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Analysis of social welfare impact of crop pest and disease damages due to climate change: a case study of dried red peppers

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Climate change can affect agricultural production both directly and indirectly. The direct impact is through climate change itself while the indirect impact is through the outbreak of pests and diseases (P&D) affected by climate change. We measured the difference in social welfare change of dried red peppers in monetary values between these two effects based on constructed three models. In the P&D damage model, the effects of climatic factors on P&D damages were analyzed. In the yield model, the direct and indirect effects of climatic factors on the dried red pepper yields were analyzed. Lastly, the effect of rising temperatures on the social welfare of dried red peppers was measured in monetary values using the equilibrium displacement model (EDM). As a key result, although these rising temperatures increase the yields and social welfare, there are differences in social welfare change between with and without P&D damages, and the difference increases over time. This implies that global climate change can affect agricultural production around the world, which can affect food security around the world beyond changes in crop prices and social welfare. So rigorous pest control and damage predictions are needed.

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Introduction

Agricultural activities have been dominated by natural and climatic conditions ever since humans began settled lives after leaving their hunting and gathering lives behind about 10,000 years ago. However, the recent rapid emergence of abnormal climate is expected to have new impacts on crop productivity and supply and demand stability. According to the National Institute of Meteorological Sciences (Kwon et al., 2020), the average global temperature is expected to rise by 3.6 °C (1.9–5.2 °C depending on the degree of greenhouse gas (GHG) emissions) by the end of the 21st century. This prediction is higher than the previous prediction of 2.5 °C (1.3–3.7 °C) and shows that global warming is accelerating. In addition, by the end of the 21st century, the average annual precipitation in the world is expected to increase by 5–10% compared to the present. In East Asia, the average summer precipitation will increase by up to 20% by the end of the 21st century. Particularly, Min et al. (2020) said that the frequency and duration of high-temperature days are increasing while the frequency and duration of low-temperature days are decreasing due to increased anthropogenic GHG emissions since the 1950s in East Asia, including the Korean Peninsula.

This ongoing climate change can affect crop production both directly and indirectly. First, climate change can directly affect crop productivity or production efficiency (Auffhammer et al., 2012; Cho et al., 2013; Challinor et al., 2014; Choi et al., 2018). Auffhammer et al. (2012) analyzed the effect of drought and extreme rainfall on rice yields in India from 1966 to 2002. They stated that climate change had already had a negative effect on the rice producers and consumers of India. Cho et al. (2013) conducted a spline regression analysis using meteorological data and rice yield panel data at 49 observation points from 1996 to 2011. They found that rice productivity decreased when the average temperature for the rice growing season was higher than 20 °C and that precipitation also had a negative effect on productivity. Challinor et al. (2014) predicted grain production would decrease significantly when the temperature increases by 2 °C or more. Choi et al. (2018) found that climatic conditions cause a statistically significant decrease in vegetable yields. They said that drought and high-temperature damage in spring and heavy rain and typhoon damage in summer and autumn significantly affect the yield of vegetables, so it is necessary to create a vegetable production infrastructure that can prepare for climate change.

Second, climate change may indirectly affect crop yields by increasing pests and diseases (P&D) and weed outbreaks (Lee et al., 2020). Several studies have proven or predicted that climate change increases the occurrence of P&D. For example, Jeong and Kim (2014) studied the relationship between climatic factors (e.g., the number of days of precipitation, precipitation, daylight hours, and temperature) and the five different kinds of major rice P&D damages using panel data from eight provinces in South Korea from 1991 to 2011. They found that specific climatic factors affect the occurrence area of particular rice P&Ds. Pareek and Meena (2017) said that the number of pests will rise with every degree the global temperature rises and that this increase in temperature would affect crop pest insect populations in several ways such as extending their geographical range, increasing their over-wintering, and changing their population growth rate. Kim et al. (2017) constructed a ginseng P&D damage function to measure the effect of climatic factors on ginseng P&D outbreaks and demonstrated that climatic factors positively affect P&D damage. Kim and Kim (2017) analyzed the effect of climatic factors such as temperature, precipitation, and humidity on rice P&D damage and found that the effect is valid. Skendzic et al. (2021) said that the main drivers of climate change (increased atmospheric CO_2 and temperature and decreased soil moisture) might significantly affect the population dynamics of insect pests and thus the percentage of crop losses. They stated that temperature has an important role in pest metabolism, metamorphosis, mobility, and host availability and determines the possibility of changes in pest population and dynamics. They also mentioned that P&Ds of different crops, such as wheat, rice, and maize, which are grown in different regions, are affected by different climatic conditions.

The outbreak of P&Ds is an exogenous shock that may lead to changes in social welfare due to changes in market prices and quantities. Several studies have calculated or analyzed the effects of P&Ds on social welfare in monetary value. For example, Oliveira et al. (2013) estimated the production losses of major crops grown in Brazil and calculated the economic losses caused by the purchase of insecticides to control insect pests and the medical expenses of humans damaged by these insecticides. Lee (2015) conducted an economic welfare analysis reflecting the exogenous impact of the pork market caused by foot-and-mouth disease (FMD) from 2010 to 2011. Lee (2015) measured not only the damage caused by mass culls due to FMD but also the additional welfare changes, with changes in the market equilibrium point for each production stage of pork and its substitutes (beef and chicken), caused by related government policies and reduction of consumer confidence. Letourneau et al. (2015) estimated the welfare changes in markets for squashes and cucumbers caused by biodiversity changes associated with the biological control of pests in Georgia and South Carolina. Using meta-analyses, they demonstrated a key framework that natural scientists could use for their studies and developed the process in terms of economic theory. Daniels et al. (2017) measured the monetary value of natural predators for biological pest control in pear production. They constructed an ecological simulation model with a production function considering the predator-prey dynamics between the pest insects and their natural enemies. They quantified the effect of reduced natural predator numbers on the net farm income within an economic model. Hwang (2020) measured the impact of a decrease in supply caused by the mass cull of pigs due to African Swine Fever (ASF) in September 2019 and a decrease in consumption due to a contraction in consumer confidence.

As stated above, direct and indirect climatic factors, through P&D damages, affect crop production. In addition, these influences affect social welfare by changing the price and quantity of crops. Therefore, this study intends to comprehensively analyze the sequential effects of climate change, P&D damage, production change, and social welfare change for a specific crop.

This sequential process also appears in the production and market of dried red peppers, one of the staple seasoning vegetables of Korea. Dried red peppers have the largest vegetable cultivation area in Korea, with an area of 18.7% in 2015. However, its productivity changes relatively easily compared to food crops. Since it is an open-field vegetable, it is more vulnerable to climatic factors and damage from P&Ds such as phytophthora blight, anthrax, soft blight, and viral diseases.[1] For instance, Koung (2014) presents an analysis result that an increase in temperature can help red pepper growth, but its production decreases by 17% when the temperature rises above 30 °C. Shin and Yun (2011) analyzed that the occurrence of anthrax in all regions of Korea would rise in the future using forecasted meteorological data from 2011 to 2100. Kim et al. (2015) analyzed the relationship between anthracnose disease incidence in red peppers and red pepper yield in fields and rain shelters. They concluded that the yield decreased as anthracnose diseases occurred in both conditions. Dried red peppers have decreased yield due to heavy rains, typhoons, and more occurrences of anthrax in the summer of 2020. This enlarged the price instability

Table 1 Cultivation area and income of major open-field vegetables in Korea.

