Abstract: Potato tuber moth (*Phthorimaea operculella*), one of the leading potato-damaging pests in the world, has caused severe damage to potato production in South Korea after its introduction in the 1960s. This study surveyed the field occurrence of potato tuber moth in various sites in South Korea and used the results to validate the CLIMEX model, which spatiotemporally evaluated the potential distribution of potato tuber moths in response to climate change. The potato tuber moths were predicted to appear throughout the country, consistent with the results obtained for potato tuber moths in 96% of the field survey area. In addition, the climatic suitability of potato tuber moths will remain high due to climate change, suggesting a high risk for damage to seasonal potato production from seeding to harvesting. This spatiotemporal assessment of potato tuber moth distribution is expected to aid in establishing control strategies optimized based on time and place.

Keywords: CLIMEX; climate change; field survey; potential distribution; potato tuber moth

1. Introduction

The potato is one of the world’s leading food sources. It is cultivated on 18 million hectares of land in 130 countries, with a total crop production of 200–300 million metric tons per year [1]. Climate change not only affects changes in potato cultivation conditions, but also lead to the spread of pests, thereby causing serious losses in potato production [2]. Based on a previous study, 16% of the loss in global potato production was caused by over 40 potato-attacking insects [3]. Among them, *Phthorimaea operculella*, also known as the potato tuber moth, is the predominant pest that damages potatoes before and after harvest [4]. For example, damage caused by potato tuber moths in the early stages of potato cultivation can result in a 25% loss of the final yield [5,6]. This species can adapt to various climatic conditions in varying agro-ecosystems and does not need periods of diapause to overcome unsuitable climatic conditions [7].
Climate change is known to have a large impact on the Earth’s ecosystem. Changes in the habitats of pests have been especially damaging to local biodiversity and agriculture, requiring investigation of their distribution and response to climate change [8–10]. From this point of view, species distribution modeling and software implementation of algorithms (e.g., CLIMEX) have been widely used to predict the potential distribution and dispersion patterns of the pests in order to provide the basic information necessary for analyzing the risk of invasive pests and for identifying control spots [11–14]. In South Korea, species distribution modeling has recently been initiated. While it is relatively limited compared to studies conducted overseas, it is gradually becoming more widely used due to an increase in the possibility of pest invasions that come with climate change and active global trade [15–18].

The potato tuber moth was introduced in South Korea as climate change accelerated, and the resultant agricultural losses have been considered serious since the mid-2000s [19]. Despite this, most studies on the potato tuber moth have focused on its life history, ecological characteristics, and insecticidal activity [20–22], whereas studies focusing on species distribution modeling for risk analysis based on predictive distribution are limited. In contrast, there are notable studies available on the changes in potato tuber moth distribution according to climate change performed overseas. Kroschel et al. [23] evaluated the changes in global distribution area, number of generations, and activity index of potato tuber moths due to climate change. They compared the simulation results for the current climate with the climate forecasted for 2050, showing a 12% increase in the number of areas with more than four generations per year in 2050, and an increase in the occurrence of potato tuber moths in areas of potato cultivation. In addition, Sporleder et al. [24] constructed temperature-dependent phenology models based on actual breeding data to predict the risk, generation, and activity of potato tuber moths.

Damage to potato production increases every year, and the potato tuber moth is one of the biggest concerns [25]. Thus, species distribution modeling can provide experts and policymakers the information required to develop and optimize quarantine and control strategies [26]. Therefore, in this study, we constructed a species distribution model and predicted the potential distribution of potato tuber moths in South Korea in response to climate change. In addition, spatiotemporal risk assessment of potato tuber moths in major domestic potato cultivation regions was conducted by relating the time required to produce potatoes in the primary areas of potato cultivation with dynamic changes in the seasonal abundance of potato tuber moth.

