

Article



# The Effects of Climate Change on Pine Wilt Disease in South Korea: Challenges and Prospects

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Abstract: This study assessed the damage and the potential economic threat of pine wilt disease, which is the most common disease caused by forest-integrated pests in Korea. To estimate the rate of damage by pine wilt disease, a structural damage function was implemented. The nonlinear panel probit model and the generalized estimated equation (GEE) were used for the estimation. The estimated damage function and representative concentration pathways (RCP)8.5 data were used to predict the future damage rate by pests caused by climate change. In the assessment of the economic impact on forests, the dynamic optimization model was introduced. The concept of environmental payment was introduced to consider the economic value of non-timber benefits. For the economic analysis, three scenarios were established, i.e., no pest outbreak (baseline), pest infestation (no control), and pest infestation (prevention and control), and the forest management revenues that included the wood and non-wood materials for each scenario were compared. On the basis of the results of the analysis, a simulation was conducted to investigate the changes in forest management revenues according to changes in timber market prices, environmental payments, and climate change. The prediction results confirmed that the future damage by pine wilt disease and the extent of the damaged areas will increase as a consequence of climate change. In addition, the analysis of the economic impact showed that the increase of pest damage caused by climate change will worsen the forest management revenues. As pest damage brought on by climate change is expected to increase uncertainties and economic losses, there is a marked need to review the policies that so far have been focusing only on post-response tasks. In addition to a proper post-incident management, it is necessary to secure the sense of control and stability over the matter through the reinforcement of pre-incident management.

Keywords: climate change; pine wilt disease; GEE; dynamic optimization; SI model

# 1. Introduction

# 1.1. Research Background

The effects of climate change, such as drought and extreme temperatures, are progressively becoming more of a reality. As pest damage is directly or indirectly influenced by environmental conditions such as temperature and precipitation, it is expected that future climate changes will result in increased damage from forest pests and economic loss. Changes in population and occurrence patterns of pests due to climate change can cause direct and indirect environmental and economic losses such as disturbance of forests' ecosystem and decrease of forest owners' income from losing forest productions. According to data from the National Institute of Forest Service, forest pests that were the most damaging to Korean pine forests ) in the 1960s and 1970s were black pine bast scale (*Matsucoccus thunbergianae*) and pine gall midge (*Thecodiplosis japonensis*). Because of intensive control, the damage

from these insects has been greatly reduced since the 1980s. However, after the year 2000, pine wood nematode (*Bursaphelenchus xylophlus*) has appeared as a new source of risk [1]. Increasing vulnerability of the pine trees is due to global warming that accelerates the pest-inflicted damage. When nematodes settle in the host trees, they spread rapidly and block water conductance in the xylem [2]. As a result, the pine needles wilt rapidly due to disrupted tree physiological process, and trees die in less than three month [3].

In 1988, the first case of pine wilt disease, caused by the pine wood nematode, was found in Korea. The major damaged areas were limited to the southern regions, such as Gyeongnam and Jeju, in the 20th century, but the pest has spread to the northern part of the country after year 2010, as the average temperature has increased. According to the Korean forest service, the total damage to forest products caused by pine wilt disease in the last 10 years is estimated to be 8.4 billion won (\$7,489,566). If environmental damages such as the loss of forest carbon sequestration and biodiversity are taken into consideration, the damage is estimated to be more than 1 billion won (\$891,225,900). In addition, an annual average of 75.6 billion won (\$67,394,376) was spent for pest control systems, so the economic losses caused by the pine wilt disease are enormous [4].

The effects of climate change on forest environments and the emersion of pests call for more deliberate prevention and control strategies. Therefore, it is necessary to examine a new preventive strategy considering the trend of climate change. Especially, analyzing the damage and the economic impact of forest-integrated pests is crucial as it provides the basic information necessary to solve upcoming ecosystem disturbances and maintain healthy and productive forests. It can also serve as an objective foundation for policy-making to prevent other pest disasters caused by climate change and to help adapt to future climates.

To achieve this goal, we should establish damage functions to specify the damage rate of pine wilt disease, because the damage rate enables measuring the economic impact, that is, the actual loss caused by the damage. Currently, the pest prediction model used in Korea focuses mainly on estimating the occurrence risk. Although the occurrence risk reflecting the external conditions is useful in selecting priority control areas, it has the limitation of measuring the specific damage rate and the economic ripple effect that it causes.

A prediction model should reflect both direct and indirect factors that affect forest diseases. The direct factors are mostly related to the average temperature and refer to the factors that directly affect the insect vector population through the disturbance of pest development speed, growth, and death rate. The indirect factors are the precipitation and management factors that affect the host tree health, distribution, and physiological change related to its resistance capability against pests. Previous studies of climate change and forest pests focused only the temperature change, which was the direct factor. However, a model of pest damage must consider various direct and indirect variables, since it is affected by the complex interactions of pest populations and host trees.

Considering this background, this study evaluates the effects of climate change on pine wilt disease in Korean pine forests. We considered both changes in physical damage rate and the profit losses of forest owners due to pine wilt disease infestation under climate change. To measure the damage rates by pests, the structural damage function used in reference [5] was implemented. The nonlinear panel probit model and the GEE (generalized estimated equation) were introduced as the estimation method. In addition, the mean per panel value was added to the model according to the method proposed by references [6] and [7] to reflect the fixed effect that has not been observed. The estimated damage function and RCP8.5 climate scenario were used to predict the future damage rate by pests caused by climate change. The RCPs (Representative Concentration Pathways) are climate scenarios that provide time-dependent projections of atmospheric GHG (Green House Gas) [8]. RCP 8.5 is the highest GHG emission scenario which assumes the radiative forcing will peak at 8.5 W/m<sup>2</sup> at the end of the century as a result of the considerable increase of GHG emission and concentrations [9]. The future damage rate of pine tree wilt for the next 80 years, from 2018 to 2100, was predicted, and GIS was used to show the future damage rate by city and county areas. In the assessment of the economic impact on forests, the concept of green payment was introduced to take into account of the revenue from timber and non-timber materials. For the economic analysis, three scenarios were established: no pest outbreak (baseline), pest infestation (no-control), and pest infestation (prevention and control), and the earnings and forest management revenues that included the wood and the non-wood materials for each scenario were compared. On the basis of the results of the analysis, a simulation was conducted to investigate the changes in forest management revenues under in relation to in wood market prices, environmental payouts, and climate change.

