sichuan provinces.

Considering the current distribution of the potato tuber moth, we think that the potato tuber moth in India may be more influenced by potato cultivation under the farmland (i.e., host) than climatic condition. In particular, India is expected to have a high density of potato tuber moths in the northern part because specific areas (e.g., Uttar Pradesh and West Bengal) with the highest potato production are concentrated in the north (Figure 4b). In China, the regions where the potato tuber moth has been found are Yunnan, Guizhou, Sichuan, and Gansu provinces. As previously mentioned, in central China, where all three types of EI were high, the occurrence of the potato tuber moth has not yet been officially recorded. However, the potato tuber moth has been officially confirmed in South Korea at the same latitude [58]; thus, the probability of a potato tuber moth invasion in central China is quite high. Particularly, Gansu and Hebei provinces were identified as risky areas. These areas are sources of potato and potato seed in China, so strategies to prevent a potato tuber moth invasion are needed in advance [5]. In order to control the potato tuber moth, when potato is sowed, it is necessary to use healthy seeds and to sow by at least 10 cm deep [59]. When germinating, the crop should be thoroughly earthed up for 30–40 days after planting [59]. To prevent further dispersion, it is necessary to focus on the management of the potato tuber moth, using, for instance, microbial control or fumigation [60–63]. In addition, Chandel and Chandra [8] reported that *Bacillus thuringiensis* and granulosis virus can reduce the infection rate of the potato tuber moth from 4.17%–8.59% to 0.32%–0.87%. In India, Karnataka, which has a high climate suitability for the potato tuber moth,

uses only approximately 12% of the total installed cold facilities in the state (approximately 1/7 of those in the northern regions) [51]. That is, most of the produced potato is stored outdoors, where the risk of damage by the potato tuber moth is high [64,65]. Cold storage should be used for potato preservation because eggs of the potato tuber moth die approximately 38 and 54 days at 3 °C and 7 °C, respectively [39]. Therefore, the utilization of effective postharvest management technology can prevent damage on potatoes caused by the potato tuber moth in India.

4. Conclusions

This study combined the distribution of field potato and potato production with climatic suitability for the potato tuber moth projected using the CLIMEX model. To comprehensively evaluate environmental and climatic factors and to increase the reliability of our model's projection, three types of EI (i.e., EI_M, EI_{N1}, and EI_{N2}) were used to evaluate the potential areas exposed to damage by the potato tuber moth in India and China under a climate change scenario. The results suggested some areas (Andhra Pradesh, Karnataka, Tamil Nadu, Uttar Pradesh, and West Bengal states in India and Henan, Hebei, Yunnan, Shaanxi, Shanxi, Shandong, and Sichuan provinces in China) as the riskiest for the establishment of the potato tuber moth. Under the climate change scenario, potato tuber moth populations would be decreased in India, while they would likely increase in most parts of western China. Because both China and India are the countries with the largest potato production, it is necessary to minimize loss caused by pests during potato cultivation and storage. To this point of view, this study provides basic management data for efficiently controlling the potato tuber moth by projecting its distribution in advance.

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