The Effects of Climate Change on Forest Insect Disturbance in South Korea - Challenges and Prospects

www.krei.re.kr

Ahn Hyeon-jin | Lee Sang-min | Choi Jun-yeong

Korea Rural Economic Institute

The Effects of Climate Change on Forest Insect Disturbance in South Korea

- Challenges and Prospects www.krei.re.kr

Ahn Hyeon-jin | Lee Sang-min | Choi Jun-yeong

Korea Rural Economic Institute

Researchers

Ahn Hyeon-jin | Deputy Research Director | Research manager, Chapters 1 through 3 and 5 through 6 Lee Sang-min | Senior Research Director | Chapters 1 and 4 though 5 Choi Jun-yeong | Researcher | Chapters 2 and 4

Research Report R840

The Effects of Climate Change on Forest Insect Disturbance in South Korea – Challenges and Prospects

| Registration | No. 6-0007 (May 25, 1979) |
|--------------|-----------------------------------------------------------------------------------------------------------|
| Published on | October 2018 |
| Publisher | Kim Chang-gil |
| Published by | Korea Rural Economic Institute (KREI) (58321) 601, Bitgaram-ro, Naju-si, Jeollanam-do TEL 1833-5500 |
| Printed by | Pribe (+82-61-332-1492) |
| ISBN | 979-11-6149-292-6 93520 |

• The contents of this book may be cited freely by specifying the source. Unauthorized reproduction or copying is a violation of the law.

PREFACE

Climate change is a serious global issue. It has occurred gradually over a long period but accelerated after the industrial revolution. Rapid climate change can cause great damage to not only humans but also the entire planet. In response to climate change, countries around the world have signed the Kyoto Protocol and the Paris Convention and are carrying out various national countermeasure programs to cope with climate change.

Climate change is also a major concern in the forest sector. It can change the benefits of forests to humans or even cause forests to damage humans. One of the damages by forest due to climate change is the emergence of forest pests. As such, studies on the relationship between climate change and the occurrence of forest pests are ongoing in steps, but there are only few studies of the economic impact of forest pests on climate change.

This study presents a method to measure the impact of damage by forest pest as the result of climate change. Specifically, it establishes the damage function with direct and indirect factors affecting the damage by forest pests and predicts the future damage rate according to future climate change. Using the predicted damage rate, it examines the impact of pests on the incomes of and the forest management decision by the forest owner by analyzing the change of future income from forest management, the change of tree forest cutting age, and the control efficacy. Lastly, it conducts a policy experiment to propose an effective forest pest management plan.

We hope that the results of this study will be of great help in establishing policies to effectively manage forest pests in response to the future climate change. We express our sincere gratitude to all who have significantly contributed to this study.

October 2018 President, KREI Kim Chang-gil

ABSTRACT

The Effects of Climate Change on Forest Insect Disturbance in South Korea: Challenges and Prospects

Research Background

The effects of climate change, such as drought and abnormal temperature, are gradually becoming more of a reality. The changes that climate change brought on the forest environments and the emergence of pests call for more delicate management measures. Therefore, it is necessary to reevaluate the current control status and establish the direction of a new preventive strategy that reflects the trend of climate change. For this effort, we need basic studies to objectively estimate the damage and assess the potential economic threat of forest pests. In particular, it is crucial to establish the damage rate (damage function) that reflects direct and indirect factors of effects of forest pests. It is because the damage rate enables measuring the economic impact such as the actual loss caused by the damage.

The pest prediction model currently used in Korea predicts the occurrence risk. However, there is a limit to the model for measuring the specific damage rate and the economic ripple effect that it causes. Analyzing the damage and the economic impact of forest pests is crucial as it provides the reference information necessary to solve upcoming ecosystem disturbances and maintain healthy and productive forests. It can also serve as an objective basis for policy-making to prevent disasters caused by pests as the result of climate change and to adapt to future climates.

Research Method

O The target subjects of this study are the most common forest pests and the widely damaged tree species in Korea. With the advice of experts in the field, we selected pine wilt disease and oak wilt disease as the target pests in consideration of the increasing trend of deciduous forests. To measure the damages inflicted by pests, we implemented the structural damage function used in studies such as Cobourn et al. (2011) and Kim Yongjun et al. (2015) and adopted the nonlinear panel probit model and the GEE estimation method to reflect the characteristics of the damage rate (D) which was the dependent variable. Moreover, we added the mean per panel value to the model according to the method proposed by Mundlak (1978) and Chamberlain (1980) to reflect the fixed effect that had not been observed.

- O We used the estimated damage function and RCP8.5 data to predict the rate of future damage caused by pests as the result of climate change. The damage rates of future pine tree wilt and oak wilt were then predicted for the next 80 years from 2018 to 2100, and we used GIS to visualize the future damage rate by cities or counties.
- O We introduced the concept of environmental payout to take into account the economics of wood and non-wood materials in the assessment of the economic impact by the forests. After setting up three scenarios of no pest outbreak as a baseline, pest infestation with no pest control, and pest infestation with prevention and control for the economic analysis, we compared the tree forest cutting age and the forest management revenues that including the incomes from wood and non-wood materials of each scenario. We then performed the simulation using the analysis results to investigate the changes in forest management revenues according to changes in wood market prices, environmental payouts, climate change, and utilization of infected trees.

Research Results and Implications

O The results of the estimation by the damage function and the future damage rate prediction confirmed that the damage rate from forest pests would increase and the extent of the damaged area would increase due to climate change. Moreover, the economic impact assessment indicated that the increased damage from pests caused by climate change would

decrease forest management revenues and increase uncertainty. As pest damage brought on by climate change is expected to increase uncertainties and economic losses, there is a need to review the policies that have been focusing only on follow-up measures. Also, it is necessary to assure stable control of pets through the reinforcement of pre-incident management and proper follow-up measures.

<Reinforcement of Preventive Measures>

O This study suggests various precautionary strengthening measures such as identification of key management subjects, improvement of tree health, improvement of resistance against pests through the development and replacement of species, and elimination of externalities through environmental payout. Until now, the government has led the efforts to control pests due to low forest management revenues leading to a lack of incentives for forest owners to focus on pest control. However, the current government-led management system is likely to face a shortage of budget and workforce if the pests increase due to climate change in the future. Therefore, there is a need to encourage individual forest owners to actively control pests by offering the incentive of higher profit from healthier forests.

<Supplementation of Follow-up Measures>

- O The ways to supplement the follow-up measures include the immediate treatment of trees killed by oak wilt disease, strengthening prevention of artificial spreading of pine wilt disease, and expansion of the use of infected trees to increase forest management income.
- O This study is considered as distinctive as it establishes a pest damage function that considers various factors and assesses the economic impact of pest insects by reflecting management factors using dynamic analysis while previous studies mostly used static methods such as par-

tial equilibrium when they assessed economic effects of the forest pests and did not consider various management factors such as pest control which could affect the real damage. However, the demographic variables used to assess anthropogenic activities in this study have limitations in that they do not reveal a specific correlation between the detailed history of activities and the damage rates. Therefore, 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 the details for pest control, the efficiency of the pest control and the profitability of the forest management may also be the topics for future research.

Researchers: An Hyunjin, Lee Sangmin, Choi Junyeong Research period: January 2018 - October 2018 E-mail address: hjan713@krei.re.kr

Table of Contents

| Chapter 1. INTRODUCTION 1 |
|----------------------------------------------------------------------|
| 1. Necessity and Purpose of Research |
| 2. Review of Previous Studies 4 |
| 3. Research Scope and Method |
| 4. Research Contents and Implementation |
| Chapter 2. Climate Change and Forest Pests |
| 1. Current Status of Domestic Forest Disease |
| 2. Proliferation Factors of Forest Pests 22 |
| 3. Changes in the Occurrence of Forest Diseases According to Climate |
| Change — 42 |
| Chapter 3. Pest Damage Function and Predicted Damage Rate 47 |
| 1. Theoretical Background 47 |
| 2. Model Setting and Analytical Data |
| 3. Analysis Results 62 |
| Chapter 4. Analysis of Economic Impact of Damage by Disease 79 |
| 1. Theoretical Background |
| 2. Assessment of Economic Impact |
| 3. Simulation 94 |
| Chapter 5. Basic Control Direction and Responses to Pest Control 107 |
| 1. Impact of Climate Change 107 |
| 2. Basic Control Direction and Response |
| Chapter 6. Summary and Conclusion 121 |
| REFERENCES |

List of Tables

| <table 1-1=""></table> | Differentiation of This Study11 |
|------------------------|--------------------------------------------------------------|
| <table 2-1=""></table> | Year-by-Year Trees Infected by Pine Wilt Disease 16 |
| <table 2-2=""></table> | Size of Oak Wilt Pest Control Project 21 |
| <table 2-3=""></table> | Method of Oak Wilt Pest Control21 |
| <table 2-4=""></table> | Climatic Factors Affecting Pine Wilt Disease, Insect Vectors |
| | and Host Trees |
| <table 2-5=""></table> | Domestic Damages by Pine Wilt Disease Due to Artificial |
| | Migration 33 |
| <table 3-1=""></table> | Key Variables and Related Previous Studies of Pine Wilt |
| | Disease Damage Function |
| <table 3-2=""></table> | Key Variables and Related Previous Studies of Oak Wilt |
| | Disease Damage Function |
| <table 3-3=""></table> | Results of Estimation by Pine Wilt Disease Damage |
| | Function (Average Marginal Effect) 62 |
| <table 3-4=""></table> | Results of Estimation by Oak Wilt Disease Damage |
| | Function (Average Marginal Effect) 66 |
| <table 3-5=""></table> | Change of Seasonal Average Temperature and Precipitation |
| | in South Korea |
| <table 4-1=""></table> | Parameters for the Analysis of Forest Cutting Age91 |
| <table 4-2=""></table> | Change of Forest Cutting Age According to the Infection of |
| | the Pine Wilt Disease 92 |
| <table 4-3=""></table> | Parameters for Forest Cutting Age Analysis |
| <table 4-4=""></table> | Change of Forest Cutting Age According to the Infection of |
| | the Oak Wilt Disease 94 |
| <table 4-5=""></table> | Change of Pine Wilt Disease Breakout Rate (β) 101 |
| <table 4-6=""></table> | Change of Oak Wilt Disease Breakout Rate (β) 102 |

List of Figures

| <figure 1-1=""> Change of Occurrence Pattern of Major Forest Insect Pests</figure> |
|------------------------------------------------------------------------------------|
| |
| <figure 2-1=""> Domestic Forest Pest Control System</figure> |
| <figure 2-2=""> Year-by-Year Increase Rates of Pine Wilt Disease and</figure> |
| Budget ······18 |
| <figure 2-3=""> Trend of Outbreak of Oak Wilt in Korea</figure> |
| <figure 2-4=""> Outbreak of Oak Wilt Disease by Metropolitan Region:</figure> |
| 2015-2016 |
| <figure 2-5=""> Infection Path of Pine Wilt Disease</figure> |
| <figure 2-6=""> Fumigation of damaged tarpaulin</figure> |
| <figure 2-7=""> Infection Path of Oak Wilt Disease</figure> |
| <figure 2-8=""> Emergence of Platypuskoryoensis in the Bukhansan National</figure> |
| Park 41 |
| <figure 2-9=""> Prediction Map of Suitable Region for Monochamus</figure> |
| alternatus 44 |
| <figure 3-1=""> Average Marginal Effect of Key Climatic Variables: Pine</figure> |
| Wilt Disease 64 |
| <figure 3-2=""> Average Marginal Effect of Key Climatic Variables: Oak</figure> |
| Wilt Disease |
| <figure 3-3=""> Distribution of Coniferous and Broad-leaved Forests 72</figure> |
| <figure 3-4=""> Forecast of Damage Rate from the Pine Wilt Disease 74</figure> |
| <figure 3-5=""> Forecast of Damage Rate from the Oak Wilt Disease 75</figure> |
| <figure 4-1=""> Change of Management Income of Pine Trees in the</figure> |
| Gangwon Region According to the Change of Timber |
| Market Price 96 |

| <figure 4-2=""></figure> | Change of Management Income of Quercus variabilis |
|--------------------------|----------------------------------------------------------------------|
| | According to the Change of Timber Market Price97 |
| <figure 4-3=""></figure> | Change of Management Income of Pine Trees in the |
| | Gangwon Region According to the Green payment |
| <figure 4-4=""></figure> | Change of Management Income of Quercus acutissima |
| | According to the Green payment |
| <figure 4-5=""></figure> | Change of Management Income According to the Change of |
| | Pine Wilt Disease Outbreak Rate (β) 102 |
| <figure 4-6=""></figure> | Change of Management Income According to the Change of |
| | Oak Wilt Disease Outbreak Rate (β) 103 |
| <figure 4-7=""></figure> | Change of Management Income of Quercus variabilis |
| | According to the Change of Utilization Rate (ρ , σ) of |
| | Infected Trees |
| <figure 4-8=""></figure> | Change of Management Income of Pine Trees in the |
| | Gangwon Region According to the Change of Timber Price |
| | after Climate Change (2071-2100) ······ 106 |

Chapter 1. INTRODUCTION

1. Necessity and Purpose of Research

1.1. Necessity of Research

The effects of climate change, such as drought and abnormal temperature, are gradually becoming more of a reality. Since environmental conditions such as temperature and precipitation affect the occurrence of pests, directly and indirectly, future climate change and resulting pests are expected to increase forest damage and economic loss in Korea. The pests like eggar and pine leaf gall midge that damaged forests gravely in Korea in the 1960s and 1970s decreased significantly due to intensive control since the 1980s, and the decrease of their occurrences is considered to have affected the overall reduction of pest-infected forest area (Figure 1-1). However, pine wilt and oak wilt have emerged as new major pests since the 2000s. The damages by pine wilt due to the vulnerability of pine trees and by oak wilt by Platypus koryoensis originating from Southeast Asia have proliferated as the result of global warming. The change of domestic forest environmental conditions caused by climate change showed that the damage by the pests which had not been a problem in the past has become serious.

The government has made great efforts to manage forest pests and achieved visible results. The government attention and effort were needed because the change of population and occurrence pattern of insect pests due to climate change can cause direct and indirect damages such as disturbance

of forest ecosystem, a decrease in forest income due to the reduction of forest resources, and imbalance in supply and demand of the wood market. However, the recent change in the forest environment and insect pest occurrence due to climate change has required more delicate management measures. Therefore, it is necessary to review the current control policies and establish the direction for a new control strategy. For this effort, we need basic studies to objectively estimate the damage and assess the potential economic threat of forest pests. In particular, it is crucial to establish the damage rate (damage function) that reflects direct and indirect factors of effects of forest pests. It is because the damage rate enables measuring the economic impact such as the actual loss caused by the damage.

<Figure 1-1> Change of Occurrence Pattern of Major Forest Insect Pests



Data: Korea Forest Service

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 the priority control areas, it has the limitation for measuring the specific damage rate and the economic ripple effect that it causes. A model must reflect both direct and indirect factors that affect forest diseases.

The direct factors are mostly related to average temperature and refer to the factors that directly affect the insect pest 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 the resistance capability against pests. Previous studies of climate change and forest pests focused only the temperature change which was the direct factor. However, the model of damage by pest must consider various direct and indirect variables since it is affected by the complex interactions of pest populations and host trees.