#### 1.2. Impacts of Climate on Pine Wilt Disease Infestation

The pine wood nematode is not able to infest trees without the vector beetle, such as the long-horned beetle of the genus *Monochamus* [10]. In Korea, the Japanese pine sawyer (*Monochamus alternatus*) has been identified as the main vector. Therefore, it is very important to understand the behavior of the vector beetle, because the spread of infection can be prevented if the vector can be controlled. *M. alternatus* has a one-year life cycle with four life stages: egg, larva, pupa, and adult [11,12]. The larva stages are usually exposed to cold in winter. In infested tree, nematodes aggregate in the pupa chambers and enter the trachea of the adult beetle when they are about to fly [11]. The adult emerges in early summer and carry the nematodes to healthy trees during maturation feeding.

Nematodes' and vector beetles' survival and development are influenced by climate factors such as temperature and precipitation [13]. The adult beetle population at time t (year) is closely related to the survival and development rates of the larva stages at t-1 [14]. The first to forth instar larva of *M. alternatus* appear in winter. They enter diapause prior to winter, and the diapause is terminated by February. The distribution of *Monochamus* is constrained by winter temperatures, since the low winter temperatures regulate the survival of the overwintering larvae [15]. In the warmer spring, summer, and fall temperatures, beetle development is likely to speed up and cause earlier occurrence of adult emergence and flights [15]. The warmer temperatures limit the flight period of *M. alternatus* in areas with cold climates due to the shortening of the oviposition period [16]. Thus, most of pine wilt disease has been detected in areas where the mean daily summer temperature exceeds 20 °C for several weeks [15]. However, overly hot summers may have adverse effects on the vector beetles. The rate of larval development of *M. galloprovincialis*, decreases above 30 °C, and the temperature between 32 and 35 °C was estimated as the lethal upper threshold [17].

Climate variables other than temperature, such as precipitation and humidity, are likely to affect beetle expansion and dynamics, but research in relation to this is not sufficient. A study [18] found that relative humidity significantly affects the longevity of adult *M. alternatus*. Precipitation is known to be an indirect cause of disease infestation, mainly related to the health of host trees. Seasonal drought and high temperature play an important role in promoting infestation, since trees' defense capability against the pine wood nematodes is disturbed by water stress, which increases tree evaporation [19]. Diseases are likely to expand to new areas if high temperature and drought occur simultaneously.

One of the major key factors that need further study is the potential spread of pine wilt disease due to human accidental transportation of infested materials [15]. Infection by human activity is characterized by a single infected tree in an unexpected area and long-distance dispersal above the moving range of vector beetles [15]. Human transportation of infested material is reported as one of the main factors for spreading pine wild disease in Korea. Unexpected damage has been spreading because the infected trees were moved out by local residents and campers to use them as cooking fuel or building materials. The human population density could be the main factor that explains these long-distance jumps [15]. The population density can be an indicator that reflects not only the magnitude of human activities but also the social overhead capital facilities, such as railways and highways, which significantly affect the pine wilt disease spreading pattern [20]. However, although the population density can represent the total amount of human activities, it has a limitation since it

does not explain the specific impacts on the spread of infection by its various intrinsic factors. It is necessary to develop indicators that can adequately represent each factor through further research.

The impact of climate change is mainly due to increasing temperatures and seasonal drought. As a result, pine wilt disease can spread to new areas that were not infected prior to climate changes. In eastern Asia, pine wilt disease was found in unexpected regions including Boryeong and Yangju in Korea, Amori in Japan [21], and Shanxi and Henan in northern China [22]. The colonization of these territories is suspected to be closely related to recent climate changes. As a consequence of climate change, both nematode development and disease expression may occur in these regions [15]. A study [23] predicted the present and future spatial distribution of the *M. alternatus* in Korea using the CLIMEX model under the RCP 8.5 climate scenario. The results showed that the whole country would be suffering from the pine wilt disease by 2050s, except some areas with extremely cold winter temperatures.

#### 2. Materials and Methods

#### 2.1. Damage Function

We used the empirical damage function proposed by reference [5] to estimate the damage of pine wilt disease. The pest damage (D), that represents by the pest damage rate, can be expressed as a function of the pest population (P) and the vulnerability of the host (z). The vulnerability of the host is an indirect factor of pest infestation because unhealthy hosts are vulnerable to pest attack, so more damage occurs. Therefore, the pest damage function can be expressed by the following equation:

$$D = f_d(z, P) \tag{1}$$

*P* is determined by *z* and the exogenous variables (*V*), such as climatic factors; *z* can be affected by the exogenous variables (*W*) such as precipitation:

$$P = f_p(z, V)$$
$$z = f_z(W)$$
(2)

Therefore, the damage function can be expressed by the following equation combining Equation (1) and Equation (2). The exogenous variables *V* and *W* would partly overlap:

$$D = f_d(z, V),$$
  
$$z = f_z(W)$$
(3)

The reduced form of the damage system can be obtained by substituting  $z = f_z(W)$  into  $D = f_d(z, V)$  to obtain

$$D = g(W, V) \tag{4}$$

The reduced form is a practical model that can reflect the direct and indirect factors of pest outbreaks using the exogenous variables *V* and *W* that are relatively easy to obtain.

#### 2.2. Empirical Model and Data

Since we introduced the damage function proposed by [5], our empirical damage function of the pine wilt disease can be expressed by the following Equation (5):

$$D = g(W, V)$$
  
Where  $P = f_z(z, V)$ ,  $z = f_z(W)$  (5)

where *D* is the pine wilt disease damage rate, *z* is the host tree health, *P* is the vector beetle density.

Forests 2019, 10, 486

The dependent variable, damage rate (D), is defined as the portion of the damaged area (ha) by pine wilt disease in terms of total conifer forest areas (ha) in Equation (6). The damaged area was calculated from the number of trees killed by pine wilt disease × basal area. The factors affecting the vector beetle density (P) are expressed by Equation (7):

$$D = \frac{\text{Total Damaged Area}}{\text{Total Conifer Forests}}, D = [0, 1]$$
(6)

$$P = f_p \quad (\text{MinWT}_{(\text{it}-1)}, \text{SnowWT}_{(\text{it}-1)}, \text{SPT}_{(\text{it})}, \text{SMT}_{(\text{it})}, \text{SMT}^2_{(\text{it})}, MinFA_{(\text{it})}, \text{RHUM}_{SP}_{(\text{it})}, \text{RHUM}_{FA_{(\text{it})}}, \text{POP}_{(\text{it})})$$
(7)

where  $MinWT_{(it-1)}$  is the average minimum winter temperature the previous year,  $SnowWT_{(it-1)}$  is the average winter snow fall the previous year,  $SPT_{(it)}$  is the average spring temperature,  $SMT_{(it)}$  is the average summer temperature,  $SMT_{(it)}^2$  is the square term of average summer temperature,  $SMP_{(it)}$  is the average summer precipitation,  $MinFA_{(it)}$  is the average minimum fall temperature,  $RHUM_SP_{(it)}$  is the average spring relative humidity,  $RHUM_FA_{(it)}$  is the average fall relative humidity,  $POP_{(it)}$  is the population, t is the year(2010–2017), i represents the 230 cities and counties.