Major open-field vegetables	Annual cultivation area (2010–2019)		Area rank	Annual income (2010–2019)	Income rank
	ha	%		KRW/10a	
Dried red pepper	36,960	22.2%	1	2,466,623	3
Garlic	25,144	15.1%	2	2,583,625	2
Onion	21,565	13.0%	3	1,963,373	8
Autumn kimchi cabbage	13,671	8.2%	4	1,767,258	9
Spring kimchi cabbage	12,276	7.4%	5	1,053,151	16
Spring radish	11,005	6.6%	6	1,097,502	15
Welsh onion	9785	5.9%	7	1,982,641	7
Autumn radish	6570	3.9%	8	1,498,504	11
Cabbage	6545	3.9%	9	1,163,139	14
Highland kimchi cabbage	5094	3.1%	10	1,231,392	13
Shallot	4736	2.8%	11	2,420,928	4
Spinach	3174	1.9%	12	1,639,279	10
Watermelon	2553	1.5%	13	2,179,130	5
Highland radish	2502	1.5%	14	1,339,884	12
Carrot	2449	1.5%	15	2,061,540	6
Ginger	2366	1.4%	16	2,849,005	1
Total	166,394	100.0%			

Source: Rural Development Administration (RDA) (2010–2019), Statistics Korea (KOSTAT) (2010–2019).

causing the wholesale price of red pepper powder to rise by 67% compared to the 5-year normal price (Kim, 2020). Thus, the harvest of dried red peppers, directly and indirectly, affected by climatic factors, has a substantial economic ripple effect in production and distribution and may further affect consumption. So, ongoing climate change is expected to have a consequential economic impact on the dried red pepper market.

Accordingly, this study aims to analyze the effects of climate change on the social welfare of dried red peppers while considering P&D damages. The research process is divided into three steps with three models (See "Empirical models").

The key difference of this study from previous studies is that it comprehensively analyzes the sequential effects of climate change, P&D damage, change in production, and change in social welfare for a specific crop. Although other studies analyzed the direct impact of climate change on crop production or the indirect impact of P&D damage on production, studies considering both impacts comprehensively are scarce. Furthermore, no studies are measuring such a sequential process of climate change to the social welfare of a crop, so the monetary impact of climate change on agricultural social welfare currently cannot be measured. Therefore, this study defines itself by considering its sequential effect comprehensively and by presenting the impacts of climate change through P&D damage on social welfare regarding monetary values.

The flow of this study is as follows. "Introduction" summarizes the background of dried red pepper and its P&Ds. "Methods" explains the data used for analysis with three models: P&D model, yield model, and equilibrium displacement model (EDM). In "Results", the results of the three models are presented. The final section presents "Conclusions".

Methods
Study materials
Dried red peppers in Korea. With an annual red pepper consumption of 2.0–2.5 kg per person, Koreans are the biggest consumers of red peppers in the world; other major countries with high red pepper consumption, Hungary, the U.S., and Japan, consume 200 g, 50 g, and 20 g of red peppers each year, respectively (Lee et al., 2016). The two main red pepper consumption methods are making them into a powder, usually called dried red

peppers, traditionally used for seasoning, and eating them raw, usually called green peppers. Koreans consume more dried red peppers than green peppers. Dried red peppers are grown in open fields and are the most important source of income for farmers as they account for the largest proportion of cultivation area at 22.2%. Furthermore, they produce the third highest income per 10a among the major open-field vegetables (Table 1).

P&Ds of dried red peppers. Grown in open fields, dried red peppers are less durable in the wind than other crops. They are vulnerable to both dryness and humidity, making them very difficult to grow due to infectious soil diseases such as phytophthora blight (Lee, 2011). In recent years, while the cultivation area of dried red peppers has remained at a constant level, the production of dried red peppers has been relatively unstable (Fig. 1), which may result from increased P&D damages caused by current global warming. Therefore, we examined the outbreak characteristics of red pepper P&Ds.

There are 29 kinds of P&Ds that damage Korean red peppers, and the four most damaging P&Ds to dried red pepper cultivation are *phytophthora blight (PB), anthrax (Ath), viral diseases (VD)*, and *tobacco moths (TM)* (Kwon and Lee, 2002; Yang et al., 2020).[2] Since these P&Ds have different occurrence conditions, it is necessary to review and examine the occurrence conditions of these four P&Ds through previous studies and the P&D damage trends by periods in recent years using data provided by the National Crop Pest Management System (NCPMS) of the Rural Development Administration (RDA).

The followings are the occurrence conditions of the four major P&Ds.

First, *PB* is a disease caused by *Phytophthora capsici* that inflicts substantial damage every year in continuous cropping lands. It occurs due to a high density of germs and low soil fertility, and it is not easy to control solely with chemical solutions. It starts from the beginning of June after planting and flourishes during the rainy season from July to August. As *Phytophthora capsici* are hydrophilic and semiaquatic bacteria, rainfall and the number of days with precipitation are decisive factors in the occurrence of *PB*, which spreads more severely at high temperatures (Jang, 2002; Yang et al., 2020).
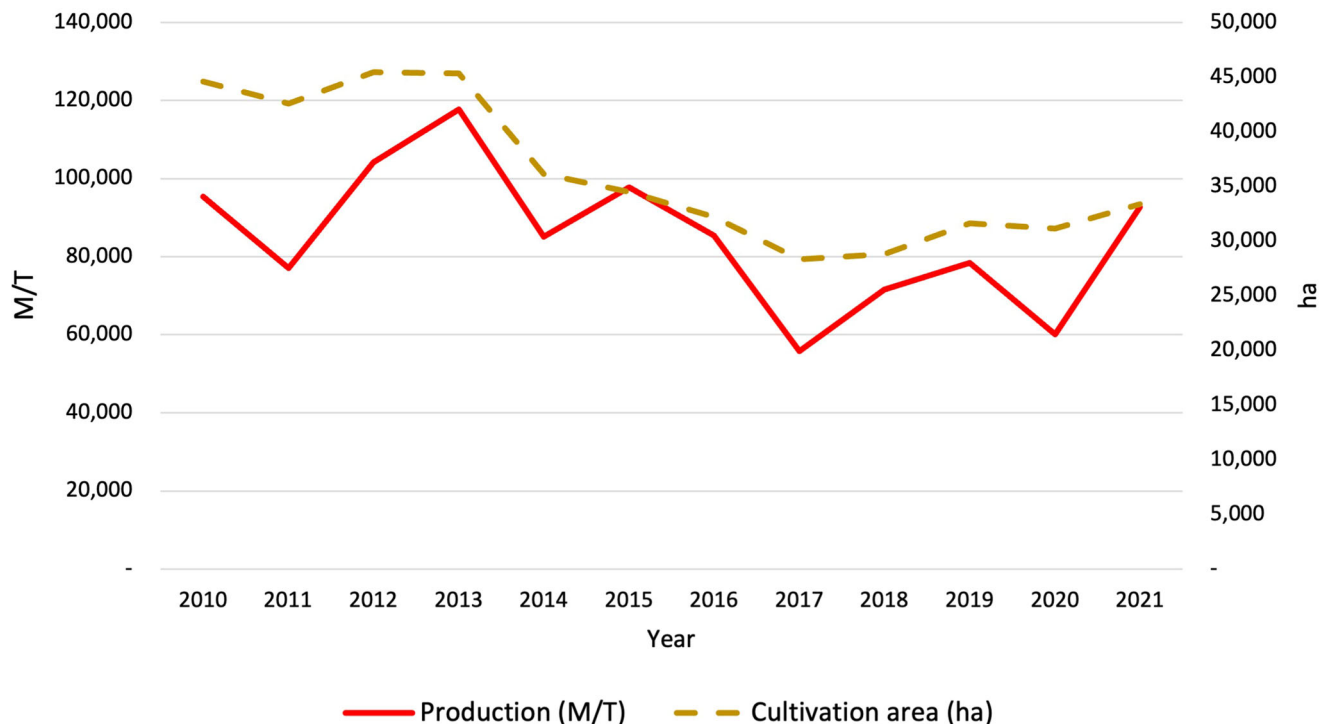
Fig. 1 Cultivation area and production of dried red peppers in 2010–2021. The production by years fluctuates while the area has stable trends by years.

Second, *Ath* is the most problematic disease along with *PB*. It starts as a small spot that is difficult to detect by eye in mid-to-late June and increases rapidly during the rainy season when the temperature and humidity are high. It shows its peak outbreak in mid-August (Jang, 2002; Yang et al., 2020).

Third, *VD* are much more damaging in open-field cultivation than in greenhouse cultivation, and 80% of the damage is due to transfer by aphids (Yang et al., 2020).[3] Bae (1999) stated that the activities of aphids begin in dry mid-April, the early stage of red pepper growth, and poor growth of red peppers due to the lack of nutrients after their mid-stage growth causes severe *VD* damage as the activities of aphids increase.