As climate change is becoming a reality, analyzing the damage of forest pests and the economic impact is crucial as it provides the reference information needed to maintain healthy and productive forests by solving the future problem of disturbance in forests. It can also serve as an objective basis for policy-making to prevent disasters caused by pests as the result of climate change and to adapt to future climates.

1.2. Purpose of Research

This study intends to present the method of measuring the damage by forest pest due to climate change. Specifically, it establishes the damage function that considers the direct and indirect factors affecting the pest damage and predicts the future damage rate according to climate change. Moreover, it uses the predicted damage rate to examine the change of future income from forest management, change of tree forest cutting age, and the effectiveness of pest control in order to analyze the impact of the forest pests on the income of the forest owners and decision making for forest management. It then performs the simulation to deduce the tasks for effective forest pest management.

2. Review of Previous Studies

2.1. Correlation between Climate and Pests

Sturrock et al. (2011) reviewed literature to understand the relationships between climate change and forest pests and forest management. The study defined terms such as the pest, cause of infection, climate change, and the outbreak of disease related to forest pests. It also classified forest pests into directly affecting pests and indirectly affecting pests depending on the way the cause of the disease is affected by climate change. It also explained how the forest declined due to the complex factors including direct and indirect impacts and summarized the correlation between forest pest and woodland mortality. Moreover, it argued that the forest pest insight, prediction, policy and the strategy to reduce the impact of climate change are necessary to manage forest pest due to climate change more effectively. In particular, it emphasized the need to clarify the impact of climate change and pathogens for prediction of forest pests.

Kang et al. (2010) predicted the proliferation of oak wilt disease in Bukhansan National Park. Although there is a wide range of environmental variables needed for explaining the spatial distribution of the oak wilt disease and predicting the potential damage area is, there are few studies on their importance and relationships. Therefore, this study estimated the relevance of environmental variables using the Ecological Niche Factor Analysis (ENFA) algorithm and then applied it to the diffusion prediction. The estimation indicated that the damaged area is highly related to slope direction and average temperature.

A study by Lim Jong-hwan (2015) investigated the effect of climate change on the dynamics and occurrence pattern of forest pest population and developed the model for it. According to the study results, the annual communities of eggar increased due to the temperature increase. Moreover, the study implemented a nonlinear regression model for cumulative temperature and accumulated eclosion rate of pine leaf gall midge, but the model calculation showed the deviation from actual climate phenomenon, and it

was due to the temperature adaptation mechanism of pine leaf gall midge. The study also suggested that the emergence of insect pests was accelerated by the temperature increase. Although the relationship between Platypus koryoensis, which was the insect vector of oak wilt disease, and the temperature increase was not yet clarified, it presumed that the proliferation and activity of the insect vector would increase as the temperature increased. Furthermore, it presented the result that showed that the lethal dose of eggs of spotted lanternfly (Lycorma delicatula) increased as the daily temperature in the winter season increased.

Kim et al. (2016) used a CLIMEX model to predict the present and future spatial distribution of Japanese pine sawyer which was the insect vector of pine wilt disease. The study configured the parameters related to the growth temperature of the dwarf beetle through the review of previous studies and used the error matrix method to consider the correlation with the actual distribution when selecting the parameter group. The simulation of the distribution according to the RCP8.5 scenario of the Korea Meteorological Administration predicted that the dwarf beetles would spread nationwide from the west and south coasts in the 2050s and 2090s.

2.2. Pest Damage Function

A study by Feder (1979) developed the damage function using the pest population-based approach. It assumed that pest damage (D) was in a linear relationship with the insect population (N)¹ and set the single-variable damage function $(D(N) = \delta N)$ that is affected only by the insect population. Here, δ refers to the damage caused by a single insect and is assumed to be a constant affected by the temperature, humidity, and the health of host plants.

A study by Kroll and Reeves (1978) used climatic variables to predict the damage from southern pine beetle (SPB) in the forest region in eastern

¹ Population of insects observed in the target area

Texas. The multiple regression model with SPB population as the dependent variable and various climate variables as independent variables showed that the mean temperature in February, the total precipitation in summer, and the total precipitation in spring affected the change of SPB population.

A study by Gan (2004) analyzed the correlation between the SPB damage rate and climatic variables using the panel data model. Moreover, it predicted the change of future income from wood due to SPB using four climate change scenarios. It added the unsalvaged volume of the tree to the climatic variables to show the correlation between the forest management and the SPB damage rate and imply that the forest management, suggesting that forest management could be used as an adaptation measure.

A study by Cobourn et al. (2011) proposed a structural damage function, that considered the climatic variables and the crop characteristics such as size and color in addition to the pest density variable, is usually used in pest damage models. The comparison of the structural damage function and the widely used population-based approach showed that the structural damage function had better the explanatory power.

A study by Kim et al. (2017) estimated the pest damage function with consideration to spatial autocorrelation of ginseng. It specified the statistical validity range of spatial autocorrelation using the packaged unit data and compared the statistical significance of the spatial autocorrelation variables in the model and the change of the model adequacy due to this. The analysis showed that the spatial autocorrelation variable had a positive relationship with the increase of outbreak of some diseases and increased the adequacy of the model. The study pointed out that it was necessary to consider the spatial correlation in addition to climatic factors when estimating the damage function. However, the spatial autocorrelation variables were not significant for some pests.

2.3. Forest Pest Prediction Model

The National Institute of Forest Science is the most active in studies of forest pest prediction models. It mostly performs the pest emergence risk prediction based on natural science knowledge, and the results are utilized for policy decision making such as setting up priority control areas. The pest prediction models developed by the National Institute of Forest Science include the Monochamus saltuarius eclosion period² prediction model³.

The individual growth rate of Monochamus saltuarius is investigated, and the eclosion period is estimated using the model⁴, and then the climate change scenario is substituted to the model to predict the future Monochamus saltuarius eclosion period. The Monochamus alternatus eclosion period is predicted using the past eclosion data of Monochamus alternatus⁵.

The institute also investigates the statistical significance of the species diversity of each family and the climatic factors with the pine wilt risk assessment model, climatic factors using the self-organizing map, the prediction of species diversity of each sporadic insect family, and multiple regression analysis. The pine wilt risk assessment model predicts the probability that a particular area can become a potential habitat for pine wilt by considering various variables such as climatic variables, altitude, slope angle, and azimuth.

² The act of emerging from the pupal case or hatching from the egg

³ Internal data of the National Institute of Forest Science

⁴ $f(x) = 1 - \exp[-((x - 0.25)/0.7)^{8.71}]$

x: Accumulated growth date of insect vector, f(x): Accumulated eclosion rate (0-1) ⁵ Model $f(x) = 1 - \exp[-(x/460.57)^{3.83}]$

x: Accumulated growth date of insect vector, f(x): Accumulated eclosion rate (0-1)

2.4. Measurement of Economic Impact of Pest Emergence

The economic damage or impact in this study refers to the financial damage or impact of the pest on the products and services generated by forests (Stark 1979). The economic analyses related to pests include the net present value (NPV) analysis and cost-benefit analysis. The effect of time is very important for wood because the growth period of wood is very long and there is a considerably long interval between the points of cost and revenue. Therefore, finding the optimal tree forest cutting age with consideration of future profits based on the dynamic analysis is crucial for the economic analysis of forests. The problem of determining the tree forest cutting age represented by wood can be solved with the equation suggested by Faustmann (1849) while the optimal cutting including wood as well as non-wood service was developed from the model suggested by Hartman (1976). The problem of determining the tree forest cutting age, which deals with the forest management related to pests, can be solved using these equations.

A study by Avalapati et al. (2007) investigated the impact of cogongrass on the pine tree logging business in the southeastern region in the United States. The study used the Faustmann model that shows the expected value of permanent forest use and applied four scenarios. Since young trees are vulnerable to infection of cogongrass, the tree forest cutting age was the shortest when there was no risk of infection. The reason is that there is no incentive for the forest owner to quickly log mature trees and reforest if there is a risk of cogongrass, and it is more useful to extend the tree forest cutting age due to the increase in the management costs incurred at the early stage of the forestation.

Macpherson et al. (2017) developed a model that added payout for non-wood services with the question of how pests would affect the tree forest cutting age of forests providing timber and non-timber services. They generalized the Hartman model that assumes the single tree forest cutting age to include pests. It is generally known that tree forest cutting age shortens when forest pests emerge. However, they discovered that the tree forest cutting age could be shortened or extended according to the spread of the pathogenic pests when the payout to non-wood value is applied. Therefore, they concluded that the ways to maximize the profits of forest owners could be found through the suitable response to the forest and pest conditions and that the payout to non-wood values could be determined according to the policy objective.

Dangerfield et al. (2017) pointed out the problem with the real option approach to determine the impact of uncertainty of forest pests on optimal management. In the case of pests, there is a natural infection upper limit represented by the host (tree), and the infection rate decreases as the upper limit is approached. However, they warned that the geometric Brownian motion (GBM) generally used by the real option approach did not reflect the infection characteristics of pathogenic pests, and thus the time to apply the management measures could be too late. They emphasized that using the logistic stochastic differential equation could reflect these two characteristics of pathogenic pests.

Ahn et al. (2018) analyzed the future potential economic effect of pathogenic pests due to climate change using the partial budget technical and partial balance model. They applied the RCP8.5 climate scenario using the CLIMEX software to deduce the EI (Ecoclimate Index) which represented the future potential range of spotted lanternfly and then set up the scenarios for future potential damage rate. The damage expected from spotted lanternfly was expressed by the change of direct income of each family and the loss of social welfare. They then presented the results that the total of the loss of direct income and the loss of welfare due to the outbreak of pathogenic pests under the scenario was about 20% higher than the baseline scenario.

2.5. Differentiation from Previous Studies

This study can be mainly divided into the damage function measurement and economic impact assessment. The differentiation in the damage function measurement is that, while the previous studies of domestic forest disease models focused on predicting the potential occurrence period and hab-

itat based on the natural science theory, this study intends to obtain the specific pest damage rate in consideration to the interaction of climatic factors, pest occurrence period, and host trees. The deduced damage rate can be used as the reference data for the establishment of the forest pest control policy since it can measure the economic ripple effect such as the change of the revenue from forest due to the pest. Secondly, the damage function of this study reflects the complicated mechanism of pest occurrence by considering both direct factor variables that directly affect the pest population and indirect factor variables that indirectly affect pets by affecting host trees. Moreover, it includes factors such as artificial factors and managerial factors in addition to climatic factors in assessing the impact of human activities on forest pests. The results are expected to deduce policy implications such as the managerial factors to strengthen when establishing the future strategy to cope with climate change.

Until now, there have been few studies on assessing the economic impact of pests due to climate change in Korea. While some studies (Ahn et al. 2018) performed the economic assessment using the future damage rate based on assumption, this study performs the economic assessment based on the directly deduced damage rate. The differentiation of the analysis method is that this method uses the dynamic model while the existing studies mostly use static analysis such as the partial balance model. This study differs from existing studies in that it considers not only the simple decrease of revenue due to the damage from pests but also the change of revenue due to the change of managerial factors such as pest control to assess the change of economic income.

While the existing studies limited the economic damage from forest pests to income from wood business, this study considered both the income from wood business and the environmental value. However, reflecting the environmental value such as carbon absorption can make the model unnecessarily complicated, and thus we introduce the concept of the environmental payout to reflect the environmental variable indirectly. This study intends to deduce the new strategic direction by suggesting the environmental payout to strengthen pest management.

| | Measurement of Damage Function | Economic Analysis |
|---------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Existing Studies | - Prediction of potential outbreak period and habitat based on natural scientific theory: the Monochamus alternatus eclosion period developed by National Institute of Forest Science | There have been few studies on assessing the economic impact of forest pests due to climate change in Korea. The study by Ahn et al. (2018) set the damage rate scenario with assumptions and analyzed economic factors. It used the static model such as the partial balance method and did not consider indirect factors such as the management factor. The study by Gan(2004) limited the damage from pests to the damage to the wood business. |
| This Study | Deduction of the specific pest damage rate Variables include the direct factors that affect the pest population and the indirect factors that affect pests through host trees. The model also considers factors such as artificial factors and managerial factors in addition to climatic factors. | This study performs the economic assessment based on the damage rate deduced by the damage function. Dynamic model The model analyzes the impact of managerial factors such as the pest control on the economy. This study also introduces the concept of the environmental payout to consider not only the economic value but also the environmental value such as carbon absorption provided through the forest. |

<Table 1-1> Differentiation of This Study

Data: Authors

3. Research Scope and Method

3.1. Research Scope

The subjects of this study are forest diseases and affected tree species. Four forest pests that are subject to national policy management in Korea include Bursaphelenchus xylophilus, Thecodiplosis japonensis, Matsucoccus thunbergianae, and Platypus koryoensis. Considering the available data and the policy and academic importance, we selected Bursaphelenchus xylophilus and Platypus koryoensis. Platypus koryoensis causes oak wilt disease which has proliferated since the middle of the 2000s, and its impact can

increase due to the trend of growth of broadleaved forests. We included the fungus as the subject to study since the damage of broadleaved forests is expected to increase due to the proliferation of broadleaved forests. On the other hand, we excluded Thecodiplosis japonensis and Matsucoccus thunbergiana from our study as the experts advised that the diseases caused by them have declined considerably and are relatively less important.

The subject region is South Korea including Jeju Island, and we used the panel data of cities and municipal districts. To measure the damage function, we collected the data of pine wilt disease for 8 years between 2010 and 2017 and the data of oak wilt for 7 years between 2011 and 2017. We then predicted the future damage rate for 80 years between 2018 and 2100.

For measuring the economic damage from pests, we included the wood business and environmental payout as the main income source. We did not consider factors such as short-term forest products that are indirectly damaged. The direct damage from pests is generally measured with decreased income due to the deterioration of wood productivity. However, the forests in Korea are tended to be valued in non-market aspects such as landscape and emotional functions more than direct benefits such as wood production. The problem is that it is difficult to reflect indirect values that are not objectively measured into quantitative analysis, and thus there are few studies related to it. Therefore, we assumed the payout for these values and assessed the economic impact of the change of this payout instead of trying to measure the values and reflect them in the analysis.

3.2. Research Method

We used the literature survey, basic statistical survey, and quantitative analysis for the study. We also consulted the experts from the National Institute of Forest Science and the Korea Forest Service for the parameter setting, pest characteristics, and policy requirements to develop the model. We also consulted with mathematical experts for the verification of the developed model. The data on forests and pests needed for the analysis were acquired from the relevant organizations such as the National Institute of Forest Science and the Korea Forest Service, and we used the public data from the Korea Meteorological Administration for the climate data. We also visited the damaged area in Gyeongbuk and Jeonnam provinces and interviewed the forest engineers.

4. Research Contents and Implementation

4.1. Research Contents

This document is organized as follows.

Chapter 1 reviews the current status of forest diseases such as pine wilt and oak wilt in Korea each year through the statistical data published by the National Institute of Forest Science and the Korea Forest Service and examines the change of the pattern of domestic forest diseases and policy interest.

Chapter 2 investigates the relationship of climate change and other conditions to the spread of forest diseases through the literature and site visits. We examined the characteristics, causes, and potential factors for the outbreak in the future of forest diseases through the literature survey and investigated the methods of controlling forest pests and improvement opportunities in the control system through the site visits.

