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An Integrated Modeling Approach for Predicting Potential Epidemics of Bacterial Blossom Blight in Kiwifruit under Climate Change

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The increasing variation in climatic conditions under climate change directly influences plant-microbe interactions. To account for as many variables as possible that may play critical roles in such interactions, the use of an integrated modeling approach is necessary. Here, we report for the first time a local impact assessment and adaptation study of future epidemics of kiwifruit bacterial blossom blight (KBB) in Jeonnam province, Korea, using an integrated modeling approach. This study included a series of models that integrated both the phenological responses of kiwifruit and the epidemiological responses of KBB to climatic factors with a 1 km resolution, under the RCP8.5 climate change scenario. Our results indicate that the area suitable for kiwifruit cultivation in Jeonnam province will increase and that the flowering date of kiwifruit will occur increasingly earlier, mainly due to the warming climate. Future epidemics of KBB during the predicted flowering periods were estimated using the Pss-KBB Risk Model over the predicted suitable cultivation regions, and we found location-specific, periodic outbreaks of KBB in the province through 2100. Here, we further suggest a potential, scientifically-informed, long-term adaptation strategy using a cultivar of kiwifruit with a different maturity period to relieve the pressures of future KBB risk. Our results clearly show one of the possible options for a local impact assessment and adaptation study using multiple models in an integrated way.

Keywords **:** adaptation, integrated modeling, kiwifruit, Korea, local impact assessment

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Kiwifruit (*Actinidia deliciosa*), a subtropical fruit vine, has been commercially grown in the southern part of Korea since the early 1980s. Among the major kiwifruit diseases that are already endemic in Korea, kiwifruit bacterial blossom blight (KBB), caused by *Pseudomonas syringae* pv. *syringae* (Pss), is known to be considerably influenced by weather conditions during the flowering period of kiwifruit (Fang et al., 1999; Koh et al., 2001; Young, 1984). KBB initially affects the flower buds of kiwifruit by causing rotting of the anthers; this becomes apparent when the bud opens (Koh et al., 2001). Alternatively, the rot may spread to other tissues in the bud, resulting in general browning. In severe cases, the infected buds drop, leaving a flower stalk attached to the vine. Recurrent, consecutive epidemics in the same location can lead to sudden outbreaks of the disease under favorable weather conditions. Here in this study, we use the word of “epidemic” as the dynamics of disease, that is, the change in the severity of disease with time (Arneson, 2001).

The diseased flowers mostly result in a loss of fruits or in malformed fruits, thus affecting overall seasonal kiwifruit production. Indeed, KBB was responsible for over 50% of production losses in Korea (Shin, 2004). Therefore, it is recommended that kiwifruit growers utilize the best available chemical and cultural practices, such as spraying agro-chemicals, trunk injection of acetic acids, girdling on trunks, and installation of rainproof covers over kiwifruit vines (Koh, 1995; Koh et al., 2001; Tachibana, 1988). To assist with the implementation of best practices, we recently developed a KBB forecasting model, the Pss-KBB Risk Model, based on relevant epidemiological information regarding blossom blight in relation to weather variables (Kim and Koh, 2015; Lightner and Steiner, 1992).

The Pss-KBB Risk Model predicts potential infection risk of the KBB, based on which kiwifruit growers can utilize the best practices related to spraying chemicals at the most effective time. In order to run the Pss-KBB Risk Model, the flowering period of kiwifruit should first be defined as the model utilizes weather information for 10 days preceding full bloom (Kim and Koh, 2015). A kiwifruit phenology model, called the Chill-day Model, predicts the flowering period using daily temperature information. The original Chill-day Model was introduced by Cesaraccio et al. (2004, 2005), and then was modified by Jung et al. (2005) to predict the flowering of fruit trees in the temperate zone. The modified Chill-day Model was applied and parameterized by Kwon et al. (2012) and Kim et al. (2015b) to estimate the flowering date for the green flesh kiwifruit cultivar Hayward in Korea. This modified Chill-day Model for Hayward was adopted in our study to predict the flowering period, during which kiwifruit is known to be vulnerable to KBB infection.

Jeonnam province is located in the southwest of the Korean Peninsula and is a major kiwifruit growing area; as of 2015, almost 44% of kiwifruit cultivation in Korea took place in this province. Owing to warming temperature on the Korean Peninsula and improved management technologies, together with the local government's policy support over the last decades, the area of kiwifruit cultivation in Jeonnam province has expanded rapidly. However, the predicted effects of climate change on the kiwifruit industry in the province need to be addressed in order for the local government to institute realistic and effective adaptation strategies and policies. In particular, changes in environmental factors owing to climate change will affect plant-microbe interactions, which influence disease epidemics at different magnitudes for a broad range of local communities (Holling, 1986; Wilbanks and Kates, 1999). Short-term countermeasures may include the establishment of a disease early warning system, and of a support system for making decisions about control sprays, to ensure the timely application of agro-chemicals and other cultural practices in high-risk areas, while long-term solutions targeting the next decades may include a breeding program for disease-tolerant or early/late-maturing cultivars equipped to resist or avoid high disease pressures.

To facilitate these planning measures, we predicted future epidemics of KBB in Jeonnam province as a case study for local impact assessments of climate change. However, in most impact studies, variables other than climate are generally assumed to remain unchanged in the future. Such assumptions, and the uncertainties inherent in climate change scenarios themselves, often result in unrealistic predicted impacts of climate change, which prevents local policymakers or stakeholders from being convinced by the results. Therefore, there is a strong need for an integrated modeling approach to incorporate a greater quantity of the factors that would play critical roles in a real situation. In fact, there have been many impact assessments using the integrated modeling approach in various sectors, where multiple models and/or algorithms were used together to determine critical interaction points between multiple socio-economic, biological, and environmental components (Keith et al., 2008; Krol and Bronstert, 2007; Wilby et al., 2006).

The objective of this study was to evaluate the effects of climate change and the corresponding adaptation strategies by leveraging multiple models in an integrated way. To achieve this objective, we conducted modeling studies investigating the responses to climatic conditions of kiwifruit and of the pathogenic bacteria that cause KBB, using the high-resolution RCP 8.5 climate change scenario. This included (1) simulating suitable areas for kiwifruit cultivation using a climate suitability model, and (2) linking a kiwifruit phenology model with a disease epidemiological model to predict the future epidemic risk of KBB. Finally, we suggest, based on this integrated modeling solution, a potential, scientifically-informed, long-term adaptation strategy of using a cultivar of kiwifruit with a different maturity period to avoid future pressures from KBB. To our knowledge, this is the first local impact assessment and adaptation study of plant disease risks under climate change linking both the host plant phenology model and the disease epidemiological model, with consideration of future climatic suitability for the host plant.