Fourth, the caterpillars of *TM* dig up the leaves, fruits, and buds of dried red peppers or make holes in the fruits, which secondarily causes bacterial soft rot. *TM* begin their metamorphosis around June, and their damage occurs in August but most severely in early September (Yang et al., 2020).

Next, we examined recent trends of each P&D damage over the past eight years (2014–2021) using data from NCPMS.[4] The data were collected eight times at 15-day intervals between June 1st and September 16th every year. *PB* and *VD* are investigated through damaged heads rate (DHR),[5] and *Ath* and *TM* are investigated through damaged fruits rate (DFR).[6] The following four figures are graphs showing the damage rate of each P&D at the investigation dates from 2014 to 2021 (Fig. 2).

Empirical models. The purpose of this study is to comprehensively analyze the sequential process of climate change, P&D damage, change in production, and change in social welfare for dried red peppers. In order to achieve this, the research process is divided into three models sequentially.

First, a P&D damage model is established to analyze the impact of climate change on P&D damages. The four major P&D damages analyzed in this model are *PB*, *Ath*, *VD*, and *TM*. Each kind of P&D damage is affected by different climatic factors, so different climatic factor variables are used as independent variables for each kind of P&D damage (Fig. 2).

Second, a yield model is established to analyze the direct and indirect effects of climate change on the yield of dried red peppers. Particularly, the indirect effect is analyzed by using the predicted P&D damage values as independent variables.

Lastly, we analyzed the effect of changed yields and production, which are directly and indirectly affected by climate change, on the market price and quantity of dried red peppers and measured the resulting social welfare changes using the EDM. However, climatic conditions mostly stay the same but gradually, and EDM analysis needs a temporary shock from outside the market, such as a crucial disease outbreak or a government policy implementation. In order to measure the impact of continuous climate change, it is appropriate to set a specific scenario and analyze based on it. For this reason, RCP 6.0 temperature change scenarios provided by the Korea Meteorological Administration (KMA) are used for the EDM analysis.[7]

P&D damage model. The purpose of the P&D damage model is to analyze the impact of climate change on P&D damages, so the dependent variables are P&D damage rates and the independent variables are climatic factors and the locations of cities.

The P&D damage rates of *PB*, *Ath*, *VD*, and *TM* provided by NCPMS are used as dependent variables. The P&D damage rate data consist of observation values from eight sessions conducted from June 1st, 2014, to September 16th, 2021. Each observation was made on the first day of each 15-day session. Spatially, these data are collected from 59 cities nationwide, where the data was averaged from the 1657 observation sites. We averaged the data of the 59 cities to construct a panel data set since each observation site varies slightly every session and year.

As independent variables, the longitude and latitude of each city and climatic factors, such as temperature (°C), rainfall (mm), humidity (%), and sunshine hours (hrs), are considered. The climatic factor data provided by the Korea Meteorological Administration (KMA) for each city and the P&D damage observation site locations were spatially interpolated using QGIS.
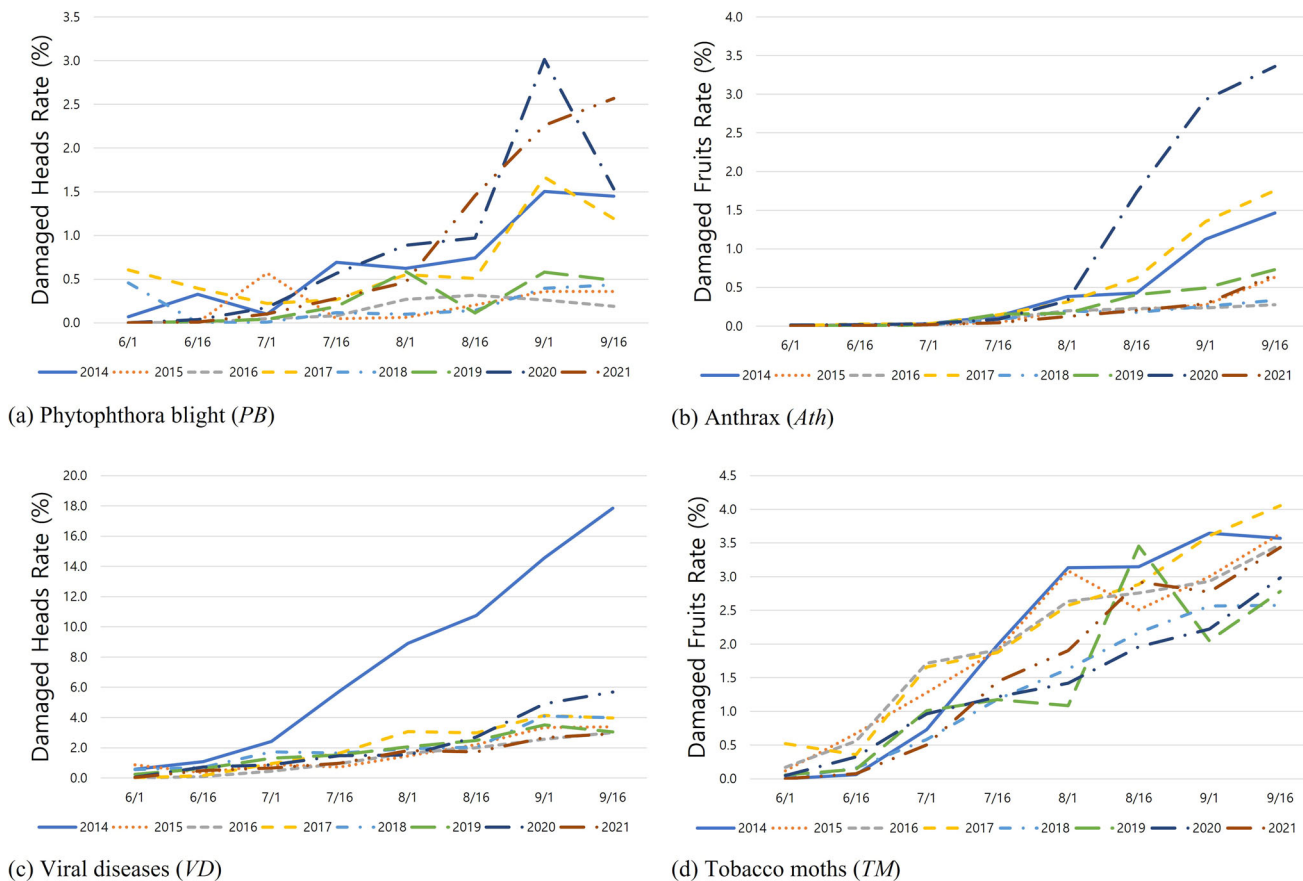
Fig. 2 The damage rates of each of the four P&Ds (2014–2021). a Damaged heads rate of *PB*; **b** Damaged fruits rate of *Ath*; **c** Damaged heads rate of *VD*; **d** Damaged fruits rate of *TM*. The rates tend to be small at the beginning of each year's investigation period and increase later, but each of them records slightly different damage rates for each year.

Summary statistics and descriptions of all of these variables are presented in Table 2.

Since P&D damage does not occur in every city, many observations with a P&D damage rate of 0 occurred. Therefore, it is appropriate to use the left-censored panel Tobit model as the empirical P&D damage model, as shown in the following Eq. (1):

$$Damage_{it}^* = \beta_1 + \beta_2 \, Location_{it}$$
$$+ \beta_3 \, Climate_{it} + \beta_4 \, Avgdev_{climate_{it}}$$
$$+ u_{it} \quad if \, Damage_{it} > 0$$

$$Damage_{it}^* = 0 \quad if \, Damage_{it} \le 0 \quad (1)$$

where the 59 different cities nationwide are represented by $I = 1,2,...,59$ and the 64 different observation sessions from 2014 to 2021 are $t = 1,2,3,...,64$. $Damage_{it}$ denotes the latent P&D damage of each city i at session t, $Damage_{it}^*$ is the P&D damage rate observed, $Location_{it}$ is the latitude and longitude, $Climate_{it}$ represents the climatic factors such as temperature, rainfall, humidity, and sunshine hours (i.e., Avgt, Avgr, Avgh, and Sun), and $Avgdev\_Climate_{it}$ represents deviations of average temperature and humidity from 1970 to 2000 (i.e., Avgt dev and Avgh dev).