Chapter 3 presents the structural damage function that considers internal and external variables such as climate factors and characteristics of host trees and estimates correlation between the pest damage rate and independent variables using the reduced form of the model. For the measurement of the damage function, we modified the structural damage function used in the studies by Cobourn et al. (2011) and Kim (2017). We then substituted the estimated coefficient into the RCP8.5 climate change scenario data to predict the expected pest damage rate for the next 80 years.

Chapter 4 performs the economic impact assessment and simulation of the forest pest damage rate on the wood and non-wood business. We used

a dynamic model to analyze the emergence of forest pests on the tree forest cutting age and the forest business income and used the simulation to examine the effects of lumber market prices, environmental payouts, and climate change on the tree forest cutting age and the objective function. The results were aggregated to suggest the direction and tasks for controlling forest pests to cope with climate change.

| | | | Study Method | | | | |
|-------------------------------------------------|-----------------------------------------|---|----------------------|-------------------------|--------------------------|--------------------|---------------|
| | Study | | Literature Review | Statistical Analysis | Quantitative Analysis | Advisor Meeting | Site Visit |
| □ C | urrent Status of forest disease | | | | - | | |
| | • Climate change and forest diseases | ⇒ | ۲ | | | ۲ | |
| | • Status of domestic forest diseases | ⇒ | ۲ | ۲ | | | ۲ |
| □ E rate | stimation and prediction of pest damage | | | | | | |
| • Development of forest pest damage function | | ⇒ | ۲ | | ۲ | ۲ | ۲ |
| Prediction of future forest pest damage rate | | ⇒ | ۲ | | ۲ | ۲ | |
| Economic ripple effect of forest disease | | | | | | | |
| • Economic impact on wood and non-wood business | | ⇒ | ۲ | | ۲ | ۲ | |
| Simulation | | ⇒ | ۲ | | ۲ | ۲ | |
| □ Management direction and tasks | | | | | | | |
| □ Summary and conclusion | | ⇒ | | Aggregati | on of research | results | |

4.2. Implementation

Û

Expected Benefits and Utilization

• Establishment of theoretical ground for analysis of rippled effect of forest pests

• Provision of reference data for establishing the efficient forest pest control strategy

• Provision of reference data for securing the budget for forest pest control

Chapter 2. Climate Change and Forest Pests

1. Current Status of Domestic Forest Disease

1.1. Pine Wilt Disease

The disease was first reported in Geumjeongsan, Busan in 1988, and it is presumed that the tree was infected by the parasites that escaped from a monkey box originated from Japan. Although the damaged areas were limited to Gyeongnam and Jeju until 2005 has spread nationwide since 2010.

The outbreak of pine wilt gradually declined as the result of the enactment of the special act in 2005 and government-wide efforts but began increasing in 2011 and rapidly increased in 2013. It is now showing the decreasing trend. The climatic factors and inadequate control response were identified as the reason for the rapid spread in 2013. Although the environment favorable to insect vector was established due to intense heat and drought in the period from June to August⁶, which was the eclosion and active period of the fungus, the disease was omitted from the control program because it was difficult to identify infected trees (Seon 2014). 20 municipalities including Pohang, Gimje, and Geoje failed to remove damaged trees or neglected the field management.

⁶ The average temperature of June - August in Jeju was 0.6-1.6°C higher while the number of rainy days was 0.7-3 days fewer than the average of the last 3 years.

16 Climate Change and Forest Pests

As a result, the government established the emergency control measures in 2013 to remove all dead trees by the end of April before the eclosion period. The government expanded the aerial and ground control during the active period of insect vectors. However, the damaged area spread further, and the control conditions deteriorated although the number of damaged trees decreased after the establishment of the emergency control measures.

<Table 2-1> Year-by-Year Trees Infected by Pine Wilt Disease

| | | | | | | | Unit: EA |
|---------------------------|---------|---------|---------|-----------|-----------|-----------|----------|
| Region | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 |
| Total by Regions | 258,444 | 486,040 | 468,372 | 1,922,269 | 1,588,546 | 1,261,717 | 930,518 |
| Seoul | 0 | 0 | 0 | 0 | 12 | 1 | 0 |
| Busan | 2,613 | 3,047 | 10,220 | 90,183 | 50,822 | 10,791 | 12,378 |
| Daegu | 2,990 | 3,796 | 3,291 | 5,001 | 1,217 | 5,872 | 4,618 |
| Gwangju | 0 | 0 | 0 | 118 | 0 | 28 | 20 |
| Ulsan | 27,811 | 53,605 | 66,149 | 147,183 | 127,462 | 200,147 | 153,671 |
| Sejong | 0 | 0 | 0 | 0 | 0 | 91 | 23 |
| Gyeonggi | 851 | 2,773 | 6,073 | 38,958 | 55,285 | 48,604 | 44,594 |
| Gangwon | 0 | 0 | 0 | 233 | 8,489 | 861 | 1,089 |
| Chungbuk | 17 | 0 | 0 | 214 | 204 | 56 | 38 |
| Chungnam | 0 | 314 | 3,207 | 2,018 | 4,066 | 65 | 39 |
| Jeonbuk | 2,720 | 206 | 1,195 | 61,670 | 17,108 | 31,211 | 11,861 |
| Jeonnam | 12,497 | 2,453 | 3,534 | 15,577 | 6,400 | 6,316 | 3,731 |
| Gyeongbuk | 4,012 | 38,384 | 125,561 | 261,471 | 327,758 | 381,511 | 311,972 |
| Gyeongnam | 197,266 | 370,876 | 222,038 | 778,425 | 445,723 | 221,346 | 158,926 |
| Jeju | 7,667 | 10,586 | 27,104 | 521,218 | 544,000 | 354,817 | 227,558 |
| Total by Regional Offices | 6,192 | 3,884 | 10,245 | 261,727 | 148,121 | 111,381 | 61,845 |
| Northern Regional Office | 0 | 0 | 117 | 14,872 | 25,615 | 23,635 | 9,551 |
| Eastern Regional Office | 0 | 0 | 0 | 0 | 0 | 8,681 | 7 |
| Southern Regional Office | 5,024 | 2,326 | 2,194 | 144,530 | 90,399 | 60,093 | 47,010 |
| Central Regional Office | 0 | 0 | 0 | 0 | 0 | 10,872 | 13 |
| Western Regional Office | 870 | 253 | 7,053 | 92,669 | 30,388 | 5,204 | 1,723 |
| NIFS | 298 | 1,305 | 881 | 9,656 | 1,719 | 2,896 | 3,541 |

Data: Internal data of the Korea Forest Service

The Korea Forest Service (KFS), which has the overall responsibility for the forecasting and control of forest pests in Korea, establishes the annual plan and operates the forecasting and control unit.⁷ The following figure shows the domestic forest protection system. The KFC establishes the control plan and allocates the budget for the next after municipal and regional offices report the forest disease outbreak for the year. The KFC then instructs the control plan to each municipal and regional office which carries out the control in the appropriate period for each pest. The total number of pest control personnel is variable since they are recruited on a case-by-case basis for short-term work.





Data: KFS (2017a).

⁷ The forecast and control group is led by the public officers or forestry engineers and consists of four members for each group. Each member is assigned a unique mission such as lumbering, forecasting, and control. The group has the mandate to establish and operate the integrated budget and designs and orders the control projects such as recruitment of control staff and injection of trees. Although it establishes the integrated budget, it can request the emergency control fund if there is a shortage of the budget. The integrated budget is advantageous for quickly responding to disease outbreaks and rationally execute the budget, but has the problem of securing the equipment such as shredder since the regional offices often conduct pest controls in the same period.

18 Climate Change and Forest Pests

The control budget has been increasing as the public has become more aware of the seriousness of pine wilt disease. The examination of the year-by-year trend of dead trees and control budget shows similar increasing patterns. The control budget for a year increased when the number of dead trees increased in the previous year because the control budget is allocated based on the damage in the previous year. The details of pine wilt forecasting and control project are provided in the Appendix.

<Figure 2-2> Year-by-Year Increase Rates of Pine Wilt Disease and Budget



Data: Authors

1.2. Oak Wilt Disease

The oak wilt disease was first confirmed in Seongnam region in Gyeonggi province in 2004 and was scientifically named as Raffaelea quercus-mongolicae. The trees were infected by pathogenic bacteria through insect vector, and the external symptoms include holes with the diameter of 1 mm by the insect vector, dried leaves of infected trees, and generation of wood dust by intruding insect vector. Tunnels by intruding insect vector are found inside the timber (NIFS 2014).

The main insect vector of oak wilt in Korea is Platypuskoryoensis. Although the insect vector has been known in Korea since 1935, the widespread damage to oak trees began in 2004 (Institute of Green-bio Science & Technology, 2011). Considering that its distribution was reported in the 1930s and that the main distribution points are Korea and Russia, it seems to be the native species (Choi 2013). No case of oak trees being dead for the biological reason had been reported in Korea, but since 2004, the density of Platypuskoryoensis has been explosively increased, resulting in the simultaneous occurrence of the disease (Kim et al. 2010).

The host trees are infected by the intrusion of Raffaelea quercus-mongolicae, which is a type of fungus species, and 20% of infected trees usually die. It causes damage to Quercus serrata, Quercus aliena, Quercus variabilis, and Quercus acutissima (Institute of Green-bio Science & Technology, 2011), but the mainly damaged species is Quercus mongolica, and the medium and large hardwoods with the diameter of 20 cm or larger are mostly affected. Although it was regarded as a secondary pest that mainly attacks dead woods and fallen woods, the cases of attacking and killing healthy trees have recently increased (Choi 2013).

Since the mass killing of oak trees by the oak wilt disease was reported in Gyeonggi Province in 2004, the outbreak had increased rapidly until 2008 (Nam et al. 2016). The number of affected trees began decreasing in 2008, briefly increased in 2011, and has been decreasing since then. Although the number of affected trees is decreasing, the affected regions are widening. More than 10,000 trees were infected in 18 municipalities in Gyeonggi, Gangwon, and Jeonbuk in 2004, and more than 1,000 trees or about 10% were killed. Then the damage rapidly increased in four years as 194,419 trees⁸ were affected in 67 municipalities in 2006, and 298,000 trees were affected in 4.087ha in 2008. The damaged areas were 68 municipalities managed by 24 local offices in 2010 but increased to 94 municipalities in 2013 and 103 municipalities in 2016. As such, there is a concern that the damage is likely to continue to increase as the density of insect vector is increasing.

⁸ The figure represents the sum of dead trees and the affected trees although not killed by the intruding insect vector.

20 Climate Change and Forest Pests



<Figure 2-3> Trend of Outbreak of Oak Wilt in Korea

<Figure 2-4> Outbreak of Oak Wilt Disease by Metropolitan Region: 2015-2016



Note: Northwestern region: Seoul, Gyeonggi, Northern Regional Office, Incheon, and NIFS Central western region: Daejeon, Chungbuk, Chungnam, and Central Regional Office Southeastern region: Gyeongbuk, Gyeongnam, Ulsan, and Southern Regional Office Northeastern region: Estern Regional Office

Data: NIFS data reorganized by authors.

The regions showed different characteristics of damage (Figure 2-4). The northwestern region, which includes Seoul and Gyeonggi Province, accounted for 91.8% of the total damage in 2016 and has continued to be the

Data: Nam et al. (2016).

center of damage since its first occurrence in 2004. It was followed by the central western region (Daejeon and Chungcheong) with 3.4% in 2016, and other regions accounted for negligible share. The mortality rate of national forests was lower than that of forests managed by municipalities, suggesting that the national forests were better controlled (Nam et al. 2017).

The size of the oak wilt pest control project has gradually increased, and thus the number of damaged trees has decreased due to the increased control budget since 2014. Details of the control projects include the removal of damaged trees, the installation of sticky roll tapes, selective cutting, and spraying of insecticides (Table 2-3).

<Table 2-2> Size of Oak Wilt Pest Control Project

Unit: KRW million

| Year | Total | National Budget | Municipal Budget |
|------|-------|-----------------|------------------|
| 2014 | 6,586 | 3,919 | 2,667 |
| 2015 | 5,675 | 3,109 | 2,566 |
| 2016 | 6,139 | 3,468 | 2,671 |
| 2017 | 6,860 | 3,916 | 2,944 |
| 2018 | 6,872 | 3,875 | 2,997 |

Data: KFS (2017b).

| <table 2-3=""></table> | Method | of Oak | Wilt | Pest | Control |
|------------------------|--------|--------|------|------|---------|
|------------------------|--------|--------|------|------|---------|

| Project | Target | Method and Standard | | |
|-------------------------------------|------------------------------------------------|----------------------------------------------------------|--|--|
| Selective cutting in small district | Damaged area | Smaller than 5 ha and lumbering of mostly oak trees | | |
| Fumigation | Dead tree | Fumigation after lumbering and stump fumigation | | |
| Sticky roll tape trap | Damaged trees in the previous and current year | Within 20 m from the managed districts and dead trees | | |
| Large capture system | Damaged trees in the previous year | Installed on the branch | | |
| Installation of trap log | Damaged area | Use of trees with the diameter of 20 cm and 10 points/ha | | |
| Spray of insecticides on the ground | Damaged area | Spray of insecticide on the branch | | |

Data: NIFS (2014).

22 Climate Change and Forest Pests

2. Proliferation Factors of Forest Pests

This section examines the impact of climate change⁹ trend on the distribution of study subject pests in the Korean Peninsula through the literature survey, data survey, and expert consultation. Moreover, it intends to investigate the effect of climate factors on the ecology and development stage of pests to support the proposition that "climate change affects forest pests" and present the academic ground for key variables of the damage function. Global warming is a typical phenomenon caused by climate change, and it affects the natural ecosystem of the Korean Peninsula broadly by increasing average temperature, rainfall, and drought.

According to the RCP climate scenario, the average temperature in Korea is expected to increase in the 21st century continuously and predicted to increase by $+1.3^{\circ}$ C (RCP2.6) to $+2.1^{\circ}$ C (RCP8.5) in 2050 and by $+1.3^{\circ}$ C (RCP2.6) to $+3.9^{\circ}$ C in 2100. The number of non-precipitation days in 2050 is expected to increase by 4.3 days (RCP2.6) to 4.4 (RCP8.5) days from 2000, and the maximum hourly precipitation is expected to increase by 0.5mm (RCP2.6) to 1.0mm (RCP8.5) (Chae et al. 2017).

The pests emerge due to the complicated interaction among the insect vector, pathogen, weather, and host plant conditions. Climate change directly affects the density of insect vectors and the health of host plants and thus can be the direct and indirect cause of the proliferation of pests (Ciesla 2011). Existing studies presumed the temperature to be the main non-biological factor that directly affects the behavioral change of insects. The temperature change is known to provide the direct cause for the change of insect density by affecting the death rate at each growth stage of pests (Bale et al. 2002). Insects have the complicated lifecycle and are exposed to the different season at each growth stage and thus react sensitively to

⁹ Climate change is generally divided into natural factors such as earth orbit crust activity and artificial factors by increasing greenhouse gas concentration and refers to the gradual change of the climate system (Climate Research Team, Korea Meteorological Administration 2008).

temperature changes in different season (Kingsolver et al. 2011). Insects and amphibians are more sensitive to external environmental conditions and thus more affected by temperature changes than mammals which are homoiotherms (Yoon et al. 2010).