We included the climate variables which affect vector's development and survival in each life stage in the model. Several climate variables such as MinWT<sub>(it-1)</sub>, and SnowWT<sub>(it-1)</sub> are likely to affect larvae development and survival. The average winter snowfall was included because the warming effect of the snow can prevent the larvae from being exposed to the cold temperatures [24]. Several climate variables (SPT<sub>it</sub>, SMT<sup>2</sup><sub>it</sub>, SMP<sup>2</sup><sub>it</sub>, MinFA<sub>it</sub>, RHUM\_SP<sub>it</sub>, RHUM\_FA<sub>it</sub>, SMP<sub>it</sub>) are related to the adult flying and oviposition periods. The human population variable represents the infestation by human activities.

The factors influencing host health (z) during the summer, when newly emerging adults carry the nematodes to healthy trees, were determined by the following equation:

$$z = f_z(\text{SMT}_{(\text{it})}, \text{SMT}_{(\text{it})}^2 \text{SMP}_{(\text{it})})$$
(8)

where  $SMT_{(it)}$  is the average summer temperature,  $SMT_{(it)}^2$  is the square term of average summer temperature,  $SMP_{(it)}$  is the average summer precipitation.

Combining  $f_p$  with  $f_z$ , the damage function of pine wilt disease is derived in Equation (9). Here,  $ct_{(2013)}$  implies a catastrophic dummy variable. In 2013, the epidemic of pine wilt disease sharply increased in Korea. The infestation area has decreased after 2013, but the causes of that temporal large outbreak have not yet been clarified. Some experts indicate drought and high summer temperatures in 2013 as the main cause of the large outbreak. The data periods (t) examined were from 2013 to 2017, and the number of panels was 230 counties and cities across the country. In total, 1839 observation were collected from 230 panels in eight-year time periods.

$$D = f_d \quad (MinWT_{(it-1)}, SnowWT_{(it-1)}, SPT_{(it)}, SMT_{(it)}, SMT^2_{(it)}, SMP_{(it)}, MinFA_{(it)}, RHUM_SP_{(it)}, RHUM_FA_{(it)}, POP_{(it)}, ct_{(2013)})$$
(9)

The forest-related data (number of killed trees and forest areas occupied by different species) by county and city were obtained from the Korean Forest Service. The population data by city and county were obtained from Statistics Korea. The climate data was provided by the Korea Meteorological Administration. We obtained the average daily climate data by city and county to derive the average monthly values and then calculated the seasonal mean values. Spring was from March to May, summer from June to August, fall from September to November, and winter from December to the following February.

Table 1 shows the climatic factors that affect insect vector and host trees at each growth stage based on the previous studies. As we see in the Table 1, the average temperature, humidity, and maximum and minimum temperatures in each season are closely related to the expansion of the pine wilt disease.

Variable	Variable Description	<b>Related Studies</b>	Unit
D	Proportion of damaged area by pine wilt disease	[5]	[0,1]
$MinWT_{(it-1)}$	Average minimum winter temperature	[25-27]	°C
SnowWT <sub>(it-1)</sub>	Average winter snow fall	[24]	Kg/m <sup>2</sup>
SPT <sub>(it)</sub>	Average spring temperature	[15,28]	°C
SMT <sub>(it)</sub>	Average summer temperature	[15,17,26,29]	°C
SMT <sup>2</sup> (it)	Square of average summer temperature	[15,17]	°C
SMP <sub>(it)</sub>	Average summer precipitation	[30]	mm
MinFA <sub>(it)</sub>	Average minimum fall temperature	[26]	°C
RHUM_SP(it)	Average spring relative humidity	[18]	%
RHUM_FA(it)	Average fall relative humidity	[18]	%
POP <sub>(it)</sub>	Population	[20]	Population unit
ct <sub>(2013)</sub>	Catastrophic dummy <sup>1</sup>		1 = 2013, 0 = Other years

Table 1. Factors affecting pine wilt disease infestation.

<sup>1</sup>. The catastrophic dummy ct<sub>(2013)</sub> is applied to filter out the temporal impacts of large outbreak in year 2013.

#### 2.3. Estimation Method

In this study, the damage rate (*D*) is the proportional response variable with a value between 0 and 1. Therefore, by applying the random or fixed-effect method with log transformation, we could omit the observations with a value of 0 during the log conversion process. Also, the effect of any independent variable  $x_{it}$  could not be constant throughout the range of X [31]. The application of the logit method has also a drawback, since the log-odd ratio cannot be true if the dependent variable takes on the value of 0 or 1. To mitigate this problem, it is possible to add a small value to zeros, but this may generate a bias estimation due to changes in the distribution of the variables.

To take into account the characteristics of the proportional response variable, we applied Papke and Wooldridge's method [32]. For cross-sectional observation *i* and time period *t* for the response variable,  $0 \le y_{it} \le 1$ , and outcomes at zero and one are available. We assumed a set of  $1 \times K$  vector explanatory variables X<sub>it</sub>. The conditional average of the fractional response variable can be expressed as form of the following nonlinear panel probit function, where  $\Phi$  is the standard normal cumulative distribution function (CDF), and  $C_i$  is an unobserved effect:

$$E(y_{it}|\mathbf{x}_{it}, c_i) = \Phi(\mathbf{x}_{it}\beta + c_i), \quad t = 1....T$$

$$(10)$$

With strictly exogeneity of { $x_{it}$ : t = 1, ..., T} and conditional normal distribution of  $c_i$  (Equation (11) [7], Equation (10) can be expressed as Equation (12):

$$E(y_{it}|\mathbf{x}_{i}, c_{i}) = E(y_{it}|\mathbf{x}_{it}, c_{i}), t = 1....T$$
(11)

$$(c_i | \mathbf{x}_{it}, \dots, \mathbf{x}_{iT}) \sim Normal(\psi + \overline{\mathbf{x}_i}\xi, \sigma^2)$$
$$E(y_{it} | \mathbf{x}_i) = \Phi(\psi + \mathbf{x}_{it}\beta + \overline{\mathbf{x}_i}\xi)$$
(12)