Materials and Methods

Study area. Jeonnam province is located in the southwestern part of the Korean Peninsula (Fig. 1). It is generally characterized by a maritime climate because of the large proportion of coastal areas; however, distinctive features of a continental climate exist in the mountainous inland areas. The average rainfall for the period covering 1984-2013 was 1,471 mm, with a large inter-annual variation between

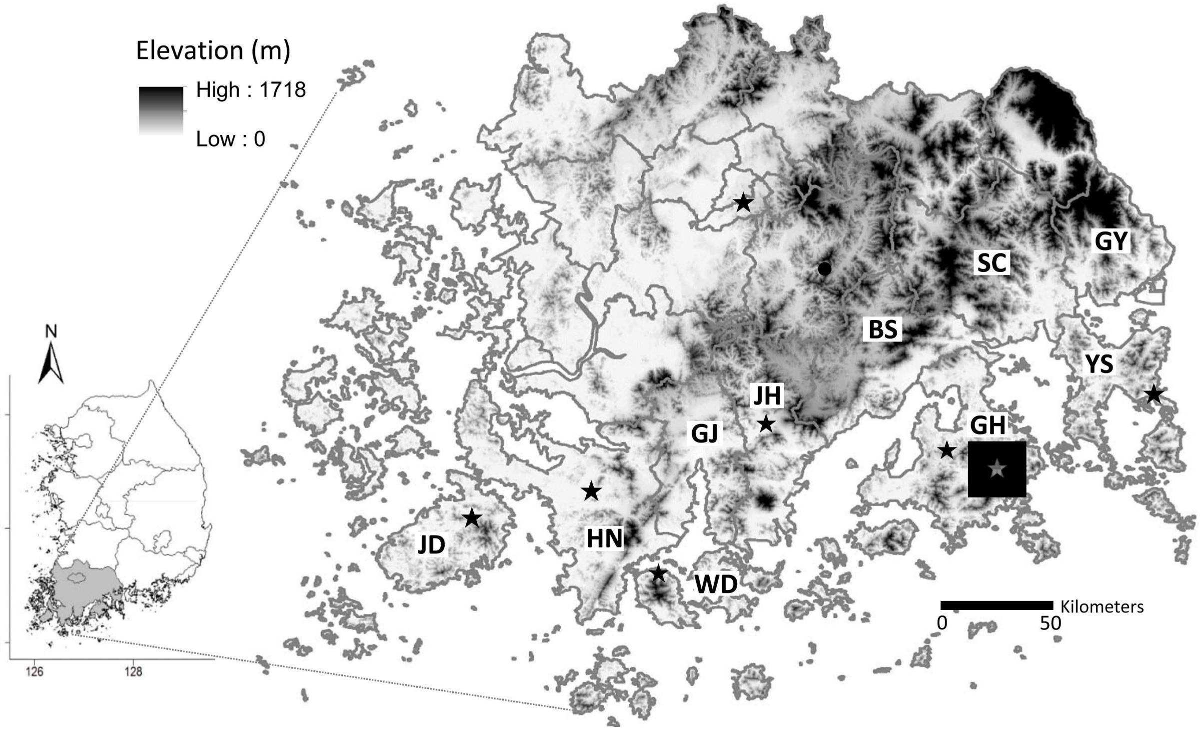

Fig. 1. Elevation map of the study area, Jeonnam province in Korea. Major counties growing kiwifruits in the province are labelled on the map: JD, Jindo; HN, Haenam; WD, Wando; GJ, Gangjin; JH, Jangheung; BS, Boseong; GH, Goheung; SC, Suncheon; YS, Yeosu; and GY, Gwangyang. Note that the 7 Automated Synoptic Observing System (ASOS) stations used for the downscaling of 11 GCM scenarios are starred on the map.

800 mm and 2,300 mm. Fifty-four percent of the annual rainfall falls during the summer monsoon season (June to August). The average temperature for the period covering 1980-2013 was 13.4°C, with an average minimum temperature of 8.7°C and an average maximum temperature of 18.9°C. Over the past 30 years, rainfall has decreased at a rate of 2.8 mm/y, while temperature has increased at the rate of 0.33°C/y (Kim et al., 2015b). Most kiwifruit cultivation occurs in the counties along the southern coast, as shown in Fig. 1. However, cultivation has slowly extended toward the mountainous inland areas because of improved farming technologies and management skills, and the increasing temperatures that result from climate change. As of 2011, there are about 1,200 kiwifruit growers in Jeonnam province, producing more than 8,000 tons of kiwifruit annually from about 520 ha of orchards (statistics obtained from the Jeonnam Provincial Government).

Climate change scenarios. The RCP 8.5, the highest greenhouse gas emission pathway in the fifth phase of the Coupled Model Intercomparison Project (CMIP5), was selected in the study to provide a baseline to reflect the continuously increasing trend of greenhouse gas (GHG) emission in the face of limited global/national policy intervention (Olivier et al., 2017; Rahmstorf et al., 2007). The RCP 8.5 climate change scenario of the HadGEM2-AO global climate model (GCM) was downscaled to a 1 km resolution by the Korea Meteorological Administration (KMA) (Kim et al., 2012a, 2012b; KMA, 2015; Lee et al., 2012). The 1 km resolution scenario by KMA (hereafter referred to as the KMA scenario) was used in all three modeling works in the study: a climate suitability model, a kiwifruit phenology model, and a disease epidemiology model.

In this study, we used the KMA scenario because it was the only available high-resolution gridded climate change scenario required for local impact assessment and adaptation study. This may indicate the predictions from this study may not accurately reflect the true state of knowledge concerning potential future conditions affecting the epidemics of KBB in Jeonnam province. This is because there are inherent uncertainties in climate projections from GCMs due to fundamental variations in initial conditions as well as structural differences in the models. Therefore, we examined whether the KMA scenario-based approach can accommodate the uncertainty from multiple GCMs. For this, we compared the potential epidemic risks of KBB simulated with the single KMA scenario and multiple scenarios from 11 GCMs. Since the multiple scenarios could be obtained by statistical downscaling to point locations where more than 30 years' climatological data exist, we selected 7 KMA Automated Synoptic Observing System (ASOS) stations in the major kiwifruit growing administrative districts in Jeonnam province for the comparison test, which are the Jindo (175), Haenam (261), Wando (170), Jangheung (260), Goheung (262), Yeosu (168), and Gwangju (156) (shown in Fig. 1). Statistical downscaling was conducted using the method implemented by Cho (2013) and Kim and Cho (2016). Briefly, we selected daily scale scenario data from 11 GCMs (information on the GCMs refers to Table 1 in Kim and Cho, 2016). The scenario data of 11 GCMs were bias-corrected and spatially downscaled to the 7 ASOS stations using the non-parametric quantile mapping method. Thirty years of observed historical data obtained from the ASOS stations were used as a reference for the quantile mapping method.

Three models leveraged. In our recent study, the suitability areas for kiwifruit growth in Jeonnam province were determined using a climate suitability model, where five selected bioclimatic conditions were used as important determinants for the optimal growth of kiwifruit: (1) minimum threshold temperature for kiwifruit growth as a mandatory condition, and (2) freezing damage-tolerant temperature, (3) minimum length of the frost-free season, (4) winter chill requirement for flowering, and (5) water requirement for optimum growth as optional bioclimatic conditions. To calculate the five bioclimatic conditions, daily minimum and maximum temperature and daily precipitation data are used. Details on the conditions of each bioclimatic variable, the suitability algorithm, and its validity can be found in Jeong et al. (2018). Areas that were predicted to be "Highly suitable" or "Suitable" for kiwifruit cultivation in the historical and future periods were subjected to further model simulations as described below.