However, most studies of pests and climate change have not focused on climatic factors such as the humidity and precipitation (Bale et al.2002; Weed et al. 2013). The precipitation can be the indirect cause of the proliferation of pests as it affects the health of host trees. Simultaneous occurrence of the heat wave and drought, in particular, is known to be the cause of deteriorated resistance by host trees against pests. Therefore, it is difficult to explain the correlation between climate change and pests only with the direct factors such as the insect population change, and thus it is necessary to consider the indirect effects such as the interaction between pests and host trees (Lawton 1994; Davis et al. 1998).

Neuvonen and Virtanen (2015) presented the following consideration to predict the correlation between forest pests and climate change. They include 1) the effect of ecological knowledge and climate variables on the behavioral change in each stage of the lifecycle of the target pests, 2) the forest ecological environment such as the forest distribution and the structure of forest age, 3) factors that affect the change of pest population and the interaction with the external factors, and 4) securing sufficient data such as the pest emergence trend and seasonal climatic variables. This section examined the climatic factors and non-climatic factors that can affect the pest ecology and proliferation directly and indirectly based on the study by Neuvonen and Virtane (2015) and the literature survey.
2.1. Pine Wilt Disease

2.1.1. Ecology of Pathogen (Bursaphelenchus xylophilus) and Insect Vectors¹⁰

Bursaphelenchus xylophilus, which is a 1mm-wide thread-like nematode, grows on the host tree and blocks the passage of water, and thus 100% of infected trees are withered. Although it mainly infects pine trees, nut pine trees can also be infected. Symptoms such as discoloration of leaves appear quickly, and then the trees wither as the leaves turn brown. It takes about six weeks for an infected tree to wither in summer when the temperature is high. There are cases of trees infected in autumn surviving into winter or next spring due to the delayed infection speed because of low temperature. However, the infected pine trees and nut pine trees are killed within one year and two years, respectively.

Bursaphelenchus xylophilus is a pathogen and cannot be transported without an insect vector. Therefore, they can be eradicated by removing the insect vector. The known insect vectors are Monochamus alternatus and Monochamus saltuarius which are most active at 18~28°C. The insect vectors become adult within a year and start laying eggs after 20 days from eclosion. They lay an average of 1 to 8 eggs per day on sparrows and dead wood bracts in spawning season¹¹. An adult female lay an average of 100 eggs. The larva hatches from the egg about 7 days later and grows by feeding mainly from the cambium part of the tree. It takes about 10-12 days at 20°C and 5-7 days at 25°C for the egg to become a larva.

The larvae make pupa nests for wintering in wooden parts of the tree until October. They remain dormant in wooden parts in winter and become pupa in March - June in the next year. The pupal period is about 20 days at 20°C and 12 days at 25°C, and Bursaphelenchus xylophilus that has grown in the wooden parts intrudes into the pupa during this period. The

¹⁰ The ecology of insect vector is based on "Basic Design Service for Bursaphelenchus xylophilus in Pohang City" (Lim et al. 2016).

¹¹ The average spawning season of Monochamus alternatus is June through September and most active in July through August.

insect vector stays in the nest for about a week after becoming an adult and then escapes to the outside of the wood part by making 5 - 6 escape holes.

The eclosion and escape occur mainly during May through August in the case of the Monochamus alternatus and during late April through late May in the case of the Monochamus saltuarius. They become adults mostly in late June. An adult carries 15,000 Bursaphelenchus xylophilus nematodes which intrude pine trees through the cuts when the insect vector feeds on the buds of the healthy pine tree.



<Figure 2-5> Infection Path of Pine Wilt Disease

Data: Daum blog (http://m.blog.daum.net/philook/15721003?categoryId=751073: March 10, 2017).

Bursaphelenchus xylophilus, which is the native species in North America, had been isolated in the long-leaf pine (Pinus palustris) sample in Louisiana since 1929 but became known to be related to the group withering of Pinus nigra in Missouri 50 years later (Dropkin et al. 1981). Pine

trees in North America generally have the resistance to Bursaphelenchus xylophilus since they have co-evolved, and thus no severe damage has occurred in the United States. However, they have caused severe damage to local pine trees that did not have the resistance since they migrated to the Eurasian region in the early 20th century (Wingfield et al. 1982; Evans et al.1996).

The first occurrence of Bursaphelenchus xylophilus in Japan was reported in Nagasaki Prefecture on the island of Kyushu in 1905. The port city had a lot of exchange with the United States, and goods were imported in wooden boxes. It was presumed that the Bursaphelenchus xylophilus spread as the larvae of Monochamus alternatus attached to wooden boxes grew into adults. However, there was no widespread of Bursaphelenchus xylophilus at that time because the withered trees were immediately used as fuel. Then the Bursaphelenchus xylophilus spread mostly in the Kansai region when the use of withered trees was restricted during the war period in 1930s.¹² The spread slowed down under the strong administrative measures such as the burning of withered trees and prohibition of migration by the Supreme Commander of the Allied Powers (SCAP) led by the US military in the 1950s.¹³ The Japanese government conducted the aerial control in the 1970s after the relationship between the withering of pine trees and Bursaphelenchus xylophilus was scientifically discovered. However, Ryukyu pine trees in Okinawa were almost wiped out, and the infection spread throughout Japan except for Hokkaido and Akita.¹⁴ Bursaphelenchus xylophilus was spread to other East Asian countries such as Korea, Taiwan, and China in the 1980s and even to Europe in the late 1990s and early 2000s (Roques et al. 2015).

Based on the differences in the damage patterns of each continent, it was discovered that the following two conditions must be satisfied for the dam-

¹² The correlation between Bursaphelenchus xylophilus and pine wilt was not scientifically discovered at the time.

¹³ The period is known to be the only time that the control of pine wilt disease was successful in Japan.

¹⁴ Cited from an interview with Professor Emeritus Kazuyoshi Hutai of Kyoto University (Financial News, http://www.co.kr: 2018. 10. 31.).

age of pine wilt disease could spread. The first condition is that the infected hosts must be vulnerable to Bursaphelenchus xylophilus, and the second condition is that the environmental factors are favorable for the spread of symptoms (Roques et al. 2015; Evans et al. 1996). Therefore, it is necessary to manage the above two conditions to prevent the spread of damage from Bursaphelenchus xylophilus.

Replacement and diversification of tree species can be the countermeasures to prevent the spread of damage. Pinus densiflora, also called the red pine, is the leading pine tree species in Korea and known to be vulnerable to Bursaphelenchus xylophilus unlike pine trees in North America. Kansas State in the United States recommends planting of the species resistant to Bursaphelenchus xylophilus and suitable to local climate such as eastern red cedar as the windbreak forest. According to the general principle of prevention of pests, it is necessary to diversify the species and minimize the damage caused by specific pests. Moreover, it is necessary to focus the pest control in the regions that have the environmental condition suitable for proliferation of infection. Climate change is expected to expand the suitable environmental regions since the environmental factors are closely related to climate conditions. Therefore, it is necessary to forecast regional damage based on the objective data and continue managing them for the future even if no major damage is currently reported.

2.1.2. Proliferation Factors of Pine Wilt Disease

The proliferation factors of pine wilt diseases can be mainly divided into climatic factors and artificial factors that affect the nematode, insect vector, and host tree. The climatic factors directly change distributed population by affecting the ecology of the nematode and insect vector and the health of host tree while the artificial factors cause spread of infection beyond the migration range of insect vector due to humans such as transport of infected trees.

A. Climatic Factors

The climate can be one of the leading causes of the spread of the disease as it affects the growth and activities of Bursaphelenchus xylophilus and the insect vectors which are Monochamus alternatus and Monochamus saltuarius. The temperature and humidity affect egg hatching rate, larval growth rate, and eclosion period at each growth stage and thus the direct factors in the insect density distribution.

Existing studies have reported that the temperature directly affects the growth rate and reproduction of Bursaphelenchus xylophilus. The study on the growth of Bursaphelenchus xylophilus under different temperature conditions by Mamiya (1975) showed that the growth of the first-generation was completed in 3 days at 30 °C, 4-5 days at 25 °C, 6 days at 20 °C and 12 days at 15 °C. However, too high temperature had a negative effect on growth and reproduction. The growth disorder was observed when the temperature exceeded 30 °C (Mamiya 1975), and the spawning activities decreased when the temperature obtained from the theoretical value was 9.5 °C, meaning that the growth did not occur at the temperature below it (Mamiya 1975).

Monochamus alternatus and Monochamus saltuarius, the insect vectors, become adults in a year, and the growth stages are seasonal. Although there are differences in eclosion period and others, they generally spend winter in larva state while the eclosion, feeding, and spawning occur through spring and summer. The activities of Monochamus alternatus are observed even in autumn. Therefore, the seasonal climatic factors are expected to affect the growth state and activities of insect vectors. The increase of average temperature in spring, summer, and autumn increases the growth rate of insect vectors, leading to the increased population, and the seasonal relative humidity is also known to affect the growth rate.

The study by Kong (2006) reported that the life of Monochamus alternatus significantly increased when the relative humidity increases at the constant temperature of 25 $^{\circ}$ C (comparison of relative humidities of 90% and 40%). The growth rate of Monochamus alternatus is reported to increase linearly at the temperature of 15-30 $^{\circ}$ C (Roques et al. 2015). Therefore, the increased average temperature in spring and summer can shorten the time of emergence and eclosion of adult and eventually lead to a decrease of in the generation period of insect vectors.¹⁵

The distribution of insect vector is constrained by the thermal barrier (Roques et al. 2015), and the activities such as growth and spawning are reportedly restrained below the certain limiting temperature. Therefore, the maximum and minimum temperature in winter, spring, and summer, when the growth and spawning occur, and the population of insect vector can have a close correlation.

Insects that spend winter in larva status tend to have limited survival due to the low temperature in the winter (Roques et al. 2015). According to the study by Ma et al. (2006), the distribution limit of Monochamus alternatus is more constraining than the distribution limit of host trees such as pine trees in China. In China, the isotherm line of the average temperature of $-10 \ ^{\circ}$ C in January is the northern limit for survival regardless of the temperature at each survival stage. The region with the average temperature of $-4 \ \sim -10 \ ^{\circ}$ C in January is potentially survival region, and the region with the higher average temperature is the survival region.

A study on Japan reported that the northern limit for survival of Monochamus alternatus was 40° north latitude (near Honshu Island in Japan and Pyeongannam-do in Korean Peninsula) (Kobayashi et al. 1984). Therefore, the northern limit of Monochamus alternatus can move further north if the average temperature increases due to global warming.

The minimum temperature in summer is also reported to be the factor that limits the survival of the Monochamus alternatus. According to the study by Kobayashi et al. (1984), the average temperature in summer must

¹⁵ The insect vectors of pine wilt disease in Korea are Monochamus alternatus in southern regions and Monochamus saltuarius in northern regions. Since the Monochamus alternatus carries more pests than the Monochamus saltuarius and is migrating further north due to the climate change, this study focuses on the Monochamus alternatus which have been the subject of many studies. Although they have different characteristics such as the developmental zero point, they are considered to have the similar patterns of reacting to climate (Roques et al. 2015).

be 21°C or higher for the adult females of Monochamus alternatus to spawn. Accordingly, it is difficult for Monochamus alternatus to survive in the Hokkaido and Tibet regions where the temperature in summer is low even though they are below the northern limit for survival.

However, it was disclosed that the population of the Monochamus alternatus decreased when the temperature in summer was too high. The growth rate of larva decreased at the temperature of 30°C or higher, and there was no growth at a temperature of 35 °C or higher (Roques et al. 2015). The lethal upper threshold of larva is 32 - 35°C (Naves and Sousa 2009).¹⁶

Climate requirements for the growth of insect vectors may vary from country to country. While the distribution regions of insect vector was constrained by the average temperature in summer and winter (21°C or higher in July and -10°C or higher in January) in China, they were constrained only by the average temperature in summer (20°C or higher in July) in Europe (Robinet et al. 2010).

In addition to the average temperature, the precipitation and relative humidity are also known to affect the proliferation of insect vectors. However, there are relatively few studies on the correlation of the precipitation and humidity with the proliferation of insect vectors. The study by Kong (2006) reported that the life of Monochamus alternatus significantly increased when the relative humidity increases at the constant temperature of 25 °C (comparison of relative humidities of 90% and 40%).

Since the climatic factors affect the health of host trees, and the health of host trees has a close correlation with the survival environment of in-

¹⁶ The developmental zero point (the suitable limit temperature needed for growth of an insect) of the larvae of Monochamus alternatus is 12.7 - 13°C, and the temperature of 12.5°C is necessary for growth (Okuda 1973). For 50% of winter larva to become adult, Monochamus alternatus needs the temperature of 11.9°C or higher, and Monochamus saltuarius needs the temperature of 8.6°C or higher. Moreover, the developmental zero point of pupa is 10.6°C (Enda 1980). A study carried out an experiment of growing insects at 30°C artificially to grow into pupa without dormancy (Davis et al. 2008). The observation of the growth of larvae and pupae at 17°C, 21°C, 25°C, and 29°C showed that the best growth occurred at 25°C (Jung 2009).

sects, the proliferation of infection can differ according to the climatic factors and the health of trees. Infection of pine trees to nematode generally occur in areas where the average temperature of 20 ° C or higher lasts for several weeks in summer (Rutherford and Webster 1987), and no infection occurs in cold areas. The fact that the infection rarely occurs in cold regions although the Bursaphelenchus xylophilus can survive in those regions indicates that the health deterioration of trees due to the high average temperature in summer is one of the factors of the proliferation of pine wilt disease (Mamiya 1984). The expansion of tree-evaporation due to the simultaneous occurrence of high temperature and drought is known to be the cause of deteriorated resistance of host trees against Bursaphelenchus xylophilus. Therefore, the infection to Bursaphelenchus xylophilus can expand due to the hot and dry climate in summer (Evans et al. 2008).

<Table 2-4> shows the climatic factors that affect the pine wilt disease, insect vector, and host trees at each growth stage based on the above. It indicates that the average temperature, humidity, and maximum and minimum temperatures in each season are closely related to the expansion of the pine wilt disease.

| <table 2-4=""></table> | Climatic | Factors | Affecting | Pine | Wilt | Disease, | Insect | Vectors | and |
|------------------------|----------|---------|-----------|------|------|----------|--------|---------|-----|
|------------------------|----------|---------|-----------|------|------|----------|--------|---------|-----|

| | Growth Stage | Season | Climatic Factor | | |
|---------------------------------------------|-------------------------------------|------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|--|
| Pine Wilt Disease | First generation at 25°C for 5 days | Summer Autumn | - Average temperature: The growth of the first generation is completed in 3 days at 30 °C, 4-5 days at 25 °C, 6 days at 20 °C, and 12 days at 15 °C. | | |
| Insect Vector (Monochamus alternatus) | Pupa → Eclosion | Spring | Average temperature: The increase of the average temperature affect the dormancy of larvae, and the larvae grow into pupae without dormancy at the average temperature of 30°C or higher. Minimum temperature: The developmental zero point of pupae is 10.6°C. Average wind velocity: The migration speed of insect vector increase when the wind velocity increases. | | |

Host Trees

(continue)

| | Growth Stage | Season | Climatic Factor | | |
|---------------------------------------------|----------------------------------------------------------------------------------------------------------------------------|--------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|--|
| | Spawning by adult Egg → larva | Summer | Average temperature: The growth rate of larvae increases linearly at the average temperature of 15°C - 30°C. Minimum temperature: The minimum average temperature needed for spawning in summer is 21°C or higher. Maximum temperature: The lethal upper threshold of larvae is 35°C. | | |
| | larva | Autumn | Average temperature: The growth rate of larvae increases linearly at the average temperature of 15°C - 30°C. Minimum temperature: The temperature of 12.5°C or higher is necessary for growth. | | |
| | larva | Winter | Average temperature: The average temperature in January must be -10°C or higher for the survival of larvae. Minimum temperature: The temperature of 11.9°C or higher is necessary for 50% of wintering larvae to become adults. | | |
| Insect Vector (Monochamus saltuarius) | larva | Winter | - Minimum temperature: The temperature of 8.6°C or higher is necessary for growth. | | |
| Host Tree | Deterioration of resistance to pine wilt disease when the high temperature and drought occur simultaneously | Summer | Average temperature: Too high temperature in summer deteriorates the health of trees.Precipitation: The resistance by trees deteriorates when the drought lasts. | | |

Data: Authors.