The error term u_{it} is

$$u_{it} = \alpha_i + v_{it} \quad (2)$$

where the individual city effect α_i is distributed $N(0, \sigma_\alpha^2)$, and the stochastic disturbance term v_{it} is distributed $N(0, \sigma_\nu^2)$. We assume that α_i is independent of $Location_{it}$, $Climate_{it}$,

$Avgdev\_climate_{it}$, and v_{it}, where $E(\alpha_i \alpha_j) = 0$, $E(\alpha_i v_{it}) = 0$, and $E(v_{it} v_{ij}) = 0$ and in all cases $i \ne j$.

In the panel Tobit model, the random effect estimation method is preferred because there are consistency issues, i.e., incidental parameter problems, for fixed effect estimates unless the time-frame of the panel data is long enough (Wooldridge, 2010; Kim and Langpap, 2016). In this case, the timeframe is not long enough, so a panel Tobit analysis based on the random effect model is performed. However, to overcome the limitation of not considering fixed effects, we applied the Chamberlain random effects (CRE) Tobit model (Wooldridge, 2010), which applies Chamberlain's conditional estimation method by including the group average as additional regressors in the model, providing a consistent way to estimate fixed effects models. We use $Avgdev\_Climate_{it}$ to control group fixed effect by employing average climate factors across the cities from 1970 to 2000 and to control abnormality of climatic conditions by using deviation from the average.

Yield model. For the dried red pepper yield model, the direct and indirect effects of climate change on the yield are analyzed. The dependent variable of this model is the dried red pepper yield, and the independent variables consist of climatic factors as direct effects and P&D damage variables as indirect effects.

The yield panel data provided by Statistics Korea (KOSTAT) are used as a dependent variable. The yield data are the average data by the eight provinces from 2014 to 2021.

As key control variables, the predicted values of the four P&D damage rates are used as independent variables for indirect

Table 2 Summary statistics and descriptions of variables in the P&D damage model (2014–2021).

Variables	Descriptions	Obs	Mean	Std. Dev.	Min	Max
PB	Damage rate of phytophthora blight	2808	0.50	3.02	0.0	78.0
Ath	Damage rate of anthrax	2808	0.38	1.25	0.0	20.1
VD	Damage rate of viral diseases	2808	2.45	7.29	0.0	82.0
TM	Damage rate of tobacco moths	2808	1.79	3.73	0.0	100.0
Longitude	Averaged longitude by each city	2808	127.65	0.80	126.2	129.6
Latitude	Averaged latitude by each city	2808	36.40	0.72	34.6	37.7
Avgt	Avg temperature of each city (°C)	2808	22.35	4.13	0.0	28.9
Avgr	Avg rainfall of each city (mm)	2808	177.74	135.41	0.2	789.1
Avgh	Avg humidity of each city (%)	2808	76.00	8.34	0.0	97.0
Sun	Sunshine hours of each city (hrs)	2808	187.63	50.12	7.6	342.8
Avgt dev	Temperature deviation from the average of 1970–2000 for each city	2808	1.67	3.90	−2.8	27.6
Avgh dev	Humidity deviation from the average of 1970–2000 for each city	2808	2.15	15.24	−20.6	92.0

All the damage rates are averaged by the 59 cities.

Table 3 Summary statistics and descriptions of variables in the yield model (2014–2021).

Variables	Description	Obs	Mean	Std. Dev.
Yield	Yield of dried red pepper (kg/10a)	64	241.78	39.92
PB	Predicted damage rate of PB	64	1.47	0.12
VD	Predicted damage rate of VD	64	4.29	0.35
ATM	Cumulative predicted damage rate of Ath & TM	64	4.99	1.29
Avgt plant	Avg Temp of planting period (Apr)	64	12.54	1.17
Avgt grow	Avg Temp of growing period (May, June & July)	64	21.54	0.66
Avgt harv	Avg Temp of harvesting period (Aug, Sep & Oct)	64	20.06	0.96
Avgr plant	Avg Rainfall of planting period (Apr)	64	93.21	46.47
Avgr grow	Avg Rainfall of growing period (May, June & July)	64	144.29	49.89
Avgr harv	Avg Rainfall of harvesting period (Aug, Sep & Oct)	64	160.55	53.32
Sun plant	Sunshine hours of planting period (Apr)	64	217.44	29.14
Sun grow	Sunshine hours of growing period (May, June & July)	64	206.41	17.25
Sun harv	Sunshine hours of harvesting period (Aug, Sep & Oct)	64	178.20	18.72
Avgt dev plant	Avg temperature deviation of planting period from 1970 to 2000 (Apr)	64	1.45	1.47
Avgt dev grow	Avg temperature deviation of growing period from 1970 to 2000 (May, June & July)	64	1.90	2.09
Avgt dev harv	Avg temperature deviation of harvesting period from 1970 to 2000 (Aug, Sep & Oct)	64	1.78	2.16

effects. The predicted values of Ath and TM are combined to prevent multicollinearity problems because their damage rate measurement methods are not only the same as DFR but also have a high correlation.[8]

As the remaining independent variables for direct effects, average temperature and average rainfall data provided by the KMA are used. These variables are divided into three growth periods, the planting period (April), the growing period (May–July), and the harvesting period (August–October), since the climatic factors of each growth period may affect the yield differently. We refer to Lee and Yang (2017) and Lee et al. (2020) for setting up the yield model and selecting climate variables. We also checked for multicollinearity among the seasonal climate variables and found that the correlation coefficients between the variables ranged from 0.05 to 0.58 in absolute value, and the average VIF (Variance Inflation Factor) was 4.83 (less than 10), indicating that multicollinearity is not a concern (Vittinghoff, 2005).

Table 3 shows a summary of the statistics and descriptions of all these variables.

The empirical yield model is shown in the following Eq. (3):

$$Yield_{it} = \beta_1 + \beta_2 \widehat{Damage}_{it} + \beta_3 Climate_{it} + \beta_4 Avgdev\_climate_{it} + u_{it}$$

(3)

where $i = 1,2,...,8$ represents the eight different provinces, $t = 1,...,8$ is the eight years from 2014 to 2021, $Yield_{it}$ is the dried red pepper yield, $\widehat{Damage}_{it}$ is the predicted P&D damages (i.e., PBVD

and ATM), $Climate_{it}$ is averages of temperature, rainfall, and sunshine hours for each period, and $Avgdev\_climate_{it}$ is average deviations of climate factors (see Table 3).

We used a fixed effect panel model in this yield model, unlike in the P&D damage model. In short panel data,[9] the estimates obtained from fixed and random effect models may be significantly different. The yield model of this study rejects the null hypothesis at a 5% significance level in the fixed effect model (p-value: 0.0179) while the null hypothesis cannot be rejected at a 5% significance level as a result of a Breusch and Pagan multiplier test for random effects. Therefore, the fixed effect model is used for the yield model.

Equilibrium displacement model. The equilibrium displacement model (EDM) is one of the comparative static analysis methods used to analyze the effect of exogenous factors on endogenous variables. In other words, EDM simulates change rates of price and quantity, which are endogenous variables, when the market equilibrium of an item moves to a new point due to changes in external conditions. For example, Lusk and Anderson (2004) analyzed the effect of country-of-origin labeling (COOL) on the welfare of participants in the livestock sector by constructing an EDM and conducted a sensitivity analysis to examine how the costs of COOL affect the welfare of the market participants. Okrent and Alston (2012) attempted to encourage the consumption of healthy food and discourage the consumption of unhealthy food. They used EDM to estimate the impact of hypothetical farm commodity and retail food policies on the

economic welfare of other alternatives to reduce obesity. In this study, the change in the social welfare of dried red peppers is measured by analyzing the effect of climate change and P&D damages on the price and quantity of dried red peppers.

For EDM analysis, it is necessary to make assumptions about the price elasticities of supply and demand and the initial values of price and quantity. It is because EDM analysis measures the change rates of endogenous variables through the total derivative of functions. For this reason, the initial price is assumed to be 9140 KRW/kg (OASIS of Korean Rural Economic Research Institute (KREI), 2014–2021)[10] and the initial quantity is assumed to be 74,672 M/T (Statistics Korea (KOSTAT), 2014–2021). The price elasticity of supply is assumed to be $0 \sim 0.2$ with the review of Lee et al. (2013), Min et al. (2022), and Lee et al. (2011)[11], and the price elasticity of demand is assumed to be $-0.16 \sim -0.24$ by referring to Choi (2017), and Kim et al. (2000) (Table 4). Since the price elasticity of demand presented in previous studies is somewhat different, we conducted a sensitivity analysis in EDM analysis.

In general, EDM analyzes the effects of large changes outside the market. In order to measure the impact of continuous climate change, it is appropriate to set a specific scenario and analyze based on it. In this study, the RCP 6.0 temperature change scenario by three growth periods of dried red peppers over the next three decades is used for EDM (Table 5).

The following three functions are empirical system equations for EDM analysis:

$$Q^S = f(P|D(T), T) \qquad (4)$$

$$Q^D = g(P|Y) \qquad (5)$$

$$Q^S = Q^D \qquad (6)$$

where Q^D, Q^S and P represent the demand, the supply, and the wholesale price of dried red peppers, respectively. Equation (6) represents the equilibrium condition of the market. D and T represent P&D damage and temperature change, which are exogenous variables that affect the supply of dried red peppers,

and D is a function of T. Y represents an exogenous variable that affects demand.

The above three equations can be transformed into total derivative forms, which are the linear combination of the change rates and elasticities of each variable. The total derivative of the function (4) is in the following Eq. (7):[12]

$$EQ^S = \varepsilon_P \cdot EP + (\varepsilon_D \cdot \beta_T \cdot ET + \varepsilon_T \cdot ET)$$
$$= \varepsilon_P \cdot EP + K \qquad (7)$$

where $EQ^S = \Delta Q^S / Q^S$, $EP = \Delta P / P$, $ET = \Delta T / T$,

$$\varepsilon_P = (\Delta Q^S / Q^S) / (\Delta P / P),$$

$$\varepsilon_D = (\Delta Q^S / Q^S) / (\Delta D / D),$$

$$\beta_T = (\Delta D / D) / (\Delta T / T),$$

$$\varepsilon_T = (\Delta Q^S / Q^S) / (\Delta T / T)$$

K is the exogenous shock that shifts the supply curve. K's first term $\varepsilon_D \cdot \beta_T \cdot ET$ is the indirect effect of temperature change on the yield of dried red peppers, and K's second term $\varepsilon_T \cdot ET$ is the direct effect of temperature change on the yield.

Equation (5) also can be transformed to a total derivative form as Eq. (8):[13]

$$EQ^D = \eta_P \cdot EP + U \qquad (8)$$

where $\eta_P = (\Delta Q^D / Q^D) / (\Delta P / P)$,

$$U = external\ shock\ of\ demand$$

The total derivative form of function (6) is as follows:[14]

$$EQ^D = EQ^S = EQ \qquad (9)$$

Based on Eq. (9), Eqs. (7) and (8) can be expressed by a system of two equations as follows:

$$\begin{cases} EQ = \varepsilon_P \cdot EP + K \\ EQ = \eta_P \cdot EP + U \end{cases} \qquad (10)$$

In order to obtain the change in equilibrium price and quantity through EDM, the unknowns EQ and EP must be solved. The solution values of EQ and EP can be expressed as functions of the exogenous variables K and U and the given parameter η_P as follows:

$$EQ = \varepsilon_P \cdot EP + K, \quad EP = \frac{K - U}{\eta_P - \varepsilon_P} \qquad (11)$$

where $-1 < \eta_P < 0$ and $0 < \varepsilon_P < 1$.

Dried red peppers are one of the agricultural products generally recognized as essential goods, so it is assumed that the price elasticity of demand η_P is more than -1 and less than 0, and the price elasticity of supply ε_P is more than 0 and less than 1. Thus, when temperature change exerts an exogenous impact on the production of dried red peppers, EQ and EP change as

Table 4 Assumption of parameters for EDM.

Parameters	Values	References
Yield (A)	241.8 kg/10a	KOSTAT (2014 ~ 2021)
Cultivation Area (B)	30,884 ha	KOSTAT (2014 ~ 2021)
Total production ($Q_0 = A \times B$)	74,672 M/T	KOSTAT (2014 ~ 2021)
Price (P_0)	9140 KRW/kg	KREI OASIS (2014 ~ 2019)
Price elasticity of supply	0 ~ 0.2	Lee et al. (2013), Min et al. (2022), Lee et al. (2011)
Price elasticity of demand	−0.16 ~ −0.24	Choi (2017), Kim et al. (2000)
Exogenous shock of demand (U)	0	(Assuming no demand shock)

Table 5 Average temperature change under RCP 6.0 scenario over the next decades.

Year	Average temperature change under RCP 6.0 by three growth periods		
	Planting period (Apr)	Growing period (May, June & July)	Harvesting period (Aug, Sep & Oct)
Present (2014–2021)	12.5	21.5	20.1
Next decade (2030)	12.1 (−0.4)	22.4 (+0.9)	21.3 (+1.2)
Next two decades (2040)	13.8 (+1.3)	22.3 (+0.8)	21.9 (+1.8)
Next three decades (2050)	14.1 (+1.6)	24.2 (+2.7)	21.3 (+1.2)

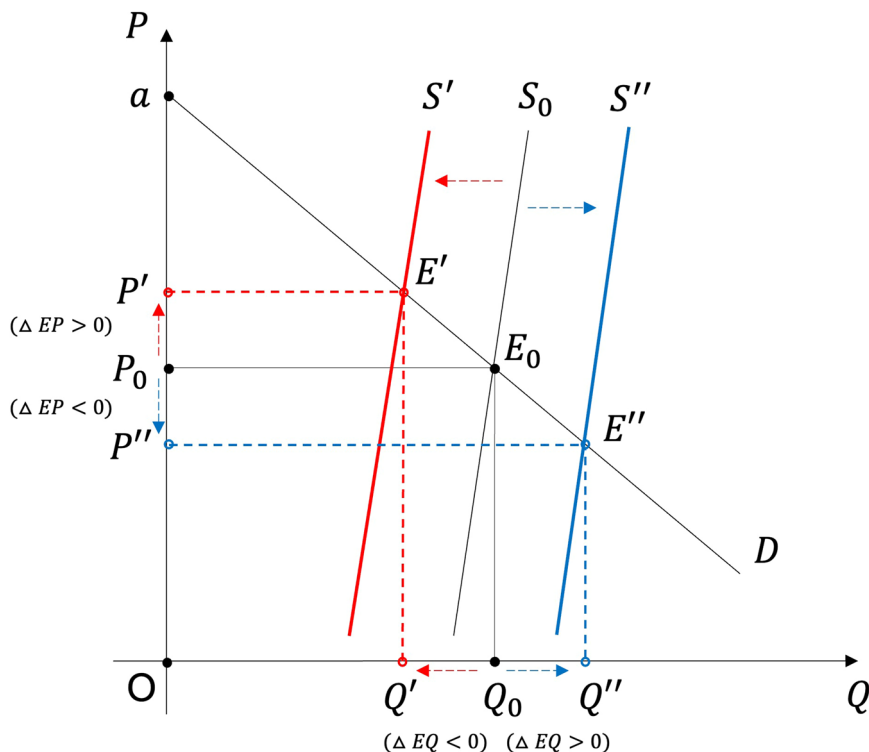Source: Korea Meteorological Administration (KMA).

Fig. 3 The shifts in the supply curve of dried red peppers due to temperature change. The social welfare decreases as a supply curve moves toward left and increases as it moves toward right.

follows:

$$dEQ/dET = (\varepsilon_D \cdot \beta_T + \varepsilon_T)\left(\frac{\eta_P}{\eta_P - \varepsilon_P}\right), \quad dEP/dET = (\varepsilon_D \cdot \beta_T + \varepsilon_T)/(\eta_P - \varepsilon_P).$$

(12)

Temperature rise increases P&D damage (Jeong and Kim, 2014; Pareek and Meena, 2017; Kim et al., 2017; Kim and Kim, 2017) and dried red pepper production decreases as P&D damage rises (Kim et al., 2015). That is, $\beta_T > 0$, $\varepsilon_D < 0$. However, since the direct effect of temperature rise may increase or decrease dried red pepper production, the change direction of EQ and EP is unknown before empirical analysis.[15] This is shown in Fig. 3.

Given the direction and the amount of change in the supply curve S_0, the difference between the changed social welfare ($\square Q'E'E_0Q_0$ or $\square Q_0E_0E''Q''$) and the initial social welfare ($\square OP_0E_0Q_0$) can be calculated based on the temperature change scenarios in Table 5. The direction and amount of change in S_0 is determined based on the analysis results of the P&D damage model and the yield model, which will be shown in the next section.

Results

The estimation results for the three empirical models are presented below. In the estimation results of the P&D damage model and the yield model, we focus more on the sign and significance of the climatic variables rather than describing all the coefficient values since this study aims to measure changes in the social welfare of dried red peppers caused by climate change.

Result of P&D damage model. The estimation results of the P&D damage model are shown in Table 5, which shows the marginal effects of each climatic variable on each of the four P&Ds.

First, the PB damage rate is significantly affected by sunshine hours (Sun), temperature deviation ($Avgt\ dev$), and humidity

deviation ($Avgh\ dev$). More specifically, the rate increases as temperature compared to the average year (1971–2000) increases and decreases as humidity compared to the average year and sunshine hours increase.

For the Ath damage rate, average temperature ($Avgt$) and its square term ($Avgt^2$), average humidity ($Avgh$), temperature deviation ($Avgt\ dev$), and $Avgh\ dev$ affect the rate significantly. Since $Avgt^2$ has not only a positive impact but both $Avgt^2$ and $Avgt$ are also significant, the Ath damage rate has a minimum value at 30.3 °C and then increases again.

Lastly, for VD and TM damage rates, $Avgt$, $Avgt^2$, $Avgh$, sunshine hours (Sun), $Avgt\ dev$, and $Avgh\ dev$ have significant effects on the rates. Like Ath damage rate, VD and TM damage rates also have minimum values at 37.5 °C and 28.6 °C, respectively, since their $Avgt^2$ variables are not only positive but both $Avgt^2$ and $Avgt$ are significant. They increase as temperature compared to the average year ($Avgt\ dev$) and average humidity ($Avgh$) increase (Table 6).

Result of yield model. The estimation results of the yield model, which takes into account climatic factors as the direct effects of climate change and the predicted P&D damage values as the indirect effects of climate change, are shown in Table 7.

As shown in the yield model analysis results, the temperature of the planting period and the harvesting period have positive effects on the yield, and the temperature of the growing period has a negative effect on the yield. Rainfall of all periods has significant effects on the yield. In detail, when the average temperature of the planting and harvesting periods increases by 1 °C, the yield increases by 25.3 kg and 47.7 kg per 10 a, respectively. When the rainfall increases by 10 mm, the yield of the planting period increases by 2.5 kg per 10 a while the yields of the growing period and the harvesting period decrease by 2.5 kg and 2.8 kg per 10 a, respectively.

Table 6 Analysis results of the P&D damage model.

Variables	PB	Ath	VD	TM
Longitude	0.173 (0.122)	0.063 (0.048)	0.586 (0.470)	−0.346 (0.783)
Latitude	−0.255* (0.134)	−0.064 (0.053)	0.177 (0.509)	−1.724* (0.897)
$Avgt^2$	−0.004 (0.003)	0.005*** (0.001)	0.011* (0.007)	0.010*** (0.003)
Avgt	0.102 (0.119)	−0.303*** (0.048)	−0.826*** (0.269)	−0.571*** (0.132)
Avgr	0.000 (0.001)	−0.000 (0.000)	−0.001 (0.001)	−0.001 (0.001)
Avgh	0.027* (0.015)	0.029*** (0.006)	0.198*** (0.036)	0.142*** (0.019)
Sun	−0.004** (0.002)	−0.001 (0.001)	−0.008** (0.004)	−0.007*** (0.002)
Avgt dev	0.123*** (0.047)	0.054*** (0.019)	0.323*** (0.109)	0.380*** (0.054)
Avgh dev	−0.037*** (0.014)	0.014** (0.006)	−0.148*** (0.034)	−0.118*** (0.019)
_cons	−13.922 (15.250)	−3.331 (6.064)	−79.941 (57.828)	107.391 (95.632)
sigma_u_cons	0.536*** (0.083)	0.211*** (0.036)	2.522*** (0.275)	5.445*** (0.605)
sigma_e_cons	2,964*** (0.040)	1.190*** (0.016)	6.694*** (0.090)	3.268*** (0.044)
rho	0.032*** (0.009)	0.031*** (0.010)	0.124*** (0.024)	0.735*** (0.044)
N	2808	2808	2808	2808
chi-square	25.006	199.320	106.838	152.527

Values in parentheses are standard errors.
*, **, and *** represent statistical significance at α = 10%, α = 5%, and α = 1%, respectively.

Table 7 Analysis results of the yield model.

Variables	Coefficient	Std. Err.
PB	−244.965*	(137.840)
VD	−7.092	(50.750)
ATM	−1.652	(29.490)
Avgt plant	25.254	(22.339)
Avgt grow	−13.014	(24.983)
Avgt harv	47.745	(30.202)
Avgr plant	0.251**	(0.121)
Avgr grow	−0.248**	(0.121)
Avgr harv	−0.281*	(0.146)
Sun plant	−0.705*	(0.390)
Sun grow	0.498	(0.463)
Sun harv	−0.807	(0.679)
Avgt dev plant	−27.791	(21.862)
Avgt dev grow	29.327	(25.761)
Avgt dev harv	−20.975	(18.775)
Year of 2015	−8.512	(25.653)
Year of 2016	−51.888	(49.182)
Year of 2017	−29.352	(19.525)
Year of 2018	2.687	(19.304)
Year of 2019	−32.987	(54.414)
Year of 2020	71.659	(46.058)
Year of 2021	38.611	(35.098)
_cons	−77.675	(481.860)
N	64	
F statistics	12.57	
p-value	0.0179	

*, **, and *** represent statistical significance at α = 10%, α = 5%, and α = 1%, respectively.

Although the signs of *Avgt* coefficients are not significant, the directions are reasonable because, in Korea, the growing season is in summer, when the temperature peaks throughout the year, and the temperature is low in the planting and harvesting seasons, spring and autumn, respectively. Especially, experiments by Koung (2014) showed that red pepper growth varies at a specific temperature. Considering the Korean seasonality and the experimental results of Koung (2014), the temperature sign direction of this model is reasonable.

A notable result is that most of the temperature variables have positive effects on the yield. In contrast, the indirect effects, the predicted values of P&D damages, negatively affect the yield. Since these two kinds of effects are offsetting each other, the sign of the total climate change effect is determined by the greater one. The EDM analysis results examine the net effect of the direct and indirect effects.

Result of EDM. The amount of yield change based on the temperature change scenarios is measured and EDM analysis using these values is conducted to derive the change rates of price and quantity. After that, social welfare changes are measured in monetary values using the assumed price elasticities of supply and demand and initial price and quantity.

Yield change based on the RCP temperature change scenarios. Table 8 measures the amount of yield change based on the three RCP 6.0 temperature change scenarios over the next three decades using the analysis results of the yield model and compares the difference of yield change between with and without P&D damages. In 2030, the yield was 1 kg less with P&D damage compared to without P&D damage. In 2040 and 2050, yields were 18.1 kg and 23.8 kg less with P&D damage than without P&D damage, respectively (see also Fig. 4).

Temperature rise has a positive effect and the predicted P&D damage values have a negative effect on the yield model results, but the yield decreases in all RCP scenarios. Thus, P&D damage offsets the positive effect of the climatic factors and causes more damage. Therefore, the reason for the decrease in the yield is not the direct effect of climate change but the indirect effect caused by P&D damage.