To predict the potential epidemic risk of KBB under a changing climate, we leveraged the Pss-KBB Risk Model developed in our recent study (Kim and Koh, 2015), along with a kiwifruit phenology model, called the Chill-day Model. The Chill-day Model was parameterized by Kwon et al. (2012), Kim et al. (2015b), and Kim et al. (2016) to estimate the flowering date for the kiwifruit cultivars, Hayward and Haegeum, in Korea. In all previous studies, this model was validated on datasets from different sites in Jeonnam province, which yielded smaller prediction errors than using climatologically averaged flowering dates in each site. This suggested its reliability when applied to climate change scenarios. Daily minimum and maximum temperature data are used for the simulation of the Chill-day Model. This model was adopted in our study to predict the flowering period, which subsequently defines the simulation dates of the Pss-KBB Risk Model.

The original Pss-KBB Risk Model estimates a risk score for KBB using daily minimum and maximum temperature and precipitation data for the 10 days preceding the full bloom date, which was highly correlated with the observed disease severity data (correlation coefficient [CC] of 0.954 with 1% significance level). To simulate disease severity (%) using the Pss-KBB Risk Model, we developed an additional algorithm based on the model: a regression equation between the simulated risk scores and the corresponding observed severity data, using the lm() function of the R statistical program (version 3.3.2) (R Development Core Team, 2008). The observed severity data consisted of ground-truth data of KBB severity covering 10 y (1999-2006 and 2008-2010) in Haenam, collected from kiwifruit orchards by Lim (2009), and KBB severity data covering the period 1997-1999 in Goheung, collected by Koh et al. (2001). The Haenam data range from 0.1% to 10.7%, while the Goheung data range from 20.7% to 35.3% representing severe epidemic situation. Weather data from the KMA ASOS stations in Haenam (261) and Goheung (262) near the kiwifruit orchards were used to run the Pss-KBB Risk Model and to generate the simulated risk scores. The resulting regression equation was validated by comparing the simulated disease severities with another set of ground-truth data collected in 2015 in multiple kiwifruit orchards. Weather data from the nearest KMA weather stations were used to simulate the Pss-KBB Risk Model.

Integrated modeling approach. Daily maximum and minimum temperature and precipitation data were extracted from the KMA scenarios for a series of modeling with three models. Three models were not physically linked or coupled to each other but were simulated in a logical order to generate base information for subsequent simulations by another model (Fig. 2). First, the Climate Suitability Model simulated suitable areas for kiwifruit cultivation in the historic and future periods, which were subjected to further model simulations with the kiwifruit Chill-day Model. The Chill-day Model simulated flowering dates of kiwifruit vines for individual grid locations in the historic and future periods, which then became the simulation periods by the Pss-KBB Risk Model to simulate the potential epidemic risks of KBB (hereafter referred to as KBB risk) in Jeonnam province.

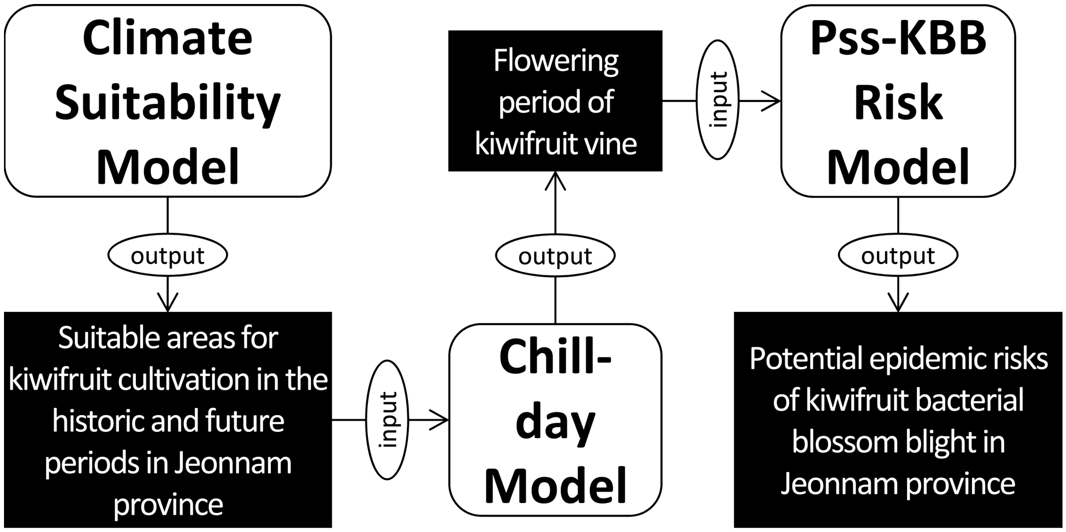

Fig. 2. Integrated modeling workflow using three models in the study. First, the Climate Suitability Model generates suitable areas for kiwifruit cultivation. Then, the Chill-day Model simulates flowering period of kiwifruit vines only on the suitable areas in Jeonnam province identified by the Climate Suitability Model. Lastly, the Pss-KBB Risk Model simulates potential epidemic risks of KBB using the flowering dates generated by the Chill-day Model as an input. Pss, *Pseudomonas syringae* pv. *syringae*; KBB, kiwifruit bacterial blossom blight.

The KBB risks over the province were represented as the frequency of severe epidemics over each 10-year-period, with a maximum of 10 severe epidemics over each period. Considering the general flower pruning practices taking place in kiwifruit orchards, where at least 20% of flowers are pruned (Jeonnam Agricultural Research Center, personal communication), severe epidemic risk was recorded when the simulated KBB severity exceeded 20% in a given year. Simulation results were divided into five periods, starting at the historical period (2000-2009) and covering future periods of every other decade, such as 2020-2029, 2040-2049, 2060-2069, and 2080-2089. These results were presented on the map to show temporal (present to future) and spatial changes of KBB risk throughout the province. To compare this result with the ones from multiple scenarios of 11 GCMs, the same modeling procedures using the Chill-day Model and the Pss-KBB Risk Model were repeated with multiple scenario data downscaled to the 7 ASOS locations. The range of uncertainty in estimating the KBB risks resulting from the uncertainty in climate projections from different GCMs was displayed with the mean and the range of ± 1 standard deviation (SD) from the mean, which was directly compared with the mean KBB risks simulated on the 7 ASOS locations using the KMA scenario.

As an example of possible adaptation strategies to the identified impacts of climate change, in this case the KBB risk, we simulated future KBB risks using another kiwifruit cultivar with earlier maturity than Hayward. Recently, we parameterized and validated the Chill-day Model to predict the flowering dates for a gold-flesh kiwifruit cultivar, Haegeum (Kim et al., 2016). Haegeum was bred by the Jeonnam Agricultural Research Institute and is currently cultivated on more than 120 ha in Jeonnam province. We replaced the Chill-day Model for Hayward with one for Haegeum and re-ran the models to generate decadal changes of the KBB risks on the cultivar Haegeum throughout Jeonnam province. The results were then compared with those obtained for Hayward.