B. Artificial Factors

Artificial factors such as the transport of infected trees by humans are some of the causes of the proliferation of pine wilt disease and are known to be the leading reason for the unforeseen and long-distance outbreak of the disease. The migration radius of Monochamus alternatus is known to be $3\sim$ 5km. However, the proliferation of infection beyond the migration radius of insect vectors is often observed in China and other countries. A study reported that 90% of recent new infections in China were located at the distance of 111 - 339 km from the origin point (Robinet et al. 2009). In Korea also, the proliferation of infection by artificial reasons such as the transport of infected trees by local residents occurs often. Unauthorized migration of infected trees to use them for cooking fuel and building materials proliferates the unforeseen damages. As an example, there was a case of a local sauna collecting the fumigated pine trees after a pest control to use them for fuel, resulting in the insect vectors escaping from firewood (Lee et al. 2014). The pine wilt disease in Korea is characterized by a widespread to the unforeseen regions. It indicates that the artificial factor is one of the key causes of the proliferation of pine wilt disease in Korea. <Table 2-5> summarizes some of the damages by pine wilt disease due to the artificial migration in Korea.

<Table 2-5> Domestic Damages by Pine Wilt Disease Due to Artificial

| Region | Damage Size | Cause | | |
|-----------------------------------------------------------------------------------------------|---------------------|-----------------------------------------------------------------------------------|--|--|
| Pohang, Gyeongbuk (Construction site of Pohang-Daegu Expressway in Gigye-myeon, Buk-gu) | 3,850 trees | - Infected trees supplied to the highway construction site or a nearby lumbermill | | |
| Okjong-myeong, Hadong-gun in Gyeongnam | More than 30 trees | - Infected trees supplied to a sawdu manufacturing plant | | |
| Changseon-myeong, Namhae-gun in Gyeongnam | More than 300 trees | - Possible supply of infected trees for cultivation of bracken | | |
| Gwangju in Gyeonggi | Unknown | - Escape of insect vectors from pillars of a newly constructed temple | | |
| Chuncheon in Gangwon | Unknown | - Escape of insect vectors from pillars of wooden building for sauna | | |

Migration

Data: Existing reports summarized by authors.

Roques et al. (2015) suggest the population change as the variable that can best explain the proliferation of pine wilt disease by an artificial factor. The study argued that the population change can be the indicator of the artificial size and frequency in the land and has a correlation with the inflow and outflow of infected trees. The population can be an indicator that reflects not only the total scope of artificial activities but also the social overhead capital (SOC) conditions such as the road and forest trail in each

region. Areas with a high population are likely to have the better infrastructure such as the road, and the increase in the anthropogenic activities and the movement radius of people may have a positive correlation with the inflow and outflow of infected trees. However, although the population change can represent the total volume of anthropogenic activities, there is a limitation of explaining the frequency and size of infection proliferation according to each activity. It is necessary to develop the indicators that show each specific activity through further studies.





Data: Photographed by authors (Wilt control site in Gurye-gun)

2.2. Oak Wilt Disease

2.2.1. Ecology of Pathogen (Bursaphelenchus xylophilus) and Insect Vectors

Oak wilt is a disease caused by the Raffaelea fungus; a kind of Ambrosia fungus destroys oak trees by blocking the moisture and nutrient pathways (NewsWide 2012). In Korea, the oak wilt disease is mainly caused by the infiltration of Raffaelea quercus-mongolicae, which is closely related to Raffaelea quercivor that critically damage to Quercus serrata and Quercus grosseserrata in Japan but differs in geographical origin and host range (Torii et al., 2014).

The insect vector of oak wilt disease in Korea is Platypuskoryoensis which is known as a type of ambrosia beetle. Woodworms can be divided into bark beetles and ambrosia beetles depending on the feeding habit. Bark beetles penetrate the bark and make tunnels, and the adults and larvae attack the phloem between bark and xylem while the adult ambrosia beetles attack the xylem of weak trees to create tunnels and infect the bacteria (Institute of Green-bio Science & Technology 2011).

Pathogens and insect vectors form mutualism. The Platypuskoryoensis larvae feed on pathogens¹⁷ while the pathogens propagate by moving from a tree to another through Platypuskoryoensis. Raffaelea inhabits in my-cangia on the back of female Platypuskoryoensis. The male pierces a tunnel of 1 mm in size on an oak stem for mating, and the mycangium bursts as the female enter the tunnel and raffaelea is cultivated on the oak tree. The larvae born through mating grow by eating fungi cultivated in tree tissues (Institute of Green-bio Science & Technology 2011).

The active period of adults is early May through early October, and early and middle of June is the most active period for eclosion (Institute of Green-bio Science & Technology 2011). Male adults create tunnels on trees in May and June and discharge frass (a mixture of wood powder and feces) to attract females. The frass contains the aggregation pheromone which differs in appearance depending on sex and lifestyle. Males discharge toothpick-shaped frass with 1.2 mm thickness during the early period of attacking host trees in May and June while females discharge ball-shaped frass with 2 mm thickness after mating in June and July. Larvae discharge powder-shaped frass in August and September. The trees exposed to the powder-shaped frass withers since its xylem is already completely destroyed from many attacks (Institute of Green-bio Science & Technology 2014).

Females spawn at the edge of the tunnel, and the larvae that hatch about a week later grow by making new tunnels branched from the mother gallery. Larvae build pupa house in mid-October and spend winter, but some spend winter as adults or pupae (Institute of Green-bio Science & Technology 2014). They then emerge into adults in May and June in the

¹⁷ The ambrosia fungi become food for insects that cannot digest wood fibers.

following an attack the host trees.

The infected trees have their vessels blocked by the multiplication and proliferation of the fungi, making it difficult for the water to rise, and thus the leaves turn dry and red and eventually die. With the penetration of insect vector in around May, oak trees show the infection beginning at the end of July, and the withered trees can be observed in August and September. Although oak trees resist the attacks by insect vectors by spraying sap, they cannot survive a mass attack of the insect vectors because of the foams of the insecticide and the aggregation pheromone generated by the frass. Since sawdust-type frass appears around the trees that have been attacked by the insect vectors, it is relatively easy to determine whether the insects are infested, and the trees on which the frass takes up 1/2 or more of the perimeter of the tree is considered unrecoverable and thus cut and incinerated (Institute of Green-bio Science & Technology 2011). The withering rate of infected trees is about 20%, and the leaves are stuck to the withered trees without falling even in the winter (Nam et al. 2016).



<Figure 2-7> Infection Path of Oak Wilt Disease

Data: NIFS (2014).

2.2.2. Proliferation Factors of Oak Wilt Disease

Although Platypuskoryoensis was discovered in Korea in the 1930s, the damage from oak wilt disease began to appear in earnest in 2004. The abnormal temperature and physiological weakness of oak tree are suggested as the reasons for the sudden proliferation of damage, but there are few studies to prove it. In Japan, the damage occurs mostly in years when the temperature is high, and the precipitation is low, and the damage is relatively low when the temperature is low, and the precipitation is high, and thus people paid attention to the relationship between the temperature/precipitation with the proliferation of oak wilt (Lee 2009).

The phenomenon that the population of some forest pests remains low for years and then explosively increases to incur extensive damage is called the population eruption or eruptive outbreak. The eruptive outbreak is often reported in bark beetles in Europe, North America, and Asia (Ciesla 2011). Although southern pine beetles (Dendroctonus frontalis) usually maintain the population within the natural range, they temporarily show explosive population growth or decline from time to time. The population rapidly increased in the 1960s and 1980s in Honduras in South America, and there is the record of an eruptive outbreak of pine bark beetle in eastern Texas, but the population has rapidly decreased since the 1990s.¹⁸

This study divided the expansion factors of oak wilt into the climatic factors and non-climatic factors. The climatic factors include the temperature and humidity that directly take part in the infection rate by affecting the ecology of insect vectors and health of trees while the non-climatic factors are related symptoms of the disease as the results of human activities, host preference by insect vectors, and management factors. Although the sudden proliferation of oak wilt in Korea may have been related to the eruptive

¹⁸ The hypotheses for the cause of eruptive outbreak include the local epicenters suitable for pest habitat and mating being formed and then the next generations spreading to adjacent areas (Ciesla 2011) and the simultaneous variation of population eruption due to the change of the related population dependency if the population dependency applicable to two or more population is the same (Ripa 2000).

outbreak, it is not in the scope of this study. However, further studies of pest expansion cycle including the eruptive outbreak would be needed.

A. Climatic Factors

The increase of average temperature due to global warming promoted the growth of insects, and the damage from sub-tropical insects, which had not been a problem in Korea, began to occur. ince Platypuskoryoensis which belongs to the Platypus genus, has the characteristics of southern species, the increased average temperature in the Korean peninsula may have created the environment favorable to the insect vector (Choi, 2009).

The high temperature and humidity climate are known to be optimal growth of fungi. Damage to trees by bark beetle to trees occurs often in tropical forests where the temperature and humidity are high. The raffaelea fungus that causes the oak wilt disease is medium to high thermophilic, and the optimal temperature for growth is reported to be $25-30^{\circ}$ (NIFS 2010). The hot and humid region is likely to have a higher probability of pest proliferation than the cold and dry region.

The period exposed to the low temperature during the growth stage and the reaction to seasonal temperature change is known to affect the population of bark beetles. Bark beetles go through the lifecycle of eggs, larvae, pupae, and adults. Platypuskoryoensis is the mature larva right before becoming the pupa and exposed during the coldest weather from December to February. Since the thermophilic insect stops growing below the critical temperature (NIFS 2010), its population can extensively decrease by the cold winter temperatures (Bentz et al. 2010). Its active adult period is affected by the temperature, and an experiment reported the low critical temperature to be 5.8 $^{\circ}$ (Youngwoo Nam et al. 2013).

Platypuskoryoensis is known to be the secondary pest that usually attacks weak trees and withered trees. Although the cases of its attacking healthy trees also are frequently found, its main attack target is weak trees. Moisture stress due to the high temperature and dry climate is known to have a significant effect on the health of host trees. Trees facing moisture stress is easily exposed to attacks by insect vector because of the decrease in the production of sap ejected as the resistor of the tree (Bentz et al. 2010). Insect vectors inhabiting on weak trees can attack adjacent healthy trees also (Gaylord 2014).

The Korea National Park Research Institute (KNPRI 2012) applied the maximum entropy model to estimate the contribution rate of climatic variables (average temperature, etc.) that affect the damage of oak wilt disease using the spatial data of emergence of the oak wilt disease in Deogyusan and Gyeryongsan National Park. The research results showed that the contribution rates of the maximum temperature, minimum temperature, and precipitation were high, and the contribution rate of the average temperature was low. The impact of the maximum temperature was usually high. However, there was no indication of the direction of each variable was not presented in the study.

B. Non-Climatic Factors

1) Diameter at Breast Height (DBH)

Since Platypuskoryoensis mostly attacks trees with the large diameter, the damage from the oak wilt disease tends to be proportional to the tree's DBH. KNPRI (2010) collected the reference data for control of the oak wilt disease in the Bukhansan National Park and the Chiaksan National Park and reported that the insect vectors preferred host trees with 30 cm or larger diameter at the breast height. NIFS (2010) compared the diameter at the breast height of Quercus mongolica for each damage level in five fixed survey sections including Namyangju and Pocheon in Gyeonggi Province, and Cheolweon and Hwacheon in Gangwon Province¹⁹ showed that the damage level increased as the diameter at the breast height increased. Lee et al. (2011) investigated the damage from the oak wilt disease in the vicinity of Mt. Wooam in 2009 and found that DBH and damage level were proportional and that trees with large DBH were preferred attack target of insect vectors.

¹⁹ The damage was divided into 3 levels; Intense, Middle, and Light.

2) Fertility of Deciduous Oak Trees According to Environmental Factors

The oak wilt disease is considered as the forest disease proliferated due to the rich fertility of oak trees caused by the change of the environmental factors in the Korean Peninsula. Although the right land for Quercus mongolica, which is the species that the insect vectors can inhabit most easily among oak trees in Korea, has recently been decreasing (Yeounggeun Lee et al. 2014), there has been a tendency that the disease of broad-leaved trees such as oak wilt is likely to increase because of the trend of decreasing (Byeonghyeon Jeong et al. 2017).

3) Artificial Factors

Artificial factors such as the roads, trails, and distance from the village are also the factors affecting the proliferation of the oak wilt disease. KNPRI (2012) investigated the status of the oak wilt disease in the Bukhansan National Park and found that the of population Platypuskoryoensis was high in the areas such as rest area, trail, and the facilities where there was a high level of people movement. However, the author argued that more detailed study was necessary to determine if the reason was the artificial migration of insect vectors and infected trees by floating population or the ecological characteristics such as a flight habit of Platypuskoryoensis.

Sangwoong Lee and Taeweon Uhm (2014) discovered that the damaged trees were concentrated within 20 m of the trail radius near Temple Sangwon in a total investigation of the damage from the oak wilt disease in the Chiaksan National Park. They suggested the possibility of Platypuskoryoensis being introduced through the forest trails or climbing trails. Moreover, logging has been suggested as a cause of the rapid increase in the number of insect pests (Ciesla 2011).



<Figure 2-8> Emergence of Platypuskoryoensis in the Bukhansan National Park Unit: Number of objects

Note: For the number of objects, a traps with a length of 2 m was installed long, and the number of objects per 50 cm was measured, and then converted into the total area.

Data: KNPRI (2012) data on p.29 reconfigured by the authors

4) Management Factors

The frass generated by trees attacked by insect vectors emits aggregation pheromone to cause proliferation of damage by group attack. Therefore, failing to manage the damaged trees properly can expand the damage to nearby healthy trees. The insect vectors tend to concentrate on attacking weak trees. Therefore, it is necessary to establish management measures to immediately dispose of withered trees and improve the health of all trees.

3. Changes in the Occurrence of Forest Diseases According to Climate Change

3.1. Changes in the Occurrence of Wilt Disease According to Climate Change

Climate change mostly leads to increased drought frequency and average temperature. The simultaneous occurrence of high temperature and drought deteriorates the health of host trees and creates the conditions that favor the growth of insect vectors and thus increase the possibility of proliferating diseases. In Japan, the most infection of the wilt disease occurred in areas where the average summer temperature exceeded 22°C and rarely occurred where the average summer temperature was below 20°C. Therefore, the average summer temperature of 20°C can be the key indicator to evaluate the regions for the breakout of the wilt disease (Roques et al. 2015).