2. Materials and Methods

2.1. Distribution Record of the Potato Tuber Moth

The potato tuber moth is a polyphagous pest originating from the Andean region in Bolivia and Peru [23]. It feeds on plants belonging to the Solanaceae family, which includes potatoes, tomatoes, tobacco, and peppers. In particular, it has caused significant damage to global potato production [27–29]. At present, the potato tuber moth inhabits more than 110 countries and has been identified in most tropical and subtropical regions of Africa, Asia, and Latin America, which is where potatoes are produced [7,29,30]. Initially, potato tuber moths were mostly distributed within regions with a 10 °C annual isotherm in both the northern and southern hemispheres [24], but its habitat was currently expected to expand up to approximately 47.5° N, which represents the highest latitude of Washington in the United States of America and of Croatia and Serbia in Europe [31]. In South Korea, they were believed to have been introduced into the Jeju Island from Japan in 1963–1964 by importing potato seeds and were initially limited to the southern part of the Korean peninsula, which has an average temperature of −8 °C or higher during winter [21]. Now, the potato tuber moth is distributed in most parts of South Korea due to climate change as well as due to its adaptation to the domestic climate [32].
2.2. Field Survey for Potato Tuber Moth

Data were collected either from field surveys conducted during this study or from previous field surveys on potato tuber moth occurrences throughout South Korea. We conducted a field survey in 18 cities for a year (2019). Three sex pheromone sticky traps (delta trap: 275 × 195 × 170 mm, sticky trap: 235 × 190 mm, lure: 20 ×10 mm) (Green Agro Tech Co., Ltd., Gyeongsan-si, South Korea) per farmland were installed in potato cultivation areas to collect individual potato tuber moths, after which the number of trapped moths was counted every 2 weeks. Potato tuber moths were observed in most areas, except for Wonju and Hoengseong in Gangwon-do. In addition, we collected field survey data from collaborators who conducted a field survey for 4 years (2009–2012) using a species-specific sex pheromone lure with a delta trap [32]. Thirty-seven areas were selected as spots for the field survey, excluding southern parts of South Korea, where their occurrence had already been reported [21]. In most areas, potato tuber moths were observed except for the areas of Pocheon, Cheorwon, Pyeongchang, and Yesan during the field survey. The overall results of domestic field surveys will be presented in a map with climatic suitability in the results section.

2.3. Species Distribution Modeling: CLIMEX Model

CLIMEX (Version 4.0, Hearne Software, Australia) is a dynamic model that can simulate the effects of climate-related processes to determine the geographic distribution and seasonal variability of a species [33–36]. Of the 2 modeling functions (Compare Locations and Match Climates), we used Compare Locations, which can predict the potential distribution of potato tuber moths in South Korea as a function of climate and its biological characteristics [33]. The CLIMEX model summarized the potential distribution of a species using the ecoclimatic index (EI), which was an index of the climatic suitability of a species in a specific region and considered both the growth index (GI) and stress index (SI); its value ranged from 0 to 100. A value close to 0 suggested that the area was not suitable for establishing a habitat, whereas a value greater than 30 indicated a very favorable climate for the species [34,37,38].

2.4. Parameter Estimation

We initially employed parameter values from a previous study [39] that predicted the distribution of the potato tuber moth using CLIMEX, but the parameter values did not adequately capture the current known distribution of this species in South Korea. The previous study by Jung et al. [39] used an irrigation scenario (2.5 mm/day of top-up irrigation throughout the year) to reflect the irrigation in potato cultivation areas where precipitation was too low to facilitate potato growth. However, precipitation was sufficient to cultivate potatoes in South Korea; as such, we removed the irrigation scenario. The GI value represented the potential growth of a species in a specific region over time-based on the given climatic conditions [33]. Therefore, the best fit of GI to occurrence patterns allowed for a highly reliable estimation of parameter values for the species [38]. For this reason, we compared the GI value with seasonal abundance obtained from the field survey in 2019 to validate the model without the irrigation scenario. We selected 2 cities (Seogwipo and Miryang) with the largest population and presented seasonal abundance as the monthly average of the collected moths. The parameter values from Jung et al. [39] are presented in Table 1.
### Table 1. Parameter values for simulating the potential distribution of potato tuber moth in CLIMEX.

| Parameters                  | Code | Values $^1$ |
|-----------------------------|------|-------------|
| Temperature                 |      |             |
| Limiting low temperature ($^\circ$C) | DV0  | 9           |
| Lower optimal temperature ($^\circ$C) | DV1  | 20          |
| Upper optimal temperature ($^\circ$C) | DV2  | 30          |
| Limiting high temperature ($^\circ$C) | DV3  | 38          |
| PDD                         |      | 497         |
| Moisture                    |      |             |
| Limiting low soil moisture  | SM0  | 0.1         |
| Lower optimal soil moisture | SM1  | 0.15        |
| Upper optimal soil moisture | SM2  | 1.0         |
| Limiting high soil moisture | SM3  | 1.5         |
| Cold stress                 |      |             |
| CS temperature threshold ($^\circ$C) | TTCS | 5           |
| CS temperature rate         | THCS | −0.00013    |
| Heat stress                 |      |             |
| HS temperature threshold ($^\circ$C) | TTHS | 38          |
| HS temperature rate         | THHS | 0.005       |
| Dry stress                  |      |             |
| DS threshold                | SMDS | 0.1         |
| DS rate                     | HDS  | −0.02       |
| Wet stress                  |      |             |
| WS threshold                | SMWS | 1.5         |
| WS threshold                | HWS  | 0.001       |
| Irrigation scenario $^2$     |      | 2.5 mm/day of top-up irrigation throughout the year |

$^1$ Values were employed from Jung et al. [39]. $^2$ Irrigation scenario was not used in this study.

### 2.5. Meteorological Data and Climate Change Scenario

For meteorological data, we downloaded 30-year climate data from 1981 to 2010 for 74 cities in South Korea from the Korea Meteorological Administration, which recorded the average maximum and minimum temperature, precipitation, and relative humidity [15,16,40]. Representative Concentration Pathway 8.5 (RCP 8.5) climate change scenarios were selected to observe the changes in the potential distribution of potato tuber moths in response to climate change [41]. The RCP 8.5 scenario was the most extreme case of climate change scenarios and assumed greenhouse gas emissions without mitigation. Prediction of distribution in the most extreme situations allowed for a broad range of risk analysis; however, we were also constructing databases of other RCP climate change scenarios (e.g., RCP 4.5, RCP 6.0), and these scenarios will be used in future analyses [42]. Next, the RCP 8.5 climate change scenario from 2020 to 2100 was reconstructed with a 1 km resolution using a 20-year interval, thus that it could be used in the CLIMEX simulation for South Korea. Consequently, the reconstructed RCP 8.5 climate change scenario was composed of a total of 97,000 coordinate data values. For database construction, MATLAB (version 2016a, The MathWorks Inc., Natick, MA, USA) was used.

### 3. Results and Discussion

#### 3.1. Field Survey Result

Field surveys showed that potato tuber moths were observed in 16 out of 18 cities from mid-February to December. The number of collected potato tuber moths from the field survey varied based on time and location. Miryang and Seogwipo were the cities wherein the highest number of potato tuber moths was collected, with a monthly average of more than 100 per month, while less than 10 potato tuber moths were caught per month in 9 cities (Figure 1A). In addition, potato tuber moths were not observed in 2 cities (Wonju and Hoengseong). The earliest and latest times for observing the first occurrence of potato tuber moth were in mid-February (Miryang and Seogwipo) and mid-May (Boseong), respectively, and occurred until mid-December. Variations in the abundance of the potato tuber moth were thought to be due to the characteristics of the terrain around the survey site. Relatively low numbers of potato tuber moths were collected in areas by rivers or mountains; thus, their introduction from neighboring cultivating areas was limited. In contrast, a large number of potato tuber moths were observed in open areas neighboring other cultivation fields, suggesting their
migration from nearby farmlands and storage facilities, as it had been reported that migration was a major factor that resulted in different populations [32]. In early occurring areas, it can be inferred that potato tuber moth overwinters in surrounding storage facilities, after which it appears under a favorable climate [22]. For instance, in Miryang and Seogwipo, where the largest number of potato tuber moths was collected, GI appeared in February, but it was difficult to expect that adults would be observed as soon as growth began due to low GI values. Hence, the observed population in the early season suggested the possibility of migration from other places after overwintering in nearby indoor locations. In addition, it was presumed that other variables such as the characteristics of the field survey areas and the location of the surrounding storage facilities were affected in areas where seasonal abundance was confirmed later than the actual GI.

Finally, it should be noted that although there was a difference between the initial occurrence and population size, potato tuber moths were found in almost all surveyed areas. When combining our field survey results with previously published data (Figure 1B), potato tuber moths were observed in 49 out of 55 areas as a result of the field survey over 3 years from 2009 to 2012 and in 2019. All the areas where the occurrence was not observed were in the north of Gyeonggi-do and Gangwon-do, with the exception of Yesan. This means that the distribution of potato tuber moths was determined partly by temperature, but also by other factors, as their occurrence had also been confirmed in nearby areas with similar climates [32].

### 3.2. CLIMEX Model Validation

Climatic suitability (Figure 2A,B), and GI agreement with seasonal abundance from the field survey (Figure 2C,D) are shown. With the parameter values and irrigation applied, as per Jung et al. [39], the climatic suitability for the potato tuber moth was low across the country (Figure 2A). Because the potato tuber moth had been observed in most areas in South Korea, we considered that these parameter values did not work correctly. In addition, as mentioned in the Section 2.4, South Korea did not use irrigation for cultivating potatoes due to sufficient precipitation. Consequently, a significantly larger discrepancy was shown between the GI and seasonal abundance of potato tuber moth collected from the field survey (green lines in Figure 2C,D). In contrast, the CLIMEX parameter without irrigation showed the climatic suitability of the potato tuber moth increased nationally (Figure 2B) and produced a more consistent pattern of the GI over seasonal abundance data compared to the model with irrigation as per Jung et al. [39] in both cities (red lines in Figure 2C,D). However, there was a discrepancy during summer seasons in Seogwipo, one of the southernmost regions of South Korea and both models with and without irrigation predicted no growth (GI = 0) from June to October because of high precipitation during summer. The discrepancy might be because the meteorological data in CLIMEX was averaged data for 30 years to remove year-specific noise, whereas field survey data were collected for only one year [43]. In addition, because the growth index was an indicator of the estimated possibility of which species can grow, it could differ from the actual population [38]. To further validate the parameter values, we predicted the potential distribution of potato tuber moth in China and India. The result showed that both models could represent the current distribution of potato tuber moth in the above countries (Figure 3), but the model without irrigation showed a better fit in north China where the potato tuber moth has not been confirmed. Therefore, we concluded that the model parameter without an irrigation scenario was applicable for predicting the potential distribution of potato tuber moth in South Korea. In general, parameters in the CLIMEX model were estimated based on spatial distribution data [12,16]. Hence, this methodology using spatiotemporal abundance from field surveys in validating parameter values has rarely been used even though there were a few studies introducing this method [33,38]. Because this study aimed at executing a region-specific prediction of potato tuber moths, which have high adaptability for regional climates [44], this model validation based on a domestic field survey would provide more reliable predictions.
Figure 1. Field survey areas with the number of collected potato tuber moths (A), and the combined occurrence record of potato tuber moths in South Korea (B).
Figure 2. Potential distribution of potato tuber moth in South Korea, (A): With irrigation scenario, as per Jung et al. (2020), (B): Without irrigation, and comparison of growth indices of potato tuber moths with seasonal abundance from field surveys in (C) Miryang and (D) Seogwipo.
3.3. Climatic Suitability Assessment

The potential distribution of potato tuber moths in South Korea was predicted by evaluating climatic suitability under the current climate (Figure 4A) and under climate change (Figure 4B–E). The simulations showed that all the regions across South Korea have an EI of 10 or more, with EI values larger than 30 predicted for Jeju Island and western coastal regions and southeastern regions under the current climate. Based on climate change theories [41], EI values are expected to increase in the inland of South Korea over time, with the highest EI values observed in 2100. Although EI varied by location and climate change scenario, none of the cities showed EI = 0, suggesting that the potato tuber moth could possibly be distributed throughout the country, which was consistent with the results of the field survey. Under the current climate, an EI value of 30 or more was concentrated in south coastal regions and Jeju Island, including areas where potato tuber moths were observed from field surveys. In contrast, 5 of the 6 cities where potato tuber moths were not observed were located in areas with relatively low EI values, suggesting a reliable region-specific prediction. An exception was observed in
Yesan, where potato tuber moths were not observed in the field survey data, although the area had an EI value larger than 30. Other cities near Yesan—which were also in the red zone where EI > 30—that have a similar climate have the moth present, but it may not have been found in Yesan because of effective control [23]. When applying the climate change scenario [41], the EI values decreased in northeastern regions, including Pyeongchang, which was the only region where the EI decreased to below 10 (Figure 4B). In 2060, the most notable change was that the areas along the south coast and Jeju island had EI values decreased (Figure 4C). The overall EI value would increase throughout the country in 2080 (Figure 4D), and would further increase until 2100 with no regions where EI value < 20 (Figure 4E). The most important factor affecting potato tuber moth distribution was temperature [24,45]. For example, the overall climatic suitability and number of areas with EI > 20 were lowest in 2080 because of low GI value. Temperatures in spring and fall were optimal for potato tuber moth growth, whereas precipitation was ideal for achieving optimal soil moisture during the summer, and these optimal temperature index (TI) and moisture index (MI) did not coincide. Consequently, the overall climatic suitability was low. This suggests that precipitation was the main determinant of potato tuber moth distribution in addition to temperature [44]. Potato cultivation requires sufficient amount of precipitation during its growth [19]. Accordingly, the water supply (e.g., irrigation) can increase the soil moisture and result in a sufficient MI in the range of adequate TI for potato tuber moth in potato cultivation countries with low summer rainfall. This was confirmed by simulating TI and MI over time in 2080, which showed that irrigation increased the climatic suitability in Miryang by expanding the period during which TI and MI were satisfied simultaneously. Therefore, it could increase potato tuber moth occurrence at the time when the climate is not suitable, suggesting a potato cultivating area that uses an irrigation system is exposed to a high risk of potato tuber moth occurrence [39]. Further, we investigated the effect of climate change on potato cultivation in South Korea by simulating the CLIMEX model on potato [39]. The result showed that high climatic suitability was expected to retain across the country until 2100 even though local variation was shown. This suggested that climate change will not have a significant impact on potato production. Rather than, a damage caused by pests can be a larger factor on potato cultivation than climate change.
Figure 4. Potential distribution maps of potato tuber moths for the current climate and other climate change scenarios ((A) = current; (B) = 2040; (C) = 2060; (D) = 2080; (E) = 2100).

![Potential distribution maps of potato tuber moths](image-url)
3.4. Spatiotemporal Risk Assessment of Major Potato Growing Areas in South Korea

In South Korea, potatoes are cultivated in the spring, summer, and fall. Among them, spring potatoes account for 73% of the national potato cultivation area, while summer and fall potatoes account for 14% and 6.6%, respectively [45]. The rest are cultivated in greenhouses during the winter season in some southern parts of South Korea. The main crop, spring potatoes, are most cultivated throughout the country, including three regions (red areas in Figure 5A: Total 2458 ha) in western parts of South Korea. Summer potatoes are most cultivated in montane areas in northeast of South Korea (blue areas in Figure 5A: Total 2388 ha), while fall potatoes are most cultivated in Jeju Island (green areas in Figure 5A: Total 834 ha) [46]. By targeting these areas, we analyzed the risk of the potato tuber moth on seasonal potato cultivation based on EI variations and periods for potato production (cultivation to harvest) by climate change (Figure 5B). Results showed that EI variation over time would not be significant. Areas for spring and fall potatoes were expected to maintain high EI values for potato tuber moth except a slight decline in 2060, while EI in the region for summer potatoes is generally increasing. Consequently, the risk assessment is that there is always a high risk, regardless of climate change.

![Figure 5](Agronomy_2020_b.png)  
**Figure 5.** Major areas cultivating seasonal potatoes in South Korea (A) and changes in the ecoclimatic index for major cultivation areas in response to climate change (B). Same colors were used for cities in (A, B).