To estimate Equation (12), we can apply the generalized linear model (GLM) with probit link function using quasi-maximum likelihood estimation (QLME). However, this method tends to ignore the serial dependence that may exist in the joint distribution, which may result in inefficiency. MWNLS (multivariate weighted nonlinear least square) is appropriate for estimating conditional means for panel data with strictly exogenous regressor when serial correlation and heteroskedasticity are present [32]. However, this method requires the parametric model of Var( $y_i|x_i$ ). Y<sub>i</sub>, here, is the Tx1 vector of response variables, and obtaining the covariance Cov( $y_{it}, y_{ir}|x_i$ ) is difficult even if Var( $y_i|x_i$ ) has a fairly simple form. A study [32] proposed the GEE approach to overcome this problem. GEE uses exchangeable correlation rather than finding a parametric model of Var( $y_i|x_i$ ), and GEE and MWNLS are asymptotically equivalent whenever they use the same estimates of the matrix Var( $y_i|x_i$ ) [33]. In this study, we used the GEE model with probit link function to estimate the damage function. The conditional average of the damage rate with N number of panels (i = 1, ..., N) and T(i = 1,...,T) years could be expressed by the following Equation (13)

$$E(D_{it}|\mathbf{x}_i) = \Phi(\psi + \mathbf{x}_{it}\beta + \overline{\mathbf{x}_i}\xi)$$
(13)

where  $D_{it}$  is the pine wilt disease damage rate,  $X_{it}$  is the vector of the explanatory variables,  $\overline{X_i}$  is the average of across panels.  $\overline{X_i}$  here is the Mundlak device [6] which reflects the unobserved effect within the panel. Since the estimated coefficient  $\beta$  cannot explain the estimation result directly in the fractional response model, we should calculate the average partial effects (APEs). Let  $m(X_{i}, \theta)$  be the conditional mean function for the vector of response variable  $Y_{it}$ . Given any consistent estimator  $\hat{\theta}$ , the APEs can be estimated by taking derivatives or changes with respect to the element X<sub>t</sub> of the following Equation (14):

$$N^{-1}\sum_{i=1}^{N}\Phi(\hat{\psi_a} + x_i\hat{\beta_a} + \overline{x_i}\hat{\xi_a})$$
(14)

#### 2.4. Projections of Pine Wilt Disease under Climate Change

We used the RCP 8.5 climate scenario to project the future damage rate of pine wilt disease due to climate change. The prediction process consisted in plugging the projected future climate data into our estimated coefficient from the damage function. We assumed the future population and total forest areas would remain the same as in 2018. Although this is somewhat inconsistent with the current population decline trend in Korea, we decided to focus more on the correlation between forest pest risk and climate change rather than on anthropogenic factors such as population.

Table A1 in the Appendix A shows the basic statistics of the projected climate data used for the prediction. According to the RCP 8.5 data obtained from the Korea Meteorological Administration, the average temperature of South Korea is expected to increase by an average of 4 °C by 2100. Precipitation shows a periodic cycle that repeats up and down every 10 years, but overall, an increasing trend is projected.

#### 2.5. Economic Evaluation of Pine Wilt Disease

This study evaluated the economic impacts of pine wilt disease by applying the Macpherson's method [33] that introduced the concept of green payment to include non-timber benefits, such as carbon sequestration, biodiversity, and wildlife habitats in the model. To consider the impacts of pest inspection and control, we included the costs of inspection and control in the objective function. The objective function also considered the amount of changes in timber production due to damage by pine wilt disease.

The objective function with inspection and control under disease outbreak can be expressed as in Equation (15), which includes timber and non-timber benefit. Through the objective function, we could find the optimal rotation age (t), which generates the greatest net present value from harvest considering timber and non-timber benefits:

$$\max tPV(t)L^{i}{}_{TB}e^{-rt} - CL + \int_{0}^{t} \left[G(L^{c}{}_{NTB}(s)) - D(I(s))\right]e^{-rs}ds + \int_{0}^{\infty} aLe^{-rs}ds$$
(15)

*P* represents the market price of timber, V(t) is the timber production per unit of land, L is the land area, C is the harvest and establishment cost, *r* is the discount factor, *a* refers to the maximum income from the forest each year after logging (after the year *t*), G(L) denotes the green payment to include non-timber benefits and is assumed to be a linear function of the land area (L), D(·) denotes the inspection and control cost and is a function of the damaged area, I(t).

Macpherson et al. also assumed that the total area L can be divided into N small areas, while  $L^{i}_{TB}(t)$  represents the sum of small areas considered for the condition of pest infestation. In this case,  $L^{i}_{TB}(t)$  is the area that produces timber:

$$L = \sum_{i=1}^{N} x_i \quad L^i{}_{TB}(t) = \sum_{i=1}^{N} \rho_i x_i, \ 0 \le \rho \le 1$$
(16)

 $\rho_i$  indicates the rate of infection of the pest and has a value between 0 and 1. The value of one indicates the uninfected condition in which timber production is not affected by pests. Small areas with zero values of  $\rho_i$  are excluded from the timber production area. Therefore, the value of  $\rho_i$  varies depending on the type of pests and can be expressed as zero for pine wilt disease.

Similarly, the area that affects the non-timber benefits is represented by  $L^{i}_{NTB}$  as follows:

$$L^{i}_{NTB} = \sum_{i=1}^{n} \sigma_{i} x_{i}, \quad 0 \le \sigma_{i} \le 1$$
(17)

When it is assumed that  $G(L^i_{NTB}(t))$  representing green payments is proportional to the area that generates non-timber benefits, the value can be calculated by multiplying the amount paid per unit area(g) and  $L^i_{NTB}$ :

$$G(L^{i}_{NTB}(t)) = g \times L^{i}_{NTB}(t)$$
(18)

We can derive Equation (19), the first-order conditions for the optimal rotation age, by differentiating Equation (15) with respect to time (t). The optimal rotation age occurs when the growth rate subtracting the discount rate is the same as the current value of the changes in land area and rent plus the changes in timber benefits and green payments:

$$\frac{V'(t)}{V(t)} - r = \frac{1}{L^{c}_{TB}(t)} \left( \left| \frac{dL^{c}_{TB}(t)}{dt} \right| + \frac{1}{PV(T)} (aL - e^{-rt} \frac{d}{dt}) \right.$$

$$\left( \int_{0}^{t} \left[ G(L^{c}_{NTB}(s) - D(I(s))] e^{-rs} ds) \right) \right)$$
(19)

We set some scenarios to compare the economic impacts of disease outbreaks. The baseline scenario assumes no disease infestation. If there is no infestation, the objective function including the timber and non-timber benefits can be expressed by Equation (20) [33]:

$$\max tPV(t)Le^{-rt} - CL + \int_0^t G(L)e^{-rs}ds + \int_0^\infty aLe^{-rs}ds$$
<sup>(20)</sup>

Also, a scenario for disease outbreak with no control is established. In that case, the damage rate is the same as in Equation (15) except for the action term. Therefore, the objective function and the condition for optimal rotation age are expressed by the following equations (21) and (22):

$$\max tPV(t)L^{i}_{TB}e^{-rt} - CL + \int_{0}^{t} G(L^{i}_{NTB})e^{-rs}ds + \int_{0}^{\infty} aLe^{-rs}ds$$
(21)

$$\frac{V'(t)}{V(t)} - r = \frac{1}{L^{i}_{TB}(t)} \left( \left| \frac{dL^{i}_{TB}(t)}{dt} \right| + \frac{1}{PV(T)} \left( aL - e^{-rt} \frac{d}{dt} \left( \int_{0}^{t} G(L^{i}_{NTB}(s)) e^{-rs} ds \right) \right) \right)$$
(22)

If no action has been taken in the infected area, the forest area can be divided into two categories: the susceptible area (S(t)) and the infected area (I(t)). That is, the total area L is the sum of S(t) and I(t) (L = S(t) + I(t)). If the forest area  $L^{i}_{TB}$ , which is affected by pests and affects wood production, is represented by the area where the same timber is produced without pests, it can be described as follows [33]:

$$L^{i}_{TB}(t) = S(t) + \rho(L - S(t))$$
 (23)

where (L-S(t)) in the right-hand side indicates the infected area (I(t)). In contrast, when the control and inspection are applied, timber areas can be divided into three categories: the susceptible area (S(t)), the controlled area (T(t)), and the infected area (I(t)). Therefore, the timber production area including the control and prevention of pests can be expressed as in Equation (24):

$$L_{TB}^{c}(t) = S(t) + T(t) + \rho I(t)$$
(24)

Here, it is assumed that the controlled area (T(t)) is free from pest infestation and does not affect timber production. In addition, assuming that the controlled area is linearly proportional to the area of infection (T(t) =  $\alpha$ I(t)), it can be expressed as follows ( $\alpha$ (alpha) here implies the control rate):

$$L_{TB}^{c}(t) = S(t) + (\alpha + \rho) \frac{L - S(t)}{1 + \alpha}$$
(25)

where the timber production area is the sum of the susceptible area and the controlled area if  $\rho = 0$ .

The areas affecting the non-timber benefits can be represented as in Equations (26) and (27).

$$L_{NTB}^{i}(\mathbf{t}) = S(t) + \sigma(L - S(t))$$
(26)

$$L_{NTB}^{c}(\mathbf{t}) = S(t) + (\alpha + \sigma) \frac{L - S(t)}{1 + \alpha}$$
(27)

The data required for a numerical analysis using the above model include timber volume production function, changes in the area of pest infestation over time, damage rates, control and prevention costs, annual land area, timber prices, and logging and afforestation costs. Most of the data are publicly available, but the area of pest infection over time can be obtained by using the SI model (Susceptible–Infected Model), which is mainly used in studies of pest spreading. The SI model for the no-action model can be described as follows [34]:

$$\frac{dS}{dt} = -\delta S(t)(I(t) + p)$$

$$\frac{dI}{dt} = \delta S(t)(I(t) + p)$$
(28)

Here, *p* represents the infected area at the initial stage, and  $\delta$  indicates the secondary infection rate, i.e., the rate of pests spreading in a forest.

As discussed in the theory section, if no action is taken against pests, the total forest area (L) is the sum of S(t) and I(t), and changes in S(t) over time are indicated as follows:

$$\frac{dS}{dt} = -\delta S(t)(L - S(t) + p)$$
<sup>(29)</sup>

When the variable separation method is applied to obtain the solution of the above differential equation, S(t) can be expressed as shown in the following expression:

$$S(t) = \frac{(L+p)}{\frac{p}{T}e^{(L+p)\delta t} + 1}$$
(30)

On the other hand, for models performing control and prevention (L is divided into S(t), T(t), and I(t)), changes in S(t) over time are indicated as follows:

$$\frac{dS}{dt} = -\delta S(t) \left( \frac{L - S(t)}{1 + \alpha} + p \right)$$
(31)

Similarly, to obtain S(t), the above expression is solved by applying the variable separation method, which appears as follows:

$$S(t) = \frac{L + p(1+\alpha)}{\frac{p(1+\alpha)}{L} \exp((L + p(1+\alpha))\frac{\delta t}{1+\alpha}) + 1}$$
(32)

Substituting Equation (30) for Equations (23) and (26), we can solve  $dL_{TB}^{i}(t)/dt$  and  $dL_{NTB}^{i}(t)/dt$ . Similarly, substituting Equation (32) for Equations (25) and (27),  $dL_{TB}^{c}(t)/dt$  and  $dL_{NTB}^{c}(t)/dt$  can be solved. If  $\rho = 0$  (the timber production is zero in the infected area),  $dL_{TB}^{c}(t)/dt$  is as follows:

$$\frac{dL_{TB}^{c}(t)}{dt} = \left(1 - \frac{\alpha}{1 + \alpha}\right)\frac{dS(t)}{dt}$$
(33)

Instead of using the timber volume production function, we used the actual data for age-specific volumes in the National Institute of Forest Science [35]. The annual average growth (m<sup>3</sup>/ha) was derived from the five-year average growth rate (m<sup>3</sup>/ha). Data for timber prices (1000 KRW/m<sup>3</sup>), afforestation costs (1000 KRW/m<sup>3</sup>) and forest management costs (1000 KRW/m<sup>3</sup>) were obtained from reference [36]. It was assumed that pests infest trees after the age of 10 because a trunk injection for disease prevention is targeted to trees over 10 cm in diameter at breast height (DBH), and the age of the trees is approximately 15 to 20 years [4,35].

We chose three target species: the Gangwon regional pine (*Pinus densiflora*), the central regional pine (*Pinus densiflora*), and the Korean pine (*Pinus koraiensis*) for our economic analysis. The parameters for the baseline scenario were set as shown in Table A2 in the Appendix A. It was assumed that the discount rate was 3% and the green payment was 100,000 KRW/ha. As introduced in the SI model, p represented the infected area, and  $\delta$  represented the secondary infection rate, i.e. the rate of pest spreading in forests. We estimated the value of p per hectare in 2010 as 0.00054 where the data in the infected area exist. Using the SI model in Equation (28) and the data of the infected area (I(t)) and the susceptible area (S(t)) from 2011 to 2017, we estimated the averaged value of  $\delta$  as 0.002. The variables  $\rho$  and  $\sigma$  shown in Equations (23) and (26) represented the rates of timber and non-timber available in the infected area, respectively. It was assumed that damaged trees do not generate any timber and non-timber value because all infected trees were cut and incinerated to prevent secondary infection. The subject area was set to 100ha which corresponds to the minimum area owned by corporate forest owners among the members of the Korea Forest Managers Association.

#### 3. Results

#### 3.1. Estimation Results

Table 2 shows the estimated average partial effects from the fractional probit damage function using the GEE estimation method.

Variable	APE	Standard error <sup>2</sup>	<i>p</i> -Value
MinWT <sub>(it-1)</sub>	0.00027 *** <sup>3</sup>	0.00009	0.003
SPT <sub>(it)</sub>	0.00065 ***	0.00016	0.000
$SMT_{(it)}$ , $SMT^{2}_{(it)}$	-0.00066 ***	0.00018	0.000
MinFA <sub>(it)</sub>	0.00037 ***	0.00014	0.009
RHUM_SP <sub>(it)</sub>	0.00018 ***	0.00006	0.002
RHUM_FA(it)	0.000003	0.00004	0.946
SMP <sub>(it)</sub>	-0.000006 **	0.000003	0.032
SnowWT <sub>(it-1)</sub>	0.00014 *	0.00007	0.061
ct <sub>(2013)</sub>	0.002258 ***	0.00048	0.000
POP <sub>(it)</sub>	0.00000001 **	0.0000000041	0.011

**Table 2.** Estimation results of the damage function (Unit: °C, mm)<sup>1</sup>.

<sup>1</sup>. Average partial effects of dependent variables, <sup>2</sup>. clustered semi-robust standard error, <sup>3</sup>. \*\*\*, \*\*, \* statistically significant at 1%, 5%, and 10% significance level, respectively.

The estimation results indicated that minimum winter temperature (t-1), average spring temperature, average summer temperature and its square term, minimum fall temperature, spring relative humidity, summer average precipitation, winter snowfall (t-1), and population had a significant impact on the damage rate of pine wilt disease. There was a positive relationship between winter minimum temperature (t-1), average spring temperature, average summer temperature, minimum fall temperature, spring relative humidity, winter snowfall (t-1), population, and damage rate. On the other hand, there was a negative correlation between the square term of summer temperature, summer precipitation, and damage rate.

As we reviewed in previous studies, the estimation results confirmed that the increasing average spring temperature and spring relative humidity contribute to increasing the damage rate. Spring temperature and relative humidity could accelerate beetle development and cause an earlier occurrence of adult emergence and flights. Figure 1 shows the marginal coves of some climate variables and the 95% confidence interval of their value. There is a quadratic relationship with a negative square term between average summer temperature and damage rate. If the other variables are not taken into consideration, the marginal effect of average summer temperature decreases from 22 °C, and the marginal effect becomes close to 0 above 27 °C. This result is supported by the literature indicating that increasing summer temperatures may have adverse effects on the vector beetles, since the rate of larval development decreases above 30 °C [17]. There was a negative correlation between summer precipitation and damage rate. Precipitation may relate to the health of the host trees. Water stress could decrease a tree's defense capability against the pine wood nematode.



**Figure 1.** Average marginal effect by major climatic variables. (a) Average summer temperature; (b) average minimum winter temperature (t-1); (c) average minimum fall temperature; (d) average summer precipitation. RCP: representative concentration pathways.

The average of minimum fall temperature and the damage rate had a positive relationship, and the damage rate of pine wilt disease increased as the minimum fall temperature increased. The minimum fall temperature is considered to expand the flight and oviposition period of the vector beetles. The oviposition of female *M. alternatus* is mostly performed during summer, but it may be continued until October in warmer fall temperatures. A study [37] indicates that the flight period of *M. alternatus* was limited by low temperature in areas with cold climates, since cold temperatures shorten the flight and oviposition periods. Therefore, a warmer minimum fall temperature is expected to increase the oviposition period of females, since a female oviposition performance is restricted by a minimum threshold temperature [26].

There was a positive correlation between the minimum winter temperature (t-1) and the damage rate. The current warm winter would increase the damage rate of pine wilt disease in the next year. The amount of snowfall and the damage rate were also positively correlated. Low winter temperatures regulate the survival of overwintering larvae because cold temperatures often terminate the diapause in early winter [37–39]. Therefore, the development of larvae is suppressed in cold winter conditions.

The population by city/district was used as a proxy variable to explain the spread of disease by human accidental transportation of infested material. We confirmed a positive correlation between population and damage rate through the estimation results. Therefore, it was considered that the artificial spread of the damage caused by human activity tends to be greater in areas with a large population. However, the demographic variable has limitations in revealing specific relationships between the damage rate and certain activities. This requires further studies with careful investigation.

## 3.2. Projection Results

Figure 2 shows the predicted future damage rate of pine wilt disease through the damage function using RCP8.5 climate data. The damage rate of 2010–2017 was calculated from the observed data. The projection results indicated that the damaged area could be expanded to the northern part of the country as climate change progressed. Currently, damages have mostly occurred in the southern part of Korea. However, after 2050, the central regions, such as Chungcheong and Gyeonggi provinces, would be expected to become major damaged areas. After 2090, the whole country will be vulnerable to pine wilt disease, except some part of the northeast region, such as Gangwon province, where the winter temperature is very low.

## 3.3. Results of the Economic Analysis

The optimal rotation age by forest type from the model calibration are shown in Table 3. In the absence of pests, it was found that the rotation age of 55–80 years is the optimal rotation age, which maximizes the net present value from timber and non-timber profit. In the case of pest infestation, the optimal rotation age appeared to be between 49 and 61 years when inspection and control were performed. When no action was taken in the case of pest infestation, the rotation age appeared to be between 32 and 34 years. Thus, pest infestation shortens the rotation age. In other words, the periods when the decline in timber and non-timber profit due to the pine wilt disease is greater than the increase in income due to the extension of rotation age come early in the case of disease outbreak. However, if pest control is applied, it can be seen that the rotation age is longer compared to the case where no action is taken.

Under the given conditions (parameters), the returns in forest management, which are the values of the objective function, all show negative values. The main reason for the negative revenue from forest management is that wood price would not be high enough to ensure sufficient profit. Korea's pine trees are mainly used as industrial wood such as pallets because of their low quality. In the case of pest infestation, their value would be significantly lower than in the absence of pests. It was also found that the present value would be worse when pest control and prevention are not performed.



**Figure 2.** Projected future damage rate of pine wilt disease (periodic average). (**a**) History: 2010–2017; (**b**) projection: 2018–2050; (**c**) projection: 2051–2070; (**d**) projection: 2071–2100.

**Table 3.** Changes in optimal rotation age and timber and non-timber profits in the presence of pine wilt disease infestation (Unit: years, KRW).

	No Pest Infestation		Pest Infestation No Control		Pest Infestation	Inspection and Control
	Rotation Age	Present Value	Rotation Age	Present Value	Rotation Age	Present Value
Gangwon Pine	64	-225,283	32	-771,220	54	-302,395
Central Pine	55	-308,987	32	-810,831	49	-422,267
Korean Pine	80	-334,826	34	-919,456	61	-444,521

## 3.4. Simulation

#### 3.4.1. Changes in the Market Price of Timber

Figure 3 shows the changes in forest management profit and rotation ages for different market prices of timber. As the market price of timber rises from 90,000 Won/m<sup>3</sup> to 160,000 Won/m<sup>3</sup>, the rotation age is shortened in all scenarios. The increases in the price of timber in the absence of actions against pine wilt disease decrease the rotation from 33 years to 30 years. If inspection and control are performed, the rotation age is reduced from 57 years to 48 years as a consequence of the increase in the timber price. The forest owners expect quick results in order for them to understand when to sell their timbers at the highest price.



Figure 3. Returns of Gangwon Pine with changes in market timber price.

The return on forest management, which is the value of the objective function, is shown to be positive only if there is no pest infestation, with a high timber price at around 160,000 Won/m<sup>3</sup> (53 years). Despite the rise in the timber price, it will likely be difficult to make up for the losses due to pest infestation.

#### 3.4.2. Changes in Green Payments

This analysis assumed that the green payment for forests is paid to the landowners in the amount of 100,000 Won/ha. In the baseline scenario, it appeared that the rotation is 64 years. In the case of pest infestation with no action taken, the rotation age is 32 years. In the case of pest control and prevention after infestation, the rotation age is 54 years.

Figure 4 illustrates the change in the rotation age and the returns of forest management when the green payments gradually increase. It is shown that the rotation age increases as the payment amount rises. This is because the higher the payment, the larger the forests that can be preserved because of increasing return from green payments. The results also showed the significant difference of rotation age between the scenario of control and that of no action.



Figure 4. Returns of Gangwon Pine with changes in green payments. The rotation age is limited to 80 years in case of no-infection because the age-volume data re only available until the age of 80 years.

control

Infestation, control

The returns of forest management also showed a wide gap between the case of control and that of no action after pest infestation. In the case of inspection and control, the forest management returns would be converted into positive value with the amount of green payment of 300,000 Won/ha. However, if no action is taken, more than 500,000 Won/ha of green payment would be necessary to achieve a positive profit.

# 3.4.3. Climate Change

Previous studies have predicted that the frequency of occurrence of pine wilt disease will increase as the habitat of the vector beetle expands with climate change and the health of the host deteriorates. In this study, the historical data and the projection data on climate change (RCP 8.5) were used to predict the damage rate of pest infestation, and it was determined that the damage rate of pine wilt would increase in Korea. In light of these results, it is conceivable that changes in the damage rate of pine wilt caused by climate change will have a negative impact on the economic benefit of forests.

We estimated the economic effect derived by changes in the value of  $\delta$  corresponding to the incidence of the pest in relation to climate change. As previously stated,  $\delta$  in the future can be estimated by applying equation (28) and using this value to derive the present value of forest management returns from timber and non-timber products. The estimated initial damaged area derived from the damage function and the forest area were used for the analysis (only the areas with pest infestation were included). Table 4 summarizes the obtained value of  $\delta$ , which was averaged for 30 years. As climate change progresses,  $\delta$  value are expected to increase gradually.

Table 4. Incidence rate of pine wilt disease by period.

Period	2011-2040	2041-2070	2071-2100
δ	0.0031	0.0046	0.0088

Figure 5 illustrates the change in the rotation and the objective function value (returns) as  $\delta$ increases. The rotation age is shown to be reduced to 11 years and 18 years from the baseline values in the case of pest infestation (32 years) and in that of pest infestation and control (54 years), respectively. The loss of forest management revenue is also shown to gradually worsen. In particular, the standard deviation of returns in the case of pest infestation (484 million Won) is larger than that in the case of pest control (403 million Won). Thus, in order to reduce the uncertainty due to climate change, intensive inspection and control are necessary to stabilize the returns from forest management.



Figure 5. Returns with changes in the damage rate of pine wilt disease.

Figure 6 shows the changes in timber profit of Gangwon pine in relation to the market prices of timber during the years 2071–2100, when climate change would intensify. We found that severe climate change will make the timber revenue much worse. The difference in revenue appeared increased between the case of applied prevention and control and that in which no action is taken under infestation. If forests are infected under severe climate change, the rotation period becomes much shorter.



Figure 6. Changes in timber profit of Gangwon Pine by market price of timber.

#### 4. Discussion

Long-term climate changes create environmental conditions favorable to pests, and pests will adequately adapt to such environments. As the area favorable for pest inhabitation expands, the damage to forests can expand nationwide. The damage from the pine wilt disease has not been significant in some regions such as Daegwalleong in Gangwon where the winter temperature is very low. However, the forecasted increasing winter temperature would expand the damaged area to areas with extremely cold winter temperatures and to high mountainous regions where the damage has not occurred until now. Also, new trees may be attacked, as the areas favorable for pest inhabitation expand nationwide. Considering that the walnut twig beetle in the United States has attacked new host trees such as the black walnut as it migrated to the north, it is necessary to pay attention to the possible damage to other conifer tree species.

The analysis results showed that several temperature variables, such as the minimum winter temperature, average spring, summer and minimum fall temperatures, have a statistically positive correlation with the damage rate. In addition, the summer precipitation and other factors that affect tree health have a significantly negative correlation with the damage rate. Therefore, the damage rate would increase gradually if severe climate conditions such as dry and warm summers, which are favorable to vectors, appear simultaneously.

The profit from forest management would be worse when the disease outbreak intensifies due to climate change. Moreover, the analysis showed that the profit from forest management decreases sharply without pest control action. The profit from forests should be a positive value in order for individual forest owners to have an incentive to appropriately manage their forests. To obtain profit, the timber price might be sufficiently high or there may be instruments that are used to compensate for factors decreasing the value of forests. However, under the current conditions set in this study, it is difficult to expect positive profits from forest management, even though both timber and non-timber returns were considered. Therefore, leaving bare land after harvesting has resulted in better return than tree replanting. This difficulty is worsened by pine wilt disease infestation, especially in conditions without disease control that further decrease the economic profit. Thus, even if the revenues from forests are not high, prevention and control should take place.

In order to prepare for the increase of the damage rate as a consequence of climate change and ensure a stable income for forest owners, inspection and control are necessary even if they require additional costs. Moreover, additional income stabilization arrangements such as green payment are necessary to compensate for the losses due to inspection and control cost as a result of climate change. However, since the income from forests is predicted to get worse in the future when climate changes become severe, the effect of economic support such as increase of timber price and green payment is reduced. We found that, as the timber price increased, the rotation period became shorter. On the other hand, higher green payment led to a longer the rotation period. However, the green payment did not extend the rotation period when no action was taken under disease infestation. In contrast, if disease control and prevention were performed, the green payment extended the rotation period.

## 5. Conclusions

This study assessed the potential damage and the economic threat of pine wilt disease under climate change. In particular, we established a damage function with consideration of the direct and indirect factors that affect the damage and the changes in forest owner's profit under different scenarios.

The estimation showed that the damage rate from the pine wilt disease increased as the average spring temperature, minimum winter temperature, relative humidity in spring, and snowfall in winter increased and it decreased as the average precipitation in summer increased. The projection of the future damage rate indicated that the damage from the pine wilt disease, which is currently concentrated in southern regions, is expected to expand to the north as a consequence of climate change. Intensely damaged areas are expected to expand to the Chungcheong and Gyeonggi regions

by 2050–2070, and the damage by the wilt disease is expected to widely spread countrywide, except for some parts in Gangwon Province after 2090.

We introduced the concept of the green payment to reflect the economic value of timber and non-timber in the economic impact assessment. For the economic analysis, we built three scenarios of no disease outbreak (baseline), disease outbreak with no control, and disease outbreak with control and prevention. We compared the changes in forest rotation age and the revenues from forest management including timber and non-timber production for each scenario. Finally, we performed a simulation to examine the change of the revenues from forest management according to the changes in timber market price, green payment, and climate change.

According to the analysis result, it appeared that it is difficult to expect a positive income from forest management even when both timber and non-timber productions are considered under the current conditions, since the timber price is not high enough to guarantee a positive revenue. The difficulties could intensify if the damage from pine wilt disease increases. In the case of the green payment, unlike for timber price, the forest rotation age increased when the payout increased.

Until now, low forest management revenues have led to a lack of incentives for forest owners to focus on pest control, leaving the job to be handled solely by the government. However, if the damage increases due to climate change in the future, the current government-based management system of Korea may face a shortage of budget and workforce. Therefore, there is a need to encourage individual forest owners to actively manage pests through better profits earned by keeping healthy forests. The green payment introduced in this study could be one of the possible solutions to encourage pest control action by individual forest owners.

The contribution of this study is that it establishes a pest damage function that considers various factors and evaluates the economic impact of pine wilt disease outbreaks considering management factors using a dynamic analysis. The advantage of our model is that we could estimate the specific damage rate of pine wilt disease using the damage function. Previous modeling approaches for the pine wilt disease such as that described in [40] focus mainly on finding a dispersal mechanism, which aims to track the possible infested area. However, this model has limitations in estimating the magnitude of the damage. Our damage function not only tracks the possible infested area but also estimates the magnitude of the damage per ha. While the previous study only considered the revenue losses from timber when the economic impact of forest pest was calculated [41], our study considered both timber losses and environmental losses by introducing the concept of green payment. This will give policy-makers indications of how marketable actions such as the green payment would affect forest pest control by changing the behavior of forest owners.

However, in this study, the demographic variables used to assess anthropogenic activities have limitations in that they do not reveal a specific correlation between the detailed history of activities and the damage rates. It is necessary to identify substitutional variables that can represent the details of future artificial activities and reflect them in the model. The relationship between specific prevention control strategies, such as trunk injection and aerial application, and profitability of the forest management can be suggested as a future research topic.

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# Appendix A

Year	Spring temperature	Summer temperature	Fall temperature	Winter temperature
2009-2017	11.22	23.92	13.95	-0.25
2018-2050	12.34	25.03	15.23	1.15
2051-2070	13.72	26.53	26.72	2.90
2071-2100	15.44	28.40	18.83	4.68
Year	Spring precipitation	Summer precipitation	Fall precipitation	Winter precipitation
2009–2017	115.90	304.52	88.02	32.54
2018-2050	113.83	314.95	93.94	44.96
2051-2070	115.13	356.44	104.68	48.07
2071-2100	130.06	327.77	94.27	61.25

Table A1. Changes in seasonal average temperature and precipitation in South Korea (Unit: °C, mm).

Table A2. Parameters for the analysis on rotation length.

	Unit	Gangwon Pine	Central Pine	Korea Pine
Timber market price	1000 KRW/m <sup>3</sup>	109.1	109.1	89.1
Afforestation costs	1000 KRW/ha	7415	7415	6066
Logging costs	1000 KRW/ha	16,109	16,109	16,109
Green payments	1000 KRW/ha	100	100	100
Discount rates	%	3	3	3
р		$0.00054 \times L$	$0.00054 \times L$	$0.00054 \times L$
δ		0.002	0.002	0.002
ρ		0	0	0
σ		0	0	0
Control and prevention costs	1000 KRW/ha	900	900	900
Handling costs for dead tree	1000 KRW/ha	3500	3500	3500
Land area (L)	ha	100	100	100

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