If the average summer temperature increases due to climate change, the wilt disease can proliferate to some regions of North Korea which is not currently the suitable regions for the wilt disease. New infections have recently been discovered in regions where there had been no report of the wilt diseases in East Asia (Aomoi Prefecture in Japan, Boryeong and Yangju in Korea, and Shaanxi Province and Hunan Province in China). Such phenomena are likely to be closely related to climate change (Roquest et al. 2015).

The study by Robinet et al. (2011) predicted that the regions suitable for the wilt disease would expand by 40% in China and 100% in Europe if the average temperature increased by 3°C. In consideration of regional characteristics, the critical temperature for the breakout of the wilt disease was set the average July temperature of 21.3°C and average January temperature of -10°C in China and the average July temperature of 20°C in Europe. It is predicted that the suitable region for the breakout of the wilt diseases, which is currently limited to the southeastern region of China, will expand to the northeastern region if the average temperature increases by 3°C. However, the Tibet plateau, northern Yunan, and western Sichuan, where the winter temperature is low, are likely to remain the unsuitable regions. In Europe, the suitable region for wilt disease, which currently mostly occurs in the southern region, is likely to expand to whole Europe and southern part of the Scandinavian Peninsula (Robinet et al. 2011).

The study by Kim Jae-wook et al. (2016) forecasted the present and future spatial distribution of Monochamus alternatus in Korea using the CLIMEX model and the RCP 8.5 climate scenario. It predicted that the suitable region for the breakout of Monochamus alternatus in Korea was likely to gradually expand to the north due to climate change such as the increased monthly average and maximum temperature. In the current distribution status, Jeju Island showed the highest ecoclimatic index (EI)²⁰, followed by Busan, Gwangju, and Ulsan. Gangwon and Chungbuk were judged to be the unsuitable region as they, except for some areas, mostly recorded the EI²¹ of less than 10. However, whole South Korea except for parts of Gangwon is likely to become the suitable region for Monochamus alternatus since the environment suitable for inhabitation of Monochamus alternatus will be created due to climate change beginning in the 2050s.

²⁰ EI represents from a value that indicates a specific organism "cannot exist because of unsustainability (EI=0)" to the value that indicates it "can be distributed as a carrying capacity density (EI=100)" in the subject area when considering only the weather. EI values are generally divided into three categories of settlement possibilities (Marginal suitability = EI<10, Favorable suitability = 10<EI<20 to 25; Very favorable = EI>20 to 25) (Jaewook Kim et al. 2016).

²¹ Jaewook Kim et al. (2016) suggested EI>10 as the criterion to be a suitable region.



<Figure 2-9> Prediction Map of Suitable Region for Monochamus alternatus

Data: Jaewook Kim et al. (2016: 508).

3.2. Changes in the Occurrence of Oak Wilt Disease According to Climate Change

There are few studies on the occurrence of the oak wilt disease. Therefore, we intend to suggest the approximate occurrence pattern of the oak wilt disease in the future by using the future weather data and studies of bark beetles.

There is a report of climate change causing the widening of the distribution range of some bark beetles, ambrosia beetles, and pathogen (Tisserat et al. 2009). Walnut twig beetles, which predominantly live in the southern United States, such as Arizona, California, and New Mexico and have damaged walnuts, have expanded its habitats to northern regions. They have been discovered in Colorado, Idaho, Oregon, and Washington since 2002 and attacked new hosts such as the black walnut.²² The damage is predicted to expand to the eastern region which is the main habitat of black walnut trees due to climate change.

Although the oak wilt disease in Japan was first discovered in the 1930s, the full-scale damage has appeared since the 1980s. Global warming is mentioned as the primary cause. The habitat of the insect vector is predicted to expand to the northern regions and high altitudes due to future climate change, and thus the damage to healthy trees is forecasted (Kamata et al. 2002). In the early 1980s, the infection by the raffaelea fungus caused by platypodidae led to group withering of Quercus mongolica forest. Although the weak and withered trees were key attack targets until then, the damage has proliferated to healthy trees also since the 1980s. The damage expanded to the western shores of Japan in the 1990s. It was presumed that the damaged area increased as the habitat of platypodidae expanded to northern regions due to the increase in the average temperature in Japan since the late 1980s.

According to the study by Gan (2004), which estimated the damage by the southern pine beetle (SPB) due to climate change, the increase in the temperature in the spring and winter had a positive correlation with the increase in the SPB damage, and the increase in the precipitation in spring, autumn, and winter had a negative correlation with the damage increase. The estimation by simulation showed that climate change would increase the future SPB damage by 2-2.5 times and incur the annual loss of 513-629 million dollars in the southern United States.

3.3. Implication

Since it first broke out in Busan in 1998, the wilt disease has incurred

²² A severe economic damage is expected since the black walnut is the highly valuable wood material used in luxury furniture.

great damages to pine forests in Korea. Although the damaged withered trees have been decreasing since the emergency control measures in 2013, the damaged areas have been increasing to make the control more difficult. The oak wilt disease first discovered in Korea in the vicinity of Seongnam in Gyeonggi Province has also shown a decrease in the number of damaged trees but the breakout areas have been increasing since 2011. The review of forest pest control budget indicates that the management of forest pests in Korea is concentrated on the follow-up control. Since the budget and responding personnel depend on the damage in the previous year, the outcome of control in the process of the Decreased damage rate after concentrated input of control budget following the increased damage rate \rightarrow Decrease in the control budget \rightarrow Re-expansion of damage rate varies widely.

The proliferation factors of forest pests can be divided into climatic factors and non-climatic factors. The climatic factors include the temperature that causes the change of population by directly affecting the pest ecology and the precipitation that is closely related to the health of host trees. A temperature increase during the growth and active period of insect vector causes population increase by decreasing the death rate of larvae and expanding the active period of adults. The decrease in precipitation can cause an increase in the damage rate by deteriorating the health of host trees. The non-climatic factors include the migration of infected trees and management factors that affect the pest damage. In the case of the pine wilt disease in Korea, the artificial migration of infected trees is pointed out as the primary cause of the proliferation of the damage. The proliferation of the oak wilt disease was also caused by non-climatic factors such as the management factor, DBH, road, and trail.

It is predicted that pest damage areas would expand and the new damage areas would be created as the average temperature increases, and drought frequency increase are forecasted due to climate change. According to a study, whole South Korea is predicted to be the suitable habitat of Monochamus alternatus after 2050. According to a Japanese study, the damage of healthy trees by the oak wilt disease is predicted to increase as the habitat of the insect vector platypodidae expands to northern regions.

Chapter 3. Pest Damage Function and Predicted Damage Rate

1. Theoretical Background

1.1. Pest Damage Function

We used the structural damage function used in the studies by Cobourn et al. (2011), Yongjun Kim et al. (2015), and Yongjun Kim et al. (2017) to measure the damage from outbreaks. According to the study by Cobourn et al. (2011), the pest damage (D) that can be represented by the pest emergence rate can be expressed as the function of the characteristics of the damaged host (Z) and the pest population (P). Even if pests break out, the actual damage does not occur if hosts are not suitable to attract the pests. Therefore, the pest damage function can be expressed as shown in Equation (3-1).

$$D = f_d(z, P)$$
 Equation (3-1)

The pest population (P) is determined by the vector of characteristics of hosts (Z) and the exogenous variables (V) such as climatic factors while the characteristics of hosts (Z) can be affected by not only the exogenous variables (W) but also the impact of the pest damage (D) such as the volume and weight loss of host trees. The pest population (P) and the characteristics of host trees (Z) can be expressed as shown in Equation (3-2) below.

$$P = f_p(z, V)$$

$$Z = f_z(D, W)$$

Equation (3-2)

The damage function affected by the pest population and characteristics of hosts can be expressed in the form of a simultaneous equation as shown in Equation (3-3) below by combining Equation (3-1) and Equation (3-2). The exogenous variables V and W can be partly overlapped.

$$D = f_p(z, V)$$

$$Z = f_z(D, W)$$

Equation (3-3)

Although the instrument variable approach is necessary to estimate Equation (3-3), we can simplify the simultaneous equation to the simplified model as shown in Equation (3-4) if we assume that the characteristics change of hosts by the pest damage does not affect the pest population²³ $(Z = f_z(W))$ as the study by Cobourn et al. (2011) did.

$$D = g(W, V)$$
 Equation (3-4)

The simplified model is the practical model that can reflect the characteristics of hosts using the exogenous variables V and W that are relatively easy to obtain. Although using W instead of Z may generate the deviation of the estimation, the model using more explanatory W would improve the prediction (Yongjun Kim et al. 2015).

1.2. Nonlinear Panel Probit and GEE Estimation

²³ It is a simultaneous structure in which the characteristics change such as the change in the host's shape caused by the pests again affects the population of the pests. However, Cobourn et al. (2011) and Yongjun Kim et al. (2015) expressed it as $Z = f_z(W)$ since there was a lack of scientific evidence to support this simultaneous structure.

The damage rate, which is the dependent variable in this study, is the proportional dependent variable that has the value between 0 and 1. There can be a deviation in the result if we estimate the coefficients by ignoring the characteristics of the proportional dependent variable. Using the random or fixed effect after a log transformation, which is widely used in panel data estimation, can omit the observation value that has the value of 0 during the log transformation, and the estimated range can deviate from the range of $0 \le y_{it} \le 1.2^4$ when estimating with a logit model, we cannot reflect the observation value with the rate of 0. If we move the value by adding a small value to 0 to mitigate it, it can generate a deviation by causing the change of variable distribution.

To reflect such characteristics of the proportional dependent variable, we can express the conditional average of the range rate with the following form of the nonlinear panel probit.

$$E(y_{it} \mid \mathbf{x}_{it}, c) = \Phi(\mathbf{x}_{it} \mid \beta + c_i), \quad t = 1....T$$
 Equation (3-5)

Here, the range of the pest damage rate is $0 \le y_{it} \le 1$, and the dependent climatic variable X_{it} is the 1×k vector. $\Phi \Box k$ expressed as the cumulative density function (CDF) of the standard normal distribution,²⁵ and c_i is expressed as the effect between the unobserved cross-section observations. Equation (3-5) can be expressed by Equation (3-6) if we include the following assumption of exogeneity and the conditional normalized distribution of c_i .

$$E(y_{it} | \mathbf{x}_i) \equiv \Phi(\psi + \mathbf{x}_{it} \beta + \mathbf{x}_i \xi)$$
 Equation (3-6)

We can use the maximum quasi-likelihood estimation (QMLE) that uses the probit link function to the generalized linear model (GLM) (Papke and Wooldridge 2008). However, it tends to ignore the serial dependence that

²⁴ Here, *Y*it is the log transformed dependent variable and refers to the pest damage rate.

²⁵ Although a logit function can be used as a link function, Papke and Wooldridge (2008) explained that the probit link function was superior to the logit link function when the unobserved heteroscedasticity and indogeneity are generated.

exists in the joint distribution $\Box (y_{i1...}y_{iT} | \mathbf{x}_i)$, and thus it may be inefficient compared to the estimation that includes it.

The multivariate weighted nonlinear least square (MWNLS) is known to be ideal to estimate the panel data that has the serial dependence and heteroscedasticity. However, we need the parametric model to $V_{ar}(Y_i | \mathbf{x}_i)$, and estimating it is very difficult (Papke and Wooldridge 2008).

To supplement the weakness, Papke and Wooldridge (2008) suggested using the generalized estimating equations (GEE) using the exchangeable correlation instead of finding the parametric model of $Var(Y_i | \mathbf{x}_i)$. If $Var(Y_i | \mathbf{x}_i)$ is the same estimate, MWNLS and GEE become the asymptotically equivalent estimation. This study that has the panel data and proportional dependent variable utilized the GEE model that applied the probit link function and exchangeable correlation.²⁶

Equation (3-7) shows the conditional average of the pest damage rate of this study that has N municipalities (i=1,..., N) and T years (i=1,..., T).

$$E(Y_{it} | \mathbf{x}_i) \equiv \Phi(\psi + \mathbf{x}_{it} \ \beta + \mathbf{x}_i \xi)$$
 Equation (3-7)

Here, the variables Yit, Xit, and $\overline{X_i}$ \square effer to the pest damage rate (dependent variable), climatic factors and non-climatic factors (explanatory variable), and the average of the panels of the explanatory variables, respectively.²⁷ Since it is difficult to analyze the estimation coefficient of the nonlinear model estimated with GEE, we must deduce the average marginal effect (AME) which means the change of the dependent variable affected by the change of a unit of the explanatory variable (Papke and Wooldridge 2008).²⁸ We can observe the effect of the change of a unit of the dependent variable on the pest damage rate using the AME.

²⁶ Existing studies using GEE for the proportional dependent variable include Papke and Wooldridge (2008) and Hyunjin An et al. (2015).

²⁷ Here, the average value of the panels was included to reflect the fixed effect not observed with devices in Mundlak (1978) and Chamberlain (1980).

²⁸ Although the marginal effect is expressed as the coefficient of the β value in the linear model, the average marginal effect must be reestimated using the deduced coefficient of the β value in the case of GEE.

$$AME_{c} = N^{-1} \sum_{i=1}^{N} \hat{\beta}_{k} \phi(\hat{\psi} + \mathbf{X}_{i} \hat{\beta} + \overline{\mathbf{X}_{i}} \hat{\zeta}) \qquad \text{Equation (3-8)}$$

Here, ϕ means the probability density function (PDF) for the standard normal distribution.

2. Model Setting and Analytical Data

2.1. Pine Wilt Disease

Since the insect vector generates the pine wilt disease, its population change is closely related to the pine wilt disease. Moreover, the actual damage can depend on the vulnerability of pine trees to the pest. The damage function of the pine wilt disease reflecting the factors can be expressed as follows.

$$D = f_d(z, P)$$

$$P = f_p(z, V)$$

$$Z = f_z(W)$$
Equation (3-9)

D = Damage rate, Z = Characteristics of hosts, P =

Population of insect vector

Here, D is defined as the value that divides the total damage area (ha) by the total broad-leave forest area (ha) as follows.

$$D = \frac{Damaged area(ha)}{Total \text{ for } est area(ha)}, D = [0,1]$$
 Equation (3-10)

The damaged area (ha) can be generally obtained from 1) the number of damaged trees \times the average area per tree, 2) approximate area measured by connecting the outlines of the damaged area in the aeronautical map, or 3) using the area where taking out pine trees is prohibited²⁹ as the surrogate variable for the damaged area.³⁰ This study used method 1).³¹

The factors that affect the population of insect vector (P) were set as follows based on previous studies <Table 3-1>.