Results

Potential changes to the climatic suitability maps for kiwifruit cultivation in Jeonnam province were determined based on climatic conditions in each 1-km-grid of the RCP 8.5 climate change scenario (Fig. 3). Three suitability zones (Not suitable, Suitable, and Highly suitable) for optimal kiwifruit cultivation were displayed depending on expected temporal changes in the climate of Jeonnam province, from the historic period (2000-2009) to future periods (2020-2029, 2040-2049, 2060-2069, and 2080-2089). The simulated suitable areas for the historic period were comparable to the current kiwifruit cultivation areas in the province (Statistics Korea, http://kosis.kr), except for the Gwangju Metropolitan City area, probably due to warmer temperatures from an urban heat island effect. This result

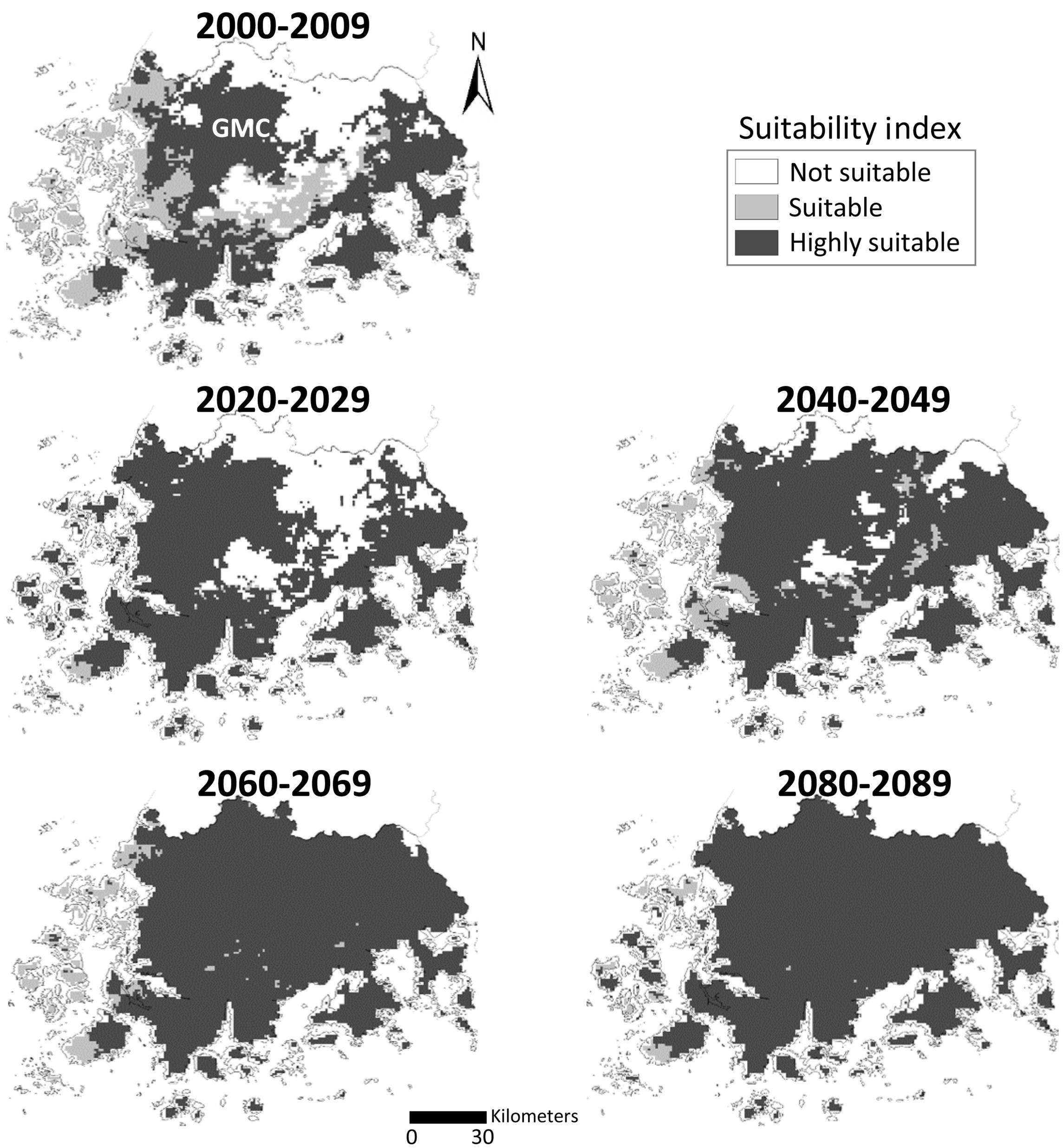

Fig. 3. Climatic suitability maps for kiwifruit cultivation under the RCP 8.5 climate change scenario in Jeonnam province, Korea. GMC, Gwangju Metropolitan City.

indicates that the climatic conditions used in this study represent real-world conditions today. The geographical locations suitable for kiwifruit cultivation expanded from the present coastal area to the high elevation inland area, and also northward, by 2090. Approximately one-third of the areas in Jeonnam province were shown as 'Not suitable' for kiwifruit cultivation at present, but almost 99% of the areas changed to 'Highly suitable' in the 2080s, supporting our understanding that this local impact assessment for the province is reasonable.

To simulate disease severity (%) using the existing Pss-KBB Risk Model, we developed an additional algorithm in the model: a regression equation between the simulated risk scores and the corresponding observed severity data. The resulting regression equation was $Y = 0.102X + 0.0552$ ($R^2 = 0.976$), where Y is the observed severity and X is the simulated risk score. The regression equation was validated by comparing the simulated disease severities with ground-truth data collected in major kiwifruit growing areas in the province (Fig. 4A). The mean absolute error (MAE) and the root-mean-square error in the assessment of the similarity between the observed and the simulated severities were

A

No.	Obs. severity	Sim. R scores	Sim. severity	Weather station	Orchard location
1	**11.3**	74.5	**7.7**	Mobile AWS 1	Boseong-gun, Joseong-myeon
2	**14.2**	74.5	**7.7**	Mobile AWS 1	Boseong-gun, Joseong-myeon
3	**13.7**	93.2	**9.6**	Mobile AWS 2	Goheung-gun, Doyang-eup
4	**5**	35.15	**3.6**	748, Beolgyo	Boseong-gun, Beolgyo-eup
5	**1**	11.26	**1.2**	748, Beolgyo	Boseong-gun, Beolgyo-eup
6	**3**	11.26	**1.2**	732, Boseong	Boseong-gun, Deungnyang-myeon
7	**1**	31.28	**3.2**	732, Boseong	Boseong-gun, Deungnyang-myeon
8	**15**	109	**11.2**	712, Suncheon	Suncheon-si, Haeryong-myeon
9	**20**	174.5	**17.9**	260, Jangheung	Jangheung-gun, Allyang-myeon
10	**5**	16.48	**1.7**	260, Jangheung	Jangheung-gun, Jangheung-eup
11	**10**	108.59	**11.1**	262, Goheung	Goheung-gun, Duwon-myeon
12	**5**	72.68	**7.5**	767, Podu	Goheung-gun, Podu-myeon
13	**0**	25.46	**2.7**	785, Bukil	Haenam-gun, Bukil-myeon
14	**10**	72.68	**7.5**	261, Haenam	Haenam-gun, Haenam-ub

B

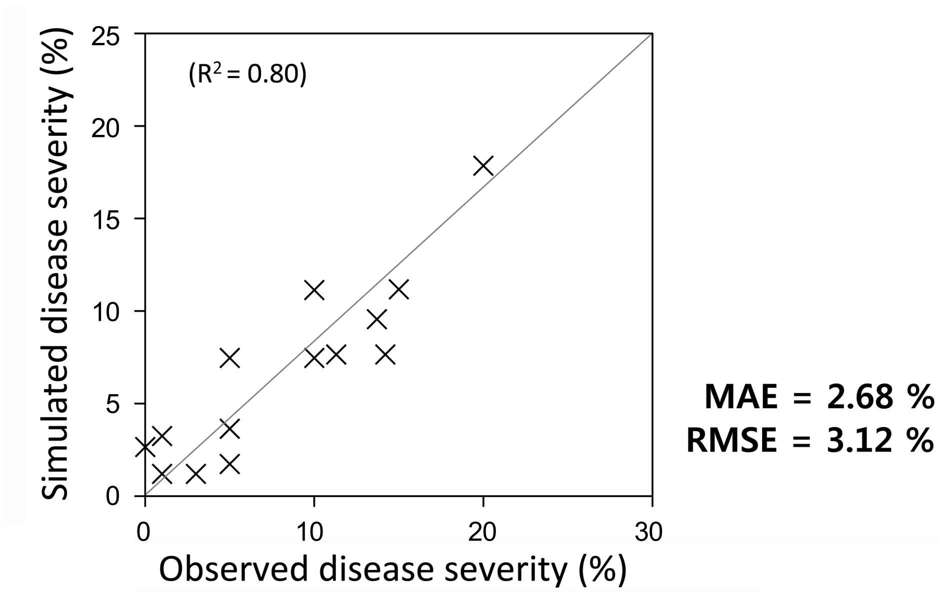

Fig. 4. Simulated severity of KBB compared to observed severity in 2015. (A) Simulated R scores (Sim. R scores) by the Pss-KBB Risk Model were converted into disease severity (Sim. severity), and then compared with the observed disease severities (Obs. severity). Weather information was collected from the weather stations near each investigated orchard. (B) Mean absolute error (MAE) and root-mean-square error (RMSE) were calculated for both simulated disease severity and observed disease severity. Pss, *Pseudomonas syringae* pv. *syringae*; KBB, kiwifruit bacterial blossom blight.

2.68% and 3.12%, respectively, indicating a reasonably high performance of the equation in predicting disease severity according to the model (Fig. 4B).

Kiwifruit becomes vulnerable to KBB infection during the flowering period. We first used the Chill-day Model to determine the flowering dates of kiwifruit using the climate change scenario. Disease severities of KBB during the simulated flowering periods were calculated using the Pss-KBB Risk Model. The resulting KBB risks (the number of severe epidemics with more than 20% disease severity) were considered as the potential epidemic risks of KBB under climate change. As shown in Fig. 5A, few areas were predicted to have more than three to four severe epidemics over the historical period (2000-2009), especially in the major kiwifruit growing counties in Jeonnam province. This is in line with the fact that there have rarely been severe epidemics of KBB with significant production losses in the province over the last years (Jeonnam Agricultural Research Center, personal communication). Towards 2090, KBB risks did not show a clear or uniform pattern of spa-

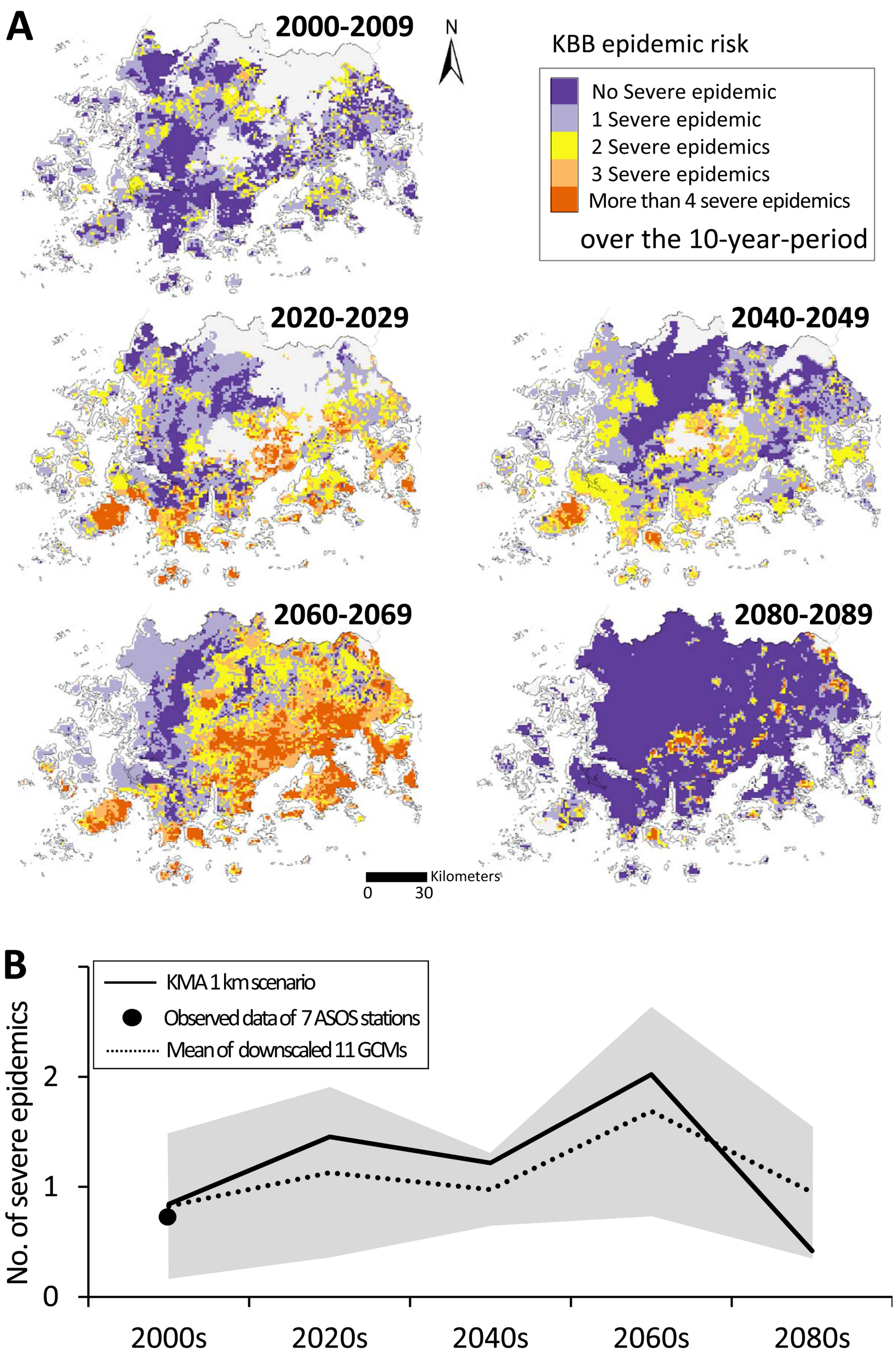

Fig. 5. Potential epidemic risks of KBB in areas of Jeonnam province suitable for kiwifruit cultivation under the RCP 8.5 climate change scenario for each 10-y period from the historical (2000-2009) to the future (2020-2029, 2040-2049, 2060-2069, and 2080-2089) periods. The frequencies of severe epidemics for each 10-year period were calculated based on the simulation results of the Pss-KBB Risk Model, with disease severity greater than 20% per year considered to be a severe epidemic. (A) Spatio-temporal trend of the KBB epidemics shown on the map of Jeonnam province. Note that the light gray areas on the map indicate the "Not suitable" areas for kiwifruit cultivation in each decadal period, which were not subject to the simulation of KBB epidemics. (B) Comparison of the mean KBB severe epidemics on 7 Automated Synoptic Observing System (ASOS) station locations in Jeonnam province (stars in Fig. 1), simulated with the Korea Meteorological Administration 1 km scenario (solid line), the observed weather data of the 7 ASOS stations only for 2000-2009 (round dot), or the downscaled scenarios of 11 GCMs (dotted line with gray shared area). Note that the dotted line indicates the mean of the simulated KBB severe epidemics from 11 GCMs, and the gray shared area indicates the range of ± 1 SD from the mean. Pss, *Pseudomonas syringae* pv. *syringae*; KBB, kiwifruit bacterial blossom blight.

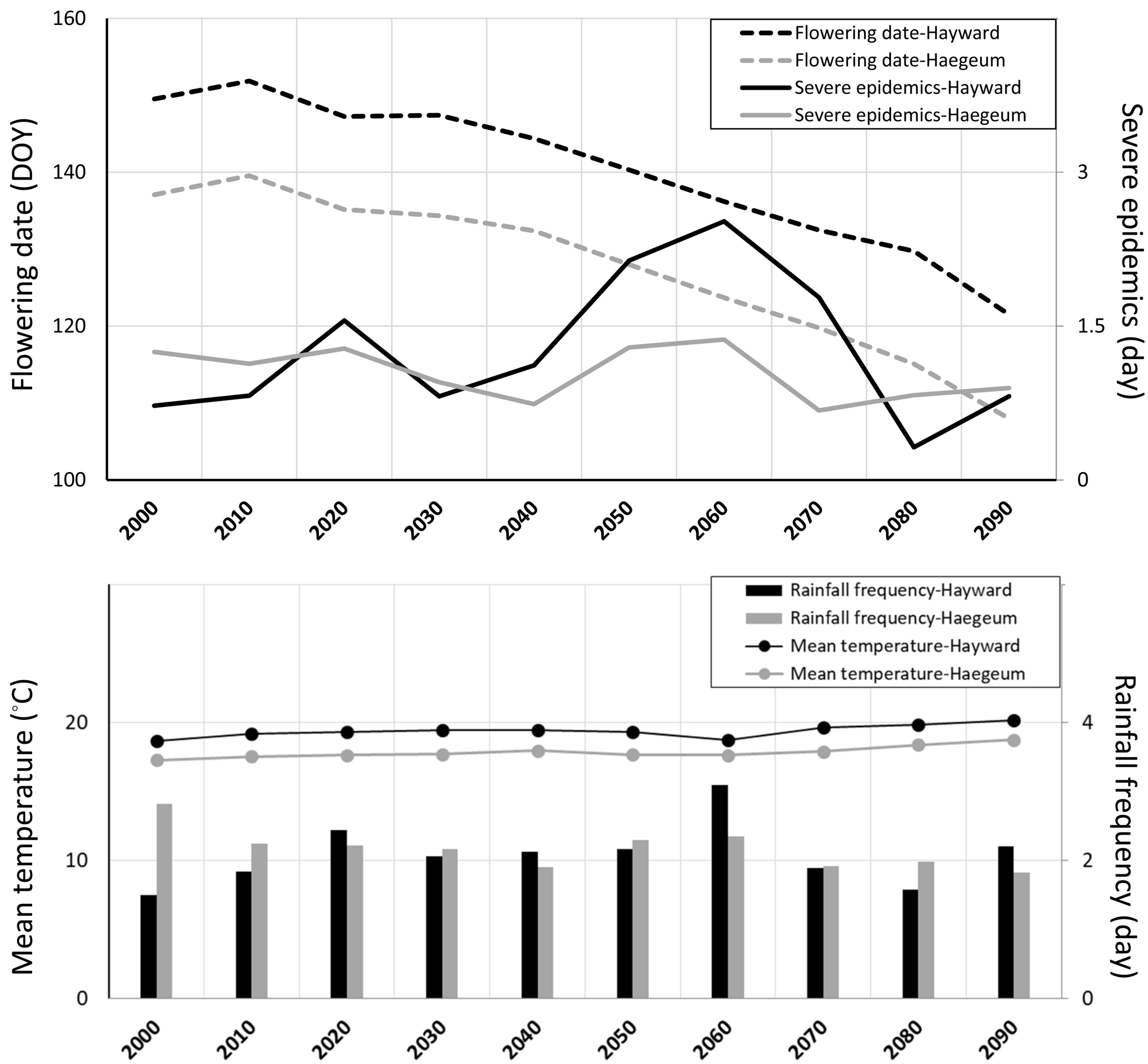

Fig. 6. Predicted changes in severe epidemics of kiwifruit blossom blight (KBB risk) and flowering dates in Jeonnam province from the 2000s to the 2090s under the RCP8.5 climate change scenario. The decadal changes of the KBB risk (black line) and the flowering date (black dotted line) for kiwifruit cultivar Hayward were compared with those of the KBB risk (gray line) and the flowering date (gray dotted line) of the kiwifruit cultivar Haegeum for the same periods (2000s-2090s). The bottom graph indicates the decadal changes of average values of temperature (°C) and rainfall frequency (days) during the 10-day periods before full bloom of Hayward (black graphs) and Haegeum (gray graphs) cultivars.

tial change, indicating some complex, location-specific interactions between kiwifruit phenology and the corresponding KBB simulations. Geographically, a greater number of severe epidemics started in the coastal island areas, such as Jindo, Haenam, Wando, Goheung, and Yeosu, and the risk expanded into southeastern inland areas of the province in 2060-2069, while in most areas, except for some parts of Wando, Jangheung, and Suncheon, no severe epidemics were predicted for the period 2080-2089.

Since the results in Fig. 5A do not show uncertainty information derived from the uncertainty in climate projections from different GCMs, we examined whether the KBB risks simulated with the KMA scenario are accommodated within the range of uncertainty from the multiple scenarios of 11 GCMs (Fig. 5B). In most periods examined, the KBB risks from the KMA scenario were within the range of the mean ± 1 SD of the risks from the 11 GCM scenarios, and the mean KBB risks of the KMA scenario followed the temporal fluctuation of the mean KBB risks from 11 GCMs. This particular example indicates the spatio-temporal trend of KBB risks obtained from the KMA scenario may not present significantly biased results beyond the climate change signals from other GCMs.

Similar to the spatial representations of the KBB risks, mean decadal changes of the severe epidemics of KBB showed that KBB risks throughout Jeonnam province continued to increase and peaked in the 2060s, and then decreased in the 2080s ('Severe epidemics-Hayward' in Fig. 6). On the other hand, the simulation of flowering dates by the Chill-day Model showed a decreasing (advancing) trend in the future periods ('Flowering date-Hayward' in Fig. 6), showing a reasonable shift of the flowering date responding to the projected warming temperature. As the flowering dates change, the corresponding temperature and rainfall patterns for the 10-day period before full bloom, which are the primary cause for the fluctuating pattern of KBB risks over future periods, should change accordingly. To investigate this relationship, we displayed the decadal change of KBB risks together with decadal changes in mean temperatures and rainfall frequencies during the 10-day periods that the Pss-KBB Risk Model used to simulate disease risk. The mean temperatures over the future periods showed a slightly increasing trend over the range of 18.7-20.2°C ('Mean temperature-Hayward' in Fig. 6). On the contrary, the rainfall frequency varied from 1.5 to 3.1 days over the future periods ('Rainfall frequency-Hayward' in Fig. 6). Statistical analyses indicated that the rainfall frequencies during the 10-day periods explained much of the variation in KBB risks, with a CC of 0.76 between the decadal changes of KBB risks and rainfall frequencies, while the CC with mean temperatures was negligible. Nevertheless, it was inferred that the decrease of KBB risks after the 2070s is caused by the mean temperature increases in the corresponding periods.

Here we suggest a possible strategy to adapt to the identified impacts of climate change, in this case the KBB risk, using an alternative kiwifruit cultivar with an early maturity period: the gold-flesh kiwifruit cultivar Haegeum. By examining the early-maturing cultivar Haegeum (approximately 2 weeks earlier than the cultivar Hayward), we hoped to show that this cultivar avoids the high KBB pressures predicted during the flowering period of Hayward. Simulation using the Chill-day Model for the cultivar Haegeum showed that the flowering dates of Haegeum were indeed 12-14 days earlier than those of Hayward, with a similar advancing trend over the future periods ('Flowering date-Haegeum' in Fig. 6). Haegeum was also predicted to carry significantly lower KBB risks than Hayward in most of the future periods ('Severe epidemics-Haegeum' in Fig. 6), indicating that the climatic conditions during the predicted flowering periods of Haegeum were less favorable to KBB development. The decadal KBB risks for Haegeum were of fewer than 1.5 days of severe epidemics over the future periods, and were significantly lower than Hayward, especially in the 2050-2070s, when Hayward carried the highest KBB pressures. Statistical analyses for the KBB risks and the decadal trends of mean temperature and rainfall frequency for Haegeum showed similar results to those of Hayward ('Mean temperature-Haegeum' and 'Rainfall frequency-Haegeum', respectively, in Fig. 6), with rainfall frequency showing a high CC. In conclusion, our findings indicate that the cultivar Haegeum can be an alternative solution to coping with future KBB risks, replacing the cultivar Hayward, which is currently planted in kiwifruit orchards in Jeonnam province.

Discussion

In this study, we successfully evaluated the effects of climate change by leveraging multiple models in an integrated way, by conducting a series of modeling studies on the responses of kiwifruit and KBB bacterial pathogen to climatic conditions. The integrated modeling approach consists of a climate suitability model simulating the suitable area for kiwifruit cultivation (the Climate Suitability Model), a kiwifruit phenology model (the Chill-day Model) simulating the flowering stage when KBB occurs, and a KBB epidemiological model (the Pss-KBB Risk Model) simulating disease infection processes (Fig. 2). All three models were simulated using the same KMA 1 km resolution, RCP8.5 climate change scenario, resulting in synchronous biophysical interactions between plants, microbial pathogens, and environmental conditions in each 1-km-grid location in Jeonnam province. Although there remains a significant challenge of not being able to account for all complicated factors affecting the biophysical interactions that might change in future, the resulting KBB risk represents more realistic information with fewer assumption compared to previous studies (Francesca et al., 2006; Kim et al., 2015a).

Potential changes to suitable areas for kiwifruit cultivation under a changing climate were simulated based on the optimal climatic conditions for kiwifruit growth. This suitability simulation based on climatic conditions was critical in mapping the areas in which it is highly likely that kiwifruit orchards will be located in the future, in an effort to make subsequent KBB risk prediction more rational. For the predicted suitable areas for kiwifruit cultivation, we linked the Pss-KBB Risk Model with the Chill-day Model to assess the interactions of kiwifruit vine and blossom blight occurrence, resulting in potential, but more realistic, KBB risk prediction for a changing climate. Reflecting the warming temperature under climate change, the simulation of flowering dates by the Chill-day Model showed a decreasing (advancing) trend over future periods, similar to phenological changes reported in previous studies (Lenoir et al., 2008; Yun, 2006). Considering that the RCP 8.5 climate change scenario from the HadGEM2-AO model projects a 4.1°C increase in temperature in the Korean Peninsula by 2100 (Baek et al., 2013), our results showed a reasonable shift in the kiwifruit flowering date corresponding to this projected temperature change, which actually provides one of the most compelling evidences of ongoing climate change. Kwon et al. (2012) and Kim et al. (2015b) showed that the modified Chill-day Model could predict flowering dates of Hayward with high accuracy (2.5 days and 2.0 days of MAEs with different ground-truth datasets, respectively) by comparing with ground-truth data representing more than 10 years. Therefore, it can be assumed that the flowering dates predicted by the Chill-day Model for the future periods may represent the actual phenophase of kiwifruit in the future, which in turn indicates that the climatic conditions determined by the predicted flowering dates may also represent the actual conditions that the KBB pathogen will encounter during future seasons. The assumption of a phenophase date for a plant is more likely to be true for perennial fruit trees (or vines) like kiwifruit, which last for more than 30 years once planted, than for annual crops such as rice, wheat, and maize. This is because perennial species do not require human-dependent planting activity, which makes prediction of the future phenophase difficult for annual species.

As the flowering dates change, the corresponding temperature and rainfall conditions for the 10-day periods before full bloom, to which the KBB pathogen will be exposed, were assumed to change accordingly. In a study by Everett and Henshall (1994), temperature, rainfall, rain duration, and flower wetness were considered to be important determinants for the incidence of KBB epidemic. Pennycook and Triggs (1991) showed that rainfall immediately before and during the flowering period was of paramount importance and determined the differences in severity of KBB between seasons. Since rainfall during flowering predisposes kiwifruit to diseases, installation of rainproof covers may contribute to reduced disease severity in kiwifruit orchards. Similar to rainfall, temperature affects population dynamics of the bacterial pathogen of KBB and its infection processes. The Plant and Food Research Institute in New Zealand reported in its bulletin a prediction model for KBB severity based on temperature data covering the 10 days before one percent of kiwifruit vines have flowered, indicating that the temperature before and during flowering affect disease development (Everett and Henshall, 2012).