Additionally, we attempted to assess the potential damage risk by considering the seasonal abundance of potato tuber moths and the time of potato production. As consistency between GI and seasonal abundance from the field surveys was shown [47], we used GI to predict the time of high risk during potato production in the major areas of potato cultivation in three example cities (Seosan, Hongcheon, and Jeju) (Figure 6). The seeding time of spring potatoes is generally from the middle of February to the beginning of April, and the harvesting time is from late May to mid-July [45]. In the areas for cultivating spring potatoes, GI gradually increased in March and maintained the maximum value until November, suggesting that a large abundance of potato tuber moths could cause severe damage during the entire potato production period. For summer potatoes, adequate seeding time is from mid-April to early May, and is harvested from early September to early October [45]. The GI of the potato tuber moth in that area began to increase from March, fell sharply from mid-July and increased again from August to October. Consequently, damage by potato tuber moths to summer potatoes would last from seeding to harvest except for a short period from early July to early September. Fall potatoes were sowed from the middle to the end of August and were harvested from the beginning to
the end of November. In areas where fall potatoes are mainly grown, GI value started to increase from the beginning of February and maintained a peak value from July to October. Hence, the occurrence of potato tuber moth steadily increases during the whole period of fall potato cultivation and harvest, indicating significant damage to fall potatoes unless adequate control is established [45]. The potato tuber moth stays inside the host from eggs to adults, damaging all parts of the potato [48], and tuber infestation during harvest time is the largest factor in yield loss [6]. For this reason, an adequate monitoring and control strategy in terms of time and site is required. Therefore, this spatiotemporal risk assessment of potato tuber moth based on the consistency between prediction and field survey can help determine control times and spots in order to prevent severe damage to potato production.

Figure 6. Timelines of seasonal occurrences of potato tuber moths in potato cultivation fields under the current climate for (A) spring potato (Seosan), (B) summer potato (Hongcheon), and (C) fall potato (Jeju).

4. Conclusions

The application of species distribution modeling to predict potential geographical distribution of species according to climate change enables the timely establishment of adequate measures that would minimize the damage caused by harmful species. This study estimated the potential distribution of potato tuber moths in response to climate change based on an actual field survey and proposed a useful methodology for evaluating the spatiotemporal risk of potato tuber moths on seasonal potato production, demonstrating the effectiveness of species distribution modeling. Results suggested that the distribution of potato tuber moths has expanded to the whole country, which could result in severe damage to seasonal potato production from seeding to harvesting. Because there are other factors affecting the distribution of potato tuber moths in addition to climate, a comprehensive analysis combining CLIMEX with other non-climate factors enables more precise predictions. We expect that this study will provide fundamental data for assisting the estimation of adequate control spots and times that would help reduce the damage caused by potato tuber moths.

Author Contributions: Conceptualization, S.J., K.-H.K. and W.-H.L.; methodology, D.-h.B. and W.-H.L.; software, D.-h.B. and W.-H.L.; validation, D.-h.B. and W.-H.L.; formal analysis, D.-h.B. and W.-H.L.; investigation, S.J., S.-G.L., S.-W.J., M.K., J.K. and K.-H.K.; resources, S.J., S.-G.L., S.-W.J., M.K., J.K. and K.-H.K.; data curation, D.-h.B. and W.-H.L.; writing—original draft preparation, D.-h.B. and W.-H.L.; writing—review and editing, D.-h.B., S.J., K.-H.K. and W.-H.L.; visualization, D.-h.B. and W.-H.L.; supervision, S.J., K.-H.K. and W.-H.L.; project administration, S.J. and K.-H.K.; funding acquisition, S.J. and K.-H.K. All authors have read and agreed to the published version of the manuscript.
**Funding:** This research was funded by the “Cooperative Research Program for Agricultural Science and Technology Development (Project No. PJ0134642018)”, Rural Development Administration, Republic of Korea.

**Acknowledgments:** This work was carried out with the support of the “Cooperative Research Program for Agricultural Science & Technology Development (Project No. PJ0134642018)”, Rural Development Administration, Republic of Korea.

**Conflicts of Interest:** The authors declare no conflict of interest.

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