P=fp(MIN_WT(it-1), Snow_WI(it-1), SPT(it), SMT(it), SMT2(it), SMP(it), MIN_FA(it), Equation (3-11) RHUM SP(it), RHUM FL(it), POP(it)

- ³⁰ We summarized the information obtained through consulting from experts.
- ³¹ Method 1) is advantageous in that it is easier to obtain the data since we can use the infected tree data published by the Korea Forest Service each year and thus directly reflect the damage to standing trees. However, its disadvantage is that the data uses the average area index, and thus it is difficult to reflect the difference of the distance between trees according to the region. Method 2) is advantageous in that it can obtain the area data the reflects the difference of the distance between trees according to the region, but it is difficult to obtain the data in the same standard since the outlines are arbitrarily set by researchers. Moreover, it is difficult to obtain a sufficient number of samples since the data are available only in the limited area where the aerial control is performed. Method 3) is advantageous in that it can understand the actually and potentially damaged areas since the pine wilt disease is very infectious. However, the area prohibited from removing trees defined as the area within 2 km from the infected area can include the non-forest areas and thus the damage can be overestimated since the area that is larger than the total broad-leaved forest can be included in the administrative district.

²⁹ The areas prohibited from removing trees is defined as the infected area and the ri and dong within 2 km from the infected as prescribed by the Special Act on the Extermination of Pine Wilt Disease.

Here, MIN_WT (it-1) refers to the minimum winter temperature in year t-1, Snow_WI (it-1) refers to the snowfall in year t-1, SPT (it) refers to the spring temperature in year t, SMT (it) refers to the summer temperature in year t, SMT2 (it)refers to the square of the summer temperature in year t, SMP (it) refers to the precipitation in summer in year t, MIN_FA (it) refers to the minimum autumn temperature in year t, RHUM_SP (it) refers to the relative humidity in spring in year t, RHUM_FL (it) refers to the relative humidity in autumn in year t, and POP (it) refers to the population.

The population of adults in year t is closely related to the survival rate during the larval and pupal stages. Therefore, the model variables included the climatic factors that affect the survival rate, growth rate, migration, and spawning during the larval and pupal stages. The insect vectors that are generated once a year spend the winter as larvae and then grow into the adult in the following spring or early summer and infect the wilt disease to pine trees when they begin feeding. Therefore, the module included the climatic factors that are affected in each growth stage. The minimum winter temperature in year t-1 is included in the model since the temperature of the minimum critical temperature (11.9°C for Monochamus alternatus and 8.6°C for Monochamus saltuarius) is necessary for 50% of wintering larvae to become adults. Larvae mostly spend the winter within the cambium in the stem of the tree. The insulation effect of snow can prevent the larvae from being exposed to the cold temperature if there is a high snowfall in the winter. Therefore, the amount of snowfall in winter was included in the variables (Neuvonen and Vitranen 2015).

The infection by the wilt disease can proliferate quickly by artificial factors. The municipality population was included as the surrogate variable to reflect the artificial factor (Roques et al. 2015). The factors that affect the health (Z) of host trees during the summer in which the wilt disease infection mostly occurs are set as follows.

Z=fz(SMT(it), PRCP_SU(it)) Equation (3-12)

Here, SMT (it) refers to the average summer temperature, and PRCP_SU (it) refers to the precipitation in summer. The year 2013 was the period in which the breakout of the wilt disease rapidly increased temporarily. We

added the catastrophic dummy variable ct (2013) which sets 1 for the year 2013 to assure the stable estimation. We then deduced the following damage function by combining f_p and f_z .

D=fd(MIN_WT(it-1), Snow_WI(it-1) SPT(it), SMT(it), SMT2(it), SMP(it), WMAX_SP(it), WMAX_SU(it), MIN_FA(it), RHUM_SP(it), RHUM_FL(it), POP(it), PRCP_SU(it), ct(2013))

The analyzed period was 2010-2017, and the total of 1839 samples was obtained from 230 municipalities nationwide. The number of trees damaged by the pine wilt disease, the forest area in each municipality, the population in each municipality, and the weather data were used. The number of trees damaged by the pine wilt disease³² was multiplied by the index³³ to calculate the damaged area in each municipality from 2010 through 2017. The damage rate in each municipality was obtained by dividing the calculated damaged area by the total coniferous forest area (coniferous forest + 45%³⁴ of mixed forest)³⁵. For the past and future weather data, we deduced the average monthly value from the daily average data of each municipality

³² We used the internal data of the Korea Forest Service that showed the number of trees infected by the pine wilt diseases in each municipality.

³³ After consulting experts, we calculated the average area of 25 m² per tree and multiplied it by the number of infected trees to calculate the total area in ha.

³⁴ According to Article 4 of the Enforcement Rules of the Mountainous Districts Management Act (Order No. 342 by MAFRA, December 4, 2018, partial amendment), a "mixed forest" refers to the forest in which the coniferous or broad-leaved trees account for more than 25% and less than 75% each. We specified 45% as the portion of coniferous trees in the mixed forest which is more conservative than 50%, which is the mean of 25% and 75%, to reflect the trend of declining coniferous trees and the decrease in coniferous trees in the Korean Peninsula due to climate change.

³⁵ KOFPL data, "Accumulation of Forest Area and Trees by Year and Clinic" (www.kofpl.or.kr: April 5, 2018).

provided by the Climate Change Information Center and then obtained the seasonal average value³⁶ using them.

2.2. Oak Wilt Disease

The damage function of the oak wilt disease reflecting the factors that affect the insect vectors, pathogens, and host trees can be expressed as follows.

$$D_{O} = f_{d}(z, P)$$

$$P_{O} = f_{p}(z, V)$$

$$Z_{O} = f_{z}(W)$$
Equation (3-14)

 D_0 =Damage rate, Z_0 =Characteristics of host trees, P_0 =Insect vector population

Here, D_0 is the total broad-leaved forest area (ha) divided by the damaged area (ha) and defined as Equation (3-15).

$$D_O = \frac{Damaged area(ha)}{Total forest area(ha)}, D_O = [0,1]$$
 Equation (3-15)

For the damaged area (ha), we used the method of multiplying the number of infected trees by the average area per tree like pint wilt disease. Since the oak wilt disease tends to break out sporadically, it is difficult to calculate the area, and calculating the damaged area by connecting the outlines of through the aerial map can result in overestimation.

We set the factors that affect the insect vectors and pathogens (P_0) based on the previous studies as follows.

³⁶ Spring is defined as March through May, summer as June through August, autumn as September through November, and winter as December through February in the following year.

PO=fp(MIN_WT(it-1), RHUM_WT(t-1), SPTX(it), RHUM_SP(it), SMTX(it), SMTX2(it), FATX(it), RHUM_FA(it), POP(it), UST(it), Diameter(it), NF(i)) Equation (3-16)

Here, MIN_WT (it-1) refers to the minimum winter temperature in year t-1, RHUM_WT (t-1) refers to the relative humidity in winter in year t-1, SPTX (it) refers to the maximum spring temperature in year t, RHUM_SP (it) refers to the relative humidity in spring in year t, SMTX (it) refers to the maximum summer temperature in year t, SMTX2 (it) refers to the square of the maximum summer temperature in year t, FATX (it) refers to the maximum autumn temperature in year t, RHUM_FA (it) refers to the relative humidity in autumn in year t, POP (it) refers to the population, UST (it) refers to damaged tree area, Diameter (it) refers to DBH, and NF (i) refers to the national forest.

We included the climatic variables that directly affect the population of insect vectors and the proliferation of pathogen in the model. The minimum winter temperature in year t-1 can cause the population decrease of insects that spend the winter as larvae while the maximum spring, summer, and autumn temperatures in year t can affect the eclosion and active period in the variables, and thus they were included in the variables. Considering that the insect vector belongs to the Platypus genus and has the characteristics of southern species and thus is adaptive to warm weather, we set the maximum temperature, not average temperature, as the variable based on the study by the KNPRI (2012). We included the relative humidity in consideration of the fungi that can proliferate more in the hot and humid environment.

We included factors such as the population, infected trees without control, and whether the forest is managed by the government to study the effect of the managerial factors and artificial factors. According to a study by the KNPRI (2012), accessibility to roads, and accessibility to urban area³⁷

³⁷ Distance from an adjacent village or urban area

were the artificial variables that affected the damage to the oak wilt disease significantly. Therefore, we included the municipality population as the surrogate variable for the road and population migration (Roques et al. 2015). Considering that the insect vectors prefer trees with the large diameter, we included DBH in the variable (Lee et al. 2011; NIFS 2010) and the damaged tree areas without control (UST)³⁸ (Gan 2004). We also included the national forest NF (i) as a dummy variable and one of the managerial variables to study the difference of the damage rate according to the managing subject.

The precipitation and temperature are the factors that are closely related to the health of host trees (Z_0). The hot and dry weather can create the environment that is vulnerable to attacks by insect vectors since it deteriorates the resistance of host trees by causing the moisture stress and thus reducing the sap (Bentz et al. 2010).

Therefore, we included the precipitation in winter in year t-1, t and precipitation in spring, summer, and autumn in year t in the variables. We also included the square of summer temperature in consideration of domestic oak trees that are broad-leaved trees with southern characteristics that are vulnerable to high temperature.

We then deduced the following damage function by combining f_p and f_z .

DO=fd(fp(MIN_WT(it-1), RHUM_WT(t-1), SPTX(it), RHUM_SP(it), SMTX(it), SMTX2(it), FATX(it), RHUM_FA(it), POP(it), UST(it), Equation (3-18) Diameter(it), NF(i), PRCP_WI(t-1), PRCP_SP(it),PRCP_SU(it),PRCP_FA(it))

³⁸ The control usually involves removing withered trees, sticky roll tape trap, chemical control, and other controls.

The analyzed period was from 2011 to 2017, and the total of 1,610 samples was obtained from 230 municipalities nationwide. The number of trees damaged by the oak wilt disease, the forest area in each municipality, the population in each municipality, DBH, the damaged tree areas without control, national forest, and the weather data were used. The number of trees damaged by the oak wilt disease³⁹ was multiplied by the index⁴⁰ to calculate the damaged area in each municipality from 2011 through 2017. The damage rate in each municipality was obtained by dividing the calculated damaged area by the total broad-leave forest area (broad-leaved forest + 55% of mixed forest⁴¹ 55%).⁴². For the past and future weather data, we deduced the average monthly value from the daily average data of each municipality provided by the Climate Change Information Center and then obtained the seasonal average value⁴³ using them. For the DBH, the DBH (cm) data of oak trees in each municipality

³⁹ Internal data of the Korea Forest Service

⁴⁰ We calculated the average area of 25^{m²} per tree and multiplied it by the number of infected trees to calculate the total area in ha. Although the area occupied by a oak tree is not the same as that by a pine tree, we confirmed the difference was not large after consulting with experts and thus used the same standard for the comparison of damage from the wilt disease.

⁴¹ According to Article 4 of the Enforcement Rules of the Mountainous Districts Management Act (Order No. 342 by MAFRA, December 4, 2018, partial amendment), a "mixed forest" refers to the forest in which the coniferous or broad-leaved trees account for more than 25% and less than 75% each. We specified 55% as the portion of broad-leaved trees in the mixed forest to reflect the trend of expanding broad-leaved trees and the increase in broad-leaved trees in the Korean Peninsula due to climate change.

⁴² Internal data of the Korea Forestry Promotion Institute

⁴³ Spring is defined as March through May, summer as June through August, autumn as September through November, and winter as December through February in the following year.

published by the NIFS were used. For the damaged tree areas without control, we calculated the area using the number of trees as the remainder of the total number of infected trees subtracted by the number of controlled trees.

<Table 3-1> Key Variables and Related Previous Studies of Pine Wilt Disease Damage Function

| Explanatory Variables and Dependent Variables | | Description of Variable | Related Previous Studies | Unit |
|--------------------------------------------------|-------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| Do | Dependent Variable | Wilt disease damage rate per ha Damaged area/Total coniferous forest area | - Coborun (2011) | % |
| MIN_WT (it-1) | Minimum winter temperature in the year (t-1) | - The death rate of wintering larvae increases as the winter temperature decreases. | Ma et al. (2006) Kobayashi et al. (1984) Okuda (1973) | °C |
| SPT (it) | Spring average temperature | - The spring average temperature affects the growth of pupae and the eclosion period and activity of insect vectors. | - Enda (1976) - Roquest et al. (2015) | °C |
| SMT (it) | Average summer temperature | The average summer temperature is related to the activities and spawning of adults. The hot summer weather causes the deterioration of the health of the coniferous forest. | Kobayashi et al. (1984) Roques et al. (2015) Naves and Sousa (2009) Rutherford and Webster (1987) | °C |
| SMT2 (it) | Square of the average summer temperature | - The activities of adults tend to decrease after the specific critical point of the temperature. | Roques et al. (2015) Naves and Sousa (2009) | °C |
| MN_FA (it) | Minimum autumn temperature | - The spawning of insect vectors lasts until October and requires the temperature of at least 21°C. | - Kobayashi et al. (1984) | °C |
| RHUM_S P (it) | Relative humidity in spring | - The life of the insect vector increases as the relative humidity is higher when the temperature is the same. | - Kong (2006) | % |
| RHUM_F L (it) | Relative humidity in autumn | - The life of the insect vector increases as the relative humidity is higher when the temperature is the same. | - Kong (2006) | % |
| PRCP_S M (it) | Average precipitation in summer | - The resistance of trees against pests tends to increase as the precipitation increases. | - Mamiya (1984) | mm |
(continue)

| Explanatory Variables and Dependent Variables | | Description of Variable | Related Previous Studies | Unit |
|--------------------------------------------------|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------|-------------|
| Snow_W T (it-1) | Snowfall in the year (t-1) | The increased snowfall increases the insulation effect and thus prevents larvae from being exposed to the cold temperature. | - Neuvonen and Vitranen (2015) | Kg⁄ m² |
| Ct (2013) | Catastrophic dummy | - The variable reflects the sudden increase of damage in 2013. | | 0,1 |
| POP (it) | Population | - The variable to reflect the artificial proliferation of the disease | - Roques et al. (2015) | Pers ons |

Data: Prepared by the authors

<Table 3-2> Key Variables and Related Previous Studies of Oak Wilt Disease

Damage Function

| Explanatory Variables and Dependent Variables | | Description of Variable | Related Previous Studies | Un it |
|--------------------------------------------------|----------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------|----------|
| Do | Dependent Variable | Oak wilt disease damage rate per ha Damaged area/Total coniferous forest area | - Coborun (2011) | % |
| MIN_WT (it-1) | Minimum winter temperature in the year (t-1) | - The death rate of wintering larvae increases as the winter temperature decreases. | - Bentz et al. (2010) | °C |
| SPTX (it) | Maximum spring temperature | - The maximum spring temperature affects the growth of pupae and the eclosion period and activity of insect vectors. | - NIFS (2010) | °C |
| SMTX (it) | Maximum summer temperature | - The average summer temperature is related to the activities and spawning of adults. | - Ciesla (2011) | °C |
| SMTX2 (it) | Square of the maximum summer temperature | - The hot summer temperature causes the deterioration of the health of temperate broad-leaved trees. | - Roquest et al. (2015) - Naves and Sousa (2009) | °C |
| FATX (it) | Maximum autumn temperature | The increase in the autumn temperature expands the activity period of insect vectors. The high temperature during the pest infection period provides the environment for proliferation of fungi. | - Gerard Meurant (2012) | °C |

| | | | (***** |) |
|--------------------------|----------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|-------------|
| Explanatory Dependent | Variables and Variables | Description of Variable | Related Previous Studies | Unit |
| RHUM_SP (it) | Relative humidity in spring | - The life of the insect vector increases as the relative humidity is higher when the temperature is the same. | - Kong (2006) - Gerard Meurant (2012) | % |
| RHUM_FL (it) | Relative humidity in autumn | The life of the insect vector increases as the relative humidity is higher when the temperature is the same. The high temperature during the pest infection period is advantageous for proliferation of fungi and enriches the food for larvae. | - Kong (2006) - Gerard Meurant (2012) | % |
| RHUM_WI (it-1) | Relative humidity in winter | - The high relative humidity is advantageous for proliferation of fungi and enriches the food for larvae. | - Gerard Meurant (2012) | % |
| PRCP_SP (it-1) | Precipitation in spring | - The moisture stress deteriorates the health of host trees. | - Bentz et al. (2010) - Gaylord(2014), Gan(2004) | mm |
| PRCP_SU (it-1) | Precipitation in summer | The moisture stress deteriorates the health of host trees. The hight temperature in summer accelerates the moisture loss. | - Bentz et al. (2010) - Gaylord 2014, Gan (2004) | mm |
| PRCP_FA (it-1) | Precipitation in autumn | - The moisture stress deteriorates the health of host trees. | - Bentz et al. (2010) - G a y l o r d (2 0 1 4) , Gan(2004) | mm |
| PRCP_WI (it-1) | Precipitation in winter | The moisture stress deteriorates the health of host trees. The dry wind in the winter causes the higher moisture loss. | Bentz et al. (2010) Gaylord (2014), Gan (2004), Kim (2012) | mm |
| POP (it) | Population | - The variable to reflect the artificial proliferation of the disease | - Roeues et al. (2015) | Pers ons |
| Diameter (it) | DBH | - Insect vectors prefer trees with large diameter, and DBH and damage level tend to be proportional. | - Lee et al. (2011) - NIFS (2010) | cm |
| UST (it) | Infected area without control | - The pheromone emitted by infected trees without control causes the infection of nearby trees. | - Gan (2004) | ha |
| NF (i) | National forest | - The change of the damage rate according to the managerial subject | | 1,0 |

(continue)

Data: Prepared by the authors

3. Analysis Results

3.1. Results of Estimation by Damage Function

3.1.1. Pine Wilt Disease

<Table 3-3> below shows the average marginal effect of the estimation of the pine wilt disease using GEE. The original estimate is included in the Appendix.