Social welfare change based on RCP temperature change scenarios. The EDM analysis process is shown in Fig. 5. Using the assumed parameters for elasticities of supply (0 ~ 0.2) and demand (−0.16 ~ −0.24) and initial price and quantity, the inverse demand curve can be derived as $P_d = K − b \cdot Q$. The supply curve shifts to the right without P&D damage rather than with P&D damage. As a result, the price with P&D damages (P_B) is higher than the price without P&D damages (P_A), and accordingly, social welfare loss occurs more with P&D damages than without P&D damages ($\square OKE_A \ Q_A$-$\square OKE_B \ Q_B$) ("□" means the area of a rectangle).

Table 9 shows the sensitivity analysis of social welfare change with the price elasticities of demand ranging from −0.16 to −0.24, holding the price elasticity of supply at 0.1 with the changed equilibrium prices and quantities based on the RCP 6.0 temperature change scenario over the next three decades. The

Table 8 Yield change based on the RCP 6.0 temperature change scenario.				
Year	Temp increase (°C) (Apr–Oct)	Yield change (kg/10a)		
		Without P&D damages (A)	With P&D damages (B)	(A-B)
Present (2014 ~ 2021)	18.05	241.8	241.8	-
2030	18.59 (+0.54)	276.3 (+34.5)	275.3 (+33.5)	1.0
2040	19.32 (+1.28)	286.0 (+44.2)	268.0 (+26.2)	18.1
2050	19.89 (+1.84)	302.5 (+60.7)	278.8 (+37.0)	23.8
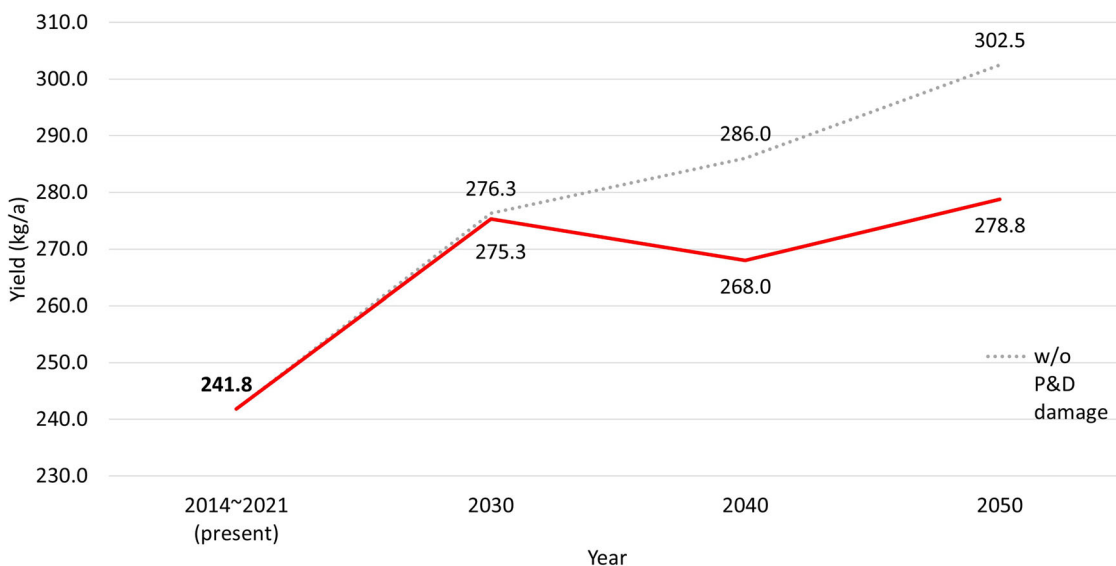
Fig. 4 Difference in yield between with and without P&D damage over the next decades. The difference becomes larger as the temperature increases over time.

results show that when the price elasticity of demand is −0.16, the social welfare loss is 9.3 billion KRW in 2030, 161.5 billion KRW in 2040, and 239.2 billion KRW more in 2050 when it is with damages rather than without P&D damages. When the price elasticity of demand is −0.20, the difference in social welfare is 7.1 billion KRW in 2030, 125.8 billion KRW in 2040, and 183 billion KRW in 2050, respectively. Lastly, when the elasticity is −0.24, the difference is 9.8 billion KRW in 2030, 174.7 billion KRW in 2040, and 251.2 billion KRW in 2050, respectively.[16] In summary, as time passes, the difference in social welfare with P&D damages and without P&D damage increases, and the difference decreases as the price elasticity of demand increases.

Table 10 shows the sensitivity analysis of the price elasticities of supply ranging from 0 to 0.2, holding the price elasticity of demand at −0.2. When the supply elasticity is 0, the social welfare loss is 6.8 billion KRW more in 2030, 116.1 billion KRW more in 2040, and 176.4 billion KRW more in 2050 with P&D damages than without the damages. When the supply elasticity is 0.1, the difference in social welfare is 7.3 billion KRW in 2030, 130.4 billion KRW in 2040, and 186.1 billion KRW in 2050, respectively. When the elasticity is 0.2, the difference is 7.6 billion KRW, 138.2 KRW in 2040, and 191.4 billion KRW in 2050, respectively.

Based on the results of all the climate change scenarios and price elasticity combinations presented above, the loss of social benefits due to direct and indirect damages from climate change and pests ranged from 6.8 billion KRW to 251.2 billion KRW. Comparing this to the total production value of dried red pepper in 2021, which is 694.2 billion KRW at real prices (2015 = 100), the loss of social benefits is estimated at around 1% to 36.2%.

Discussion and conclusions

Recent rapid climate change may affect the productivity of crops and have a new impact on supply stability. Climate change itself can directly affect the production of crops or indirectly affect them by increasing the occurrence of P&Ds. Furthermore, changes in crop production can affect supply and social welfare. Therefore, this study examined the effect of climate change on social welfare by considering the indirect effects of P&D damages.

The analysis target in this study is dried red peppers. The productivity of open-field vegetables fluctuates more easily than food crops due to climatic conditions, and dried red peppers account for the largest cultivation area among the open-field vegetables. In addition, dried red peppers account for a high proportion of farm income and are also major seasoning vegetables for Koreans as they are an ingredient in kimchi. Therefore, changes in dried red pepper production may affect social welfare significantly.

This study goes through three steps. First, a P&D damage model is constructed to measure the effect of climatic factors on P&D damage rates. Second, a yield model is constructed to measure the direct and indirect impact of climate change on dried red pepper production. Lastly, EDM analysis of RCP temperature change scenarios examines social welfare changes in monetary value.

In the P&D damage model, the effect of climatic factors on the damage rates of four major P&Ds, phytophthora blight (PB), anthrax (Ath), viral diseases (VD), and tobacco moths (TM), was analyzed. Since the occurrence conditions differ for each P&D, they were reviewed in advance while considering climatic factors. As the analysis results show, the P&D damages of Ath, VD, and TM have minimum values at 30.3 °C, 37.5 °C, and 28.6 °C, respectively,
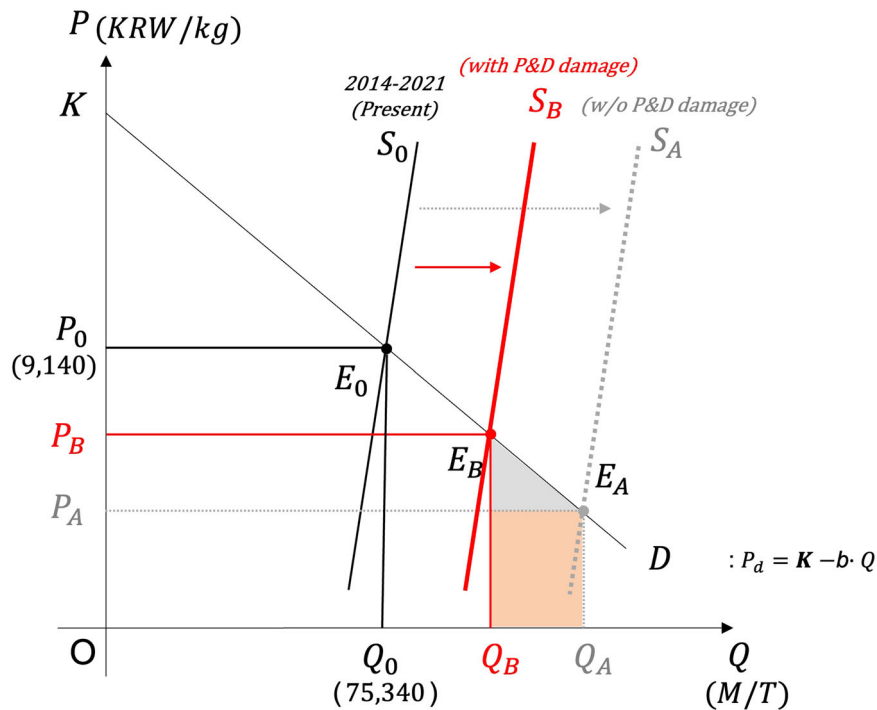
Fig. 5 Change of social welfare due to direct and indirect effects of climate change. Social welfare increases less with P&D damage than without the damage.

Table 9 Sensitivity analysis of social welfare change by demand elasticities (with supply elasticity $\varepsilon_P = 0.1$).

Price elasticity of demand (η_P)	Year	Without P&D damage		With P&D damage		Difference in Q (Q_A-Q_B, M/T)	Difference in social welfare ($\square OKE_A Q_A$-$\square OKE_B Q_B$, 1 billion KRW)
		Changed P (P_A, KRW/kg)	Changed Q (Q_A, M/T)	Changed P (P_B, KRW/kg)	Changed Q (Q_B, M/T)		
−0.16	2030	1215	85,326	1232	85,031	295	9.26
	2040	2953	88,343	3719	82,760	5583	161.53
	2050	402	93,439	534	86,093	7345	239.17
−0.20	2030	2800	85,326	2833	85,031	295	7.12
	2040	4190	88,343	5132	82,760	5583	125.80
	2050	2150	93,439	2761	86,093	7345	182.99
−0.24	2030	3857	85,326	3869	85,031	295	9.81
	2040	5015	88,343	5601	82,760	5583	174.74
	2050	3315	93,439	3416	86,093	7345	251.20

Table 10 Sensitivity analysis of social welfare change by supply elasticities (with demand elasticity $\eta_P = -0.2$).

Price elasticity of supply (ε_P)	Year	Without P&D damage		With P&D damage		Difference in Q (Q_A-Q_B, M/T)	Difference in social welfare ($\square OKE_A Q_A$-$\square OKE_B Q_B$, 1 billion KRW)
		Changed P (P_A, KRW/kg)	Changed Q (Q_A, M/T)	Changed P (P_B, KRW/kg)	Changed Q (Q_B, M/T)		
0.0	2030	2800	85,326	2841	85,031	295	6.77
	2040	4190	88,343	5368	82,760	5583	116.05
	2050	2150	93,439	2941	86,093	7345	176.42
0.1	2030	2800	85,326	2829	85,031	295	7.28
	2040	4190	88,343	5021	82,760	5583	130.39
	2050	2150	93,439	2689	86,093	7345	186.08
0.2	2030	2800	85,326	2822	85,031	295	7.56
	2040	4190	88,343	4832	82,760	5583	138.20
	2050	2150	93,439	2567	86,093	7345	191.36

because their average temperature square terms ($Avgt^2$) are not only positive but both $Avgt$ and $Avgt^2$ are also significant. Additionally, the abnormal climate that will further become severe may increase the P&D damages since all the temperature deviation variables from its normal trends have a significant positive effect.

In the yield model, a notable result is that P&D damage inhibits the positive effect of temperature rise. In other words, despite the positive effect of temperature itself on the yield of dried red peppers, the future yield will not increase significantly because the P&D damages inhibit the positive effect.

Furthermore, the difference in yields between with and without P&D damages increases over time, affecting social welfare change.

The results of EDM analysis show that the difference in yields can affect in difference in social welfare between with and without P&D damages. EDM analysis result shows the social welfare loss with P&D damage tends to increase over time. Based on the results of all the climate change scenarios and price elasticity combinations presented above, the loss of social benefits due to direct and indirect damages from climate change and pests ranged from 6.8 billion KRW to 251.2 billion KRW, which is 1% ~ 36.2% of the total production value of dried red pepper in 2021 (694.2 billion KRW).

The key differences between this study and previous studies are that it analyzes the sequential effects of climate change, P&D damage, change in production, and change of social welfare for dried red peppers and measures the degree of actual damages in monetary values using RCP temperature change scenarios. Previous studies analyzed only the trends of climate change and the marginal effects of climate change on dried red pepper production or focused on only one specific P&D damage, so they are limited in that they do not consider the overall P&D damage of a certain crop. In addition, it was difficult to examine comprehensive damage because no studies considered both the effects of climate change and P&D damage on crop production. In this study, a P&D damage model is constructed, and the predicted values of the P&D damages are used in the yield model as independent variables to consider the indirect impact of climate change.

In summary, although rising temperatures increase the dried red pepper yields and lead to an increase in social welfare, P&D damages inhibit the increase in yield and social welfare, so it is necessary to manage the P&Ds.

This study analyzed dried red peppers in Korea, but the sequential process of climate change, P&D damage, production change, and social welfare change may not be just a problem for dried red peppers in Korea. Rising global temperatures and more intense global precipitation affect insect diapause. They can change pest populations and dynamics to have more impact on crop yields, so more efforts are needed to predict and control P&D damages. Moreover, if this process causes economic losses to major crops worldwide, such as rice in Asia and corn in Western countries, it can have a substantial impact on food security for countries beyond the issue of crop prices and social welfare.

This study only considered a supply-side shock. However, if the decline in demand is greater than the P&D damage, prices may eventually fall or change due to government policies. In other words, the change in the left-shifted demand curve may be larger than the change in the left-shifted supply curve due to the impact of rising temperatures shown in the analysis results of this study. Thus, prices can decrease or be controlled through government price stabilization policies. Since this study did not consider the demand side shock or government policies, future studies are needed to develop these factors further.

Data availability

Notes

1. When pest damage occurs in red peppers, their yield may decrease by at least 15%, at most 60% (Yang et al., 2020).
2. In the terms and conditions of crop insurance operated by Korean agricultural cooperative, PB, Ath, and VD are also compensated for P&D damage as a high priority, with the first grade and the second grade for TM.
3. There are 16 types of VD that occur in red peppers, and 7 of them mainly occur in domestic red peppers (Yang et al., 2020).
4. NCPMS has provided P&D damage rate data since 2014.
5. DHR (%) = {(the number of damaged heads) / (the number of investigated heads)} * 100
6. DFR (%) = {(the number of damaged fruits) / (the number of investigated fruits)} * 100
7. Since RCP 6.0 scenario is the case where the greenhouse gas reduction policy is properly realized (Korea Environment Corporation), this study determines that the RCP 6.0 scenario is the most realistic than the other three scenarios, RCP 2.6, RCP 4.5, RCP 8.5.
8. Variables with a medium ($r > 0.5$) or even high ($r > 0.7$) correlation need to be reduced in the model to avoid multicollinearity problems (Donath et al., 2012). The correlation between Ath and TM is 0.6827.
9. Short panel: $i > t$, long panel: $i < t$ (Gujarati, 2004).
10. https://oasis.krei.re.kr/index.do
11. Since there are no values of supply elasticity for Korean dried red peppers, we reviewed the supply elasticities of Lee et al. (2013), Min et al. (2022), and Lee et al. (2011), where they analyzed subtropical vegetables, rice, and bean and tofu, respectively.
12. Please refer to the equation (A1) in the Appendix for the mathematical induction.
13. Please refer to equation (A2) in the Appendix for the mathematical induction.
14. Please refer to the equation (A3) in an Appendix for the mathematical induction.
15. The change in production directly and indirectly affected by climatic factors is discussed in the analysis results of the yield model in the "Results" section.
16. While we project changes in social welfare due to the direct and indirect impacts of climate change through 2050, we acknowledge that forecast errors will increase as we move further into the future due to limitations in the temporal scope of our data. Therefore, while we believe that the trends over time are reliable, the accuracy of the projected values should be interpreted with caution.

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DH contributed to data analysis and interpretation and manuscript writing and revision; DY contributed to manuscript editing and proofreading; and TK contributed to the overall conceptual design of the manuscript, data interpretation, manuscript writing, and revision. All authors approved the version to be published and agreed to take responsibility for all aspects of the work.

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The authors declare no competing interests.

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