The Pss-KBB Risk Model has a rainfall function that generates a temperature-dependent daily risk score only on rainy days, translating the temperature and rainfall conditions for the 10-day period before full bloom into a KBB risk score (Kim and Koh, 2015). Indeed, the comparisons between the KBB risks and both mean temperature and rainfall frequencies during the 10-day periods before full bloom in the future periods revealed that the rainfall frequency explained much of the variation in KBB risks, while the effect of mean temperature was negligible (Fig. 6). However, temperature might explain some of the interdecadal KBB risk fluctuations, *i.e.*, the difference in KBB risks for the cultivar Hayward in the 2040s and 2050s, when rainfall frequencies were predicted to be similar but differences in the severity of epidemics were large, and the decrease of KBB risks after the 2070s, probably caused by the mean temperature increases during the critical infection periods. Nevertheless, we admit that it is difficult to determine the exact causes of annual variations in KBB risk level based on the mean values for each climate variable, as their accumulated and combined contributions in a daily scale resulted in such KBB risks (Everett and Henshall, 1994; Kim and Koh, 2015; Pennycook and Triggs, 1991).

Based on the temporal changes in severe epidemics of KBB in Jeonnam province, we can predict that KBB will be more serious in the future, due to a complicated interaction between biological responses and climatic factors. This indicates that continuous studies are required to prevent occurrence of the KBB disease in Jeonnam province. Impact assessment in each district in the province will also aid in the development of localized adaptation strategies for local government units. An early warning system using the Pss-KBB Risk Model and short-term (2-3 days) to mid-term (7-15 days) weather forecasts will be useful for kiwifruit growers in Korea for the implementation of timely preventative disease control, as recently demonstrated for the kiwifruit bacterial canker disease (Kim et al., 2018). Over the next 10 to 30 y, long-term adaptation strategies need to be considered. These include replacing kiwifruit cultivars in local orchards with cultivars with higher disease tolerance or different maturity periods to avoid a high disease pressure season in the future (Datson, et al., 2013; Reglinski et al., 2013).

Our study showed that Haegeum, a gold-flesh kiwifruit that normally blooms about 2 weeks earlier than Hayward, is expected to carry significantly lower KBB risks than Hayward, especially in the 2050s-2070s when Hayward was predicted to face the highest KBB pressures. Based on this finding, we suggest that other kiwifruit cultivars with a different maturity such as Haegeum can be an alternative solution to cope with future KBB risks. The feasibility of replacing the major cultivar Hayward with the Haegeum can be supported by a simple economic analysis utilizing currently available information on agrochemical-based KBB control practices and the market price of Hayward and Haegeum kiwifruits. Shin et al. (2004) suggested that the optimum spray program of preventive bactericides for the control of KBB is three consecutive applications at 10-day intervals, starting in early May during the flowering season of kiwifruits. Based on the survey by Kim et al. (2015b), one-time spray with agro-chemicals costs 110 Korean won (KRW) per unit area (3.3 m^2). Looking to the 2060 s, when Hayward was predicted to be exposed to the highest KBB risk, the total costs of controlling KBB with the recommended optimum spray program (Shin et al., 2004) for Hayward and Haegeum are 8,250 KRW and 4,620 KRW per unit area, respectively, with the assumption that kiwifruit growers spray only when severe epidemics (more than 20% disease severity) are expected. Furthermore, the market price of Haegeum is twice that of Hayward as of 2015 (Kim et al., 2015b). However, there is a risk in changing cultivars: during the first 5 years, growers will obtain no income from newly planted Haegeum vines, because it generally takes 5 years for a new kiwifruit vine to reach an average level of kiwifruit production. Nevertheless, the overall income of the growers can be sustained given the above-mentioned advantages of lower agro-chemical spray costs and higher market price of Haegeum compared to Hayward. With this kind of economic evaluation against scientifically-informed adaptation strategies to address the predicted KBB risks, it becomes highly plausible for local government units to proactively implement these strategies, unless other matters, such as consumer preferences that influence market price and pest and disease concerns, conflict with these strategies.

Our results, using multiple models in an integrated way, clearly suggested one of the possible options for a local impact assessment and adaptation study, though there are still several factors further to be improved. Firstly, we used a single climate change scenario from the HadGEM2-AO model, which could not provide the uncertainty information that different GCMs carry. Although we showed the direct comparison results between the KMA scenario and the 11 GCM scenarios downscaled to 7 ASOS stations, it doesn't mean the same results in other locations in the province. Once more high-resolution scenarios from multiple GCMs become available and are utilized in our integrated modeling approach in the near future, better decision-making for adaptation to climate change will possibly be realized by accounting for fundamental uncertainty inherent from the GCMs (Mathukumalli et al., 2016; Ouma et al., 2016). Secondly, the uncertainty from individual biophysical models should be addressed, which results in low reliability of the models. The main causes of the model uncertainty include lack of integration of non-climatic confounding factors in modeling and insufficient calibration and validation due to limited ground-truth data. As more location-specific ground-truth data are secured through experiments and regular surveys, more reliable models can be used for the local impact studies. Lastly, our results should be taken with caution due to the limited factors considered for the integrated modeling. There are considerable uncertainties accounting for all of the factors affecting the host-disease dynamics, some of which may be impossible to project with currently available knowledge and technologies. For example, a range of environmental factors not directly considered by the models, such as elevated CO^2 concentrations, soil fertility, and other weather variables, might affect the biophysical interactions in the future. Therefore, a comprehensive mechanistic modeling approach that includes the biophysical responses of the host plant, the microbial pathogen, and their interaction with environmental factors can be an option for future research. In addition, more input information should be gathered in order to increase the overall reliability of the final results, including the creation of high-resolution maps for soil types, land use, plant cultivar, and additional meteorological variables, after which the results can be used to generate practical agricultural advice and policies by local government units (Geerts et al., 2006; Tuck et al., 2006).

In this study, we presented for the first time the local impact assessment and adaptation study of climate change on a plant disease epidemic using the integrated modeling approach with multiple models. The resulting high-resolution maps for future KBB epidemics, in particular, will ensure and enhance the usability of our results in the development of local government policies and adaptation strategies for local communities (Roberts, 2008). Using the Climate Suitability Model for kiwifruit, we found that suitable areas for kiwifruit cultivation in Jeonnam province gradually increase over future periods. Through adoption of the Pss-KBB Risk Model and linking it with the Chill-day Model, we also revealed that as the flowering dates of kiwifruit became earlier through 2100, the potential risk of severe epidemics of KBB resulted in location-specific, periodic fluctuations in future periods. Notably, KBB risks throughout Jeonnam province continued to increase and peaked in the 2060s, then drastically decreased in the 2080s, a shift that was highly correlated with corresponding climatic conditions. To relieve future KBB pressures, a potential, scientifically-informed, long-term adaptation strategy using a cultivar of kiwifruit with a different maturity period was investigated using the integrated modeling solution, resulting in the identification of the Haegeum cultivar as an alternative kiwifruit vine that will experience less KBB pressure over the coming decades. As this kind of integrated modeling platforms are developed and continuously improved with more quality-controlled data and more reliable modeling algorithms, local policymakers and stakeholders will be able to prepare more realistic, rational adaptation strategies to cope with the upcoming threats of climate change based on the evidence-based scientific results. To ensure this, there are many follow-up researches necessary in the near future, as our results directly point that urgent necessity.

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