<Table 3-3> Results of Estimation by Pine Wilt Disease Damage Function

| Explanatory Variables and Dependent Variables | Coefficient | Standard Error ⁴⁴ | P Value |
|--------------------------------------------------------------|---------------|------------------------------|------------|
| Minimum winter temperature (it-1) | 0.000274*** | 0.0000915 | 0.003 |
| Average spring temperature (it) | 0.0006445*** | 0.000161 | 0.000 |
| Average summer temperature ⁴⁵ and its square (it) | 0006603*** | 0.0001844 | 0.000 |
| Minimum autumn temperature (it) | 0.000367*** | 0.0001414 | 0.009 |
| Relative humidity in spring (it) | 0.0001835*** | 0.0000593 | 0.002 |
| Relative humidity in autumn (it) | 0.00000279 | 0.0000411 | 0.946 |
| Average precipitation in summer (it) | -0.00000566** | 0.00000263 | 0.032 |
| Snowfall in winter (it-1) | 0.0001368* | 0.0000729 | 0.061 |
| Catastrophic dummy (ct(2013)) | 0.0022579*** | 0.000484 | 0.000 |
| Population: POP (it) | 0.00000001** | 0.0000000041 | 0.011 |

(Average Marginal Effect)

Note: ***, ** and * mean the statistical significance at 1%, 5%, and 10% confidence interval, respectively.

Data: Prepared by the authors

⁴⁴ clustered semirobust standard error

⁴⁵ Although the average summer temperature is + sign, and the square of the average temperature is statistically significant at the 5% significance level in the original estimate, the average marginal effect is the average of the sum of the two values.

According to the estimation results, the minimum winter temperature in the previous year (it-1), average spring temperature, average summer temperature and its square, minimum autumn temperature, relative humidity in spring, average precipitation in summer, snowfall in the previous year (it-1), catastrophic dummy, and population variables were statistically significant. The minimum winter temperature (it-1), average spring temperature, the first term of the average summer temperature, minimum autumn temperature, relative humidity in spring, snowfall in winter (it-1), and population variables have the positive correlation with the damage rate, and the square of the average summer temperature and precipitation in summer have a negative correlation with the damage rate.

The average temperature and relative humidity in spring are in a positive correlation with the damage rate, meaning that the wilt disease damage rate increases as the average temperature and the relative humidity increase. Considering that the eclosion period of Monochamus alternatus is spring and summer and the main eclosion period of Monochamus saltuarius is spring, the eclosion period of insect vectors becomes earlier, and thus the wilt disease damage rate increases as the spring temperature increases. Moreover, the increase in the average spring temperature expands the distribution range of Monochamus alternatus to the north and thus can increase the wilt disease damage rate by Monochamus alternatus.

<Figure 3-1> shows the marginal effect according to the level of key climatic variables (average summer temperature, minimum winter temperature (it-1), minimum autumn temperature, and precipitation in summer) and 95% confidence interval⁴⁶ of the value. The correlation between the average summer temperature and the wilt disease damage rate is the quadratic function with a negative square value. When ignoring other variables, the average marginal effect of the summer temperature to the wilt disease damage rate gradually decreases as the temperature increases at the average summer temperature of 22°C or higher and approaches 0 at 27°C or higher. The

⁴⁶ The confidence interval refers to the section in which the actual parameter is expected to be present, and the higher confidence interval means the higher possibility of the difference between the actual parameter and the estimate.

confidence interval of the parameter also decreases. It relatively matches the existing study showing that, although the wilt disease mostly broke out where the average summer temperature is 20°C or higher, the infection rate decreased due to the migration of insect vectors and slowing down of spawning activities at the high summer temperature.

<Figure 3-1> Average Marginal Effect of Key Climatic Variables: Pine Wilt Disease





The precipitation in summer has a negative correlation with the damage rate. It means that the increase in precipitation in summer, which is feeding and spawning period of Monochamus alternatus, mitigates the moisture stress of trees and thus decrease the damage rate by improving the resistance. Moreover, the increase in precipitation during the active period of adults is likely to deteriorate the flying activities of adults partially. The minimum autumn temperature has a positive correlation with the damage rate, and thus the wilt disease damage rate tends to increase as the minimum autumn temperature increases. The minimum autumn temperature is considered to be related to the spawning of insect vectors and the outbreak of the wilt disease. Although Monochamus alternatus mostly spawns in the summer, it can last to October. Since the minimum critical temperature exists for spawning, the spawning of insect vectors is expected to be active even in autumn if the minimum autumn temperature increases. Moreover, the growth period of the pest shortens as the average temperature increases in the period of life cycle (larva \rightarrow adult \rightarrow mating \rightarrow spawning). The positive correlation between the relative humidity in spring and the damage rate can be explained with the results of the existing study that reported that the life of insect vectors increased as the relative humidity increased.

The positive correlation between the minimum winter temperature in the previous year and the wilt disease damage rate indicates that the damage from the wilt disease will increase when the minimum winter temperature increases. The snowfall in the previous year also has a positive correlation with the damage rate. Therefore, the temperature and snowfall in the previous year are presumed to be related to the survival rate of the wintering larvae. The damage by the wilt disease can increase due to the increase in the survival rate and the increase in the adult population during the eclosion period if larvae are not exposed to the cold winter weather.

We set the municipality population as the surrogate variable to explain the artificial factors of the proliferation of the wilt disease. The population has a positive correlation with the wilt disease damage rate. It indicates that the damage by migration and activity of people would increase more in the populous regions. However, the population variable has a limitation in showing the definite correlation between the detailed activities and the damage rate and thus should be supplemented in future studies.

3.1.2. Oak Wilt Disease

<Table 3-4> shows the average marginal effect of the estimation by the oak wilt disease damage function. Refer to the Appendix for the original estimate.

<Table 3-4> Results of Estimation by Oak Wilt Disease Damage Function (Average Marginal Effect)

| Explanatory Variables and Dependent Variables | Coefficient | Standard Error ⁴⁷ | P Value |
|--------------------------------------------------|---------------|---------------------------------|---------|
| Infected area without control (it) | 0.000031*** | 0.00000859 | 0.000 |
| DBH SPT (it) | 0.000042*** | 0.00000820 | 0.000 |
| Population | 6.91e-09*** | 0.00000002 | 0.000 |
| Minimum winter temperature (it-1) | 0.000213* | 0.000126 | 0.089 |
| Average precipitation in winter (it-1) | -0.000058*** | 0.000014 | 0.000 |
| Relative humidity in winter ⁴⁸ (it-1) | 0.000020 | 0.000022 | 0.910 |
| Maximum spring temperature (it) | 0.000333** | 0.000146 | 0.022 |
| Relative humidity in spring (it) | 0.0000089 | 0.000060 | 0.988 |
| Average precipitation in spring (it) | 0.0000088 | 0.00000696 | 0.900 |
| Maximum summer temperature and its square: | -0.000382** | 0.000193 | 0.048 |
| Average precipitation in summer (it) | -0.000003740* | 0.0000021 | 0.075 |
| Maximum autumn temperature (it) | 0.000092 | 0.000164 | 0.574 |
| Relative humidity in autumn (it) | 0.000026 | 0.000100 | 0.798 |
| Average precipitation in autumn (it) | -0.000017*** | 0.000005780 | 0.003 |
| National forest (i) | 0.000102 | 0.000168 | 0.544 |

Note: State***, ** and * mean the statistical significance at 1%, 5%, and 10% confidence interval, respectively.

Data: Prepared by the author

⁴⁷ clustered semirobust standard error.

⁴⁸ Although the relative humidity has some correlation with the precipitation, they are not in the complete proportional relationship. The relative humidity is also related to other factors such as atmospheric pressure and urbanization (Myeongchan Goh and Seungho Lee 2013).

The estimation showed that the climatic factors that affected the proliferation of the oak wilt disease included the minimum winter temperature and precipitation, maximum spring temperature, maximum summer temperature and precipitation, and autumn precipitation. Increased temperature is likely to increase the disease outbreak rate. Since the correlation between the damage rate and the marginal effect of the minimum winter temperature and the marginal effect of the maximum spring temperature in the year t-1 is the linear function with a positive (+) sign, the damage rate from the oak wilt disease is likely to increase if the minimum winter temperature and the maximum spring temperature increases. However, the maximum summer temperature shows the quadratic function with a negative (-) sign. When ignoring other variables, the marginal effect of the maximum summer temperature to the damage rate gradually decreases at 27°C or higher and approaches 0 at 35°C or higher. Although the maximum autumn temperature and the damage rate have a positive correlation, it is not statistically significant.

The precipitation shows a negative (-) correlation with the damage rate from the oak wilt disease. Regarding the seasonal factors, the average precipitation in winter, average precipitation in summer, and average precipitation in autumn in the year t-1 are statistically significant in 1%, 10%, and 5% level. The average precipitation in spring has the positive (+) sign but is not statistically significant. According to existing studies, the temperature increase causes the expansion of the insect vector active period due to the decreases in the death rate of larvae and early eclosion of adults, and the increase in the activity and population of the insect vector is the direct cause of the proliferation of disease. Therefore, the estimation result in this study is consistent with the results of the existing study that one of the causes of the proliferation of disease is the temperature increase. Moreover, the fact that the square of the summer temperature has a negative sign relatively matches the existing study that showed that the high summer temperature could cause the decrease in infection rate due to the migration and slowing spawning of insect vectors.

The decrease in precipitation causes moisture stress and weakens the resistance by host trees, and thus it is likely to increase the damage due to the quick proliferation of the disease. The decrease in precipitation in the

summer when the concentrated attacks by pests occur, in the autumn when the infection symptoms intensify, and in the winter when the larvae spend in host trees are statistically significant with the damage rate from the disease.

<Figure 3-2> shows the marginal effect according to the level of key climatic variables (maximum summer temperature, average precipitation in summer, maximum spring temperature, and precipitation in autumn) and the 95% confidence interval of the value. The 95% confidence interval tends to increase as the maximum spring temperature increases and the precipitation in summer and autumn decreases. It indicates that the uncertainty will increase due to the large gap between the estimate and parameter if the weather changes intensify. However, under the RCP8.5 scenario, which predicts the average temperature to rise by 4°C by 2100, the uncertainty due to the differences in the estimate and parameter is not likely to be significant.



<Figure 3-2> Average Marginal Effect of Key Climatic Variables: Oak Wilt

autumn, and maximum spring temperature clockwise from the upper left Data: Prepared by the authors

The non-climatic factors such as the infected area without control, DBH, and population are also closely related to the damage rate by pests. The estimation results show that the damage rate from the pests increases as the infected tree area without control increases, DBH increases, or the population is larger. Increases in the infected trees without control can proliferate the damage to nearby healthy trees. It is because an attacked tree is likely to be attacked by insect vectors again, and the pheromone emitted by the infected tree can attract the insect vectors so that nearby trees can be attacked. Therefore, neglecting infected trees can increase the damage rate of nearby trees. The study by Gan (2004) also estimated the positive correlation between the infected trees without control and the damage rate. Therefore, managing infected trees properly is likely to reduce the proliferation of the damage rate.

The fact that the damage rate increases as the DBH increases is confirmed by the result of the exiting study that the damage mostly occurs in trees with large diameter. In other words, the preference of large trees by Platypuskoryoensis indicates that the trees with larger diameter are more likely to be the attack targets.

We used the population as the surrogate variable that shows the artificial activities and the infrastructure such as roads. According to the estimation results, the damage rate from pest is likely to increase as the accessibility and floating population increase. The existing study also reported that the population of insect vectors in the regions such as the roads, trails, and rest areas where there is a high floating population was higher than the regions such as the forest where it is difficult to access. Although the phototaxis of insect vectors is mentioned as the main cause, there are few studies that specifically describe the scientific cause. It is necessary to acquire scientific grounds through sufficient research and reference to establish the control strategy in the future.

It is known that the pest control in national forests is better managed than the forests managed by municipalities or the private sector. However, the dummy variable that indicates the national forest is not statistically significant. The reason that managerial effect of national forests does not seem significant is that there is the large difference in the number of samples between the national forests and the forests owned by the municipality

and the private sector since the unit of the panel is the municipalities and that the national forests are limited to specific regions. Using the detailed data of the national forests and the forests owned by the municipalities and private sector, it will be possible to study the difference of damage rate by disease according to the managerial system.

3.2. Forecast of Future Damage Rate According to Climate Change

We used the RCP8.5 data provided by the Korea Meteorological Administration (KMA) to forecast the future damage rate according to climate change in the Korean Peninsula. The forecast measured the dependent variable (damage rate) by applying the future weather data to the estimated coefficient. We assumed the non-climatic variables to be the same as 2018 or created the future data through the assumption. The damage rates of the pine wilt disease and the oak wilt disease in each municipality in South Korea from 2018 and 2020 were calculated in the process.

We assumed that the population and the area of infected trees without control were the same as 2018. Although it may not be consistent with the declining population trend in Korea, this study focuses on the correlation between climate and disease rather than the artificial factors such as the population. For the DBH, we applied the average DBH change rate with reference to the "Timber Biomass and Harvesting Table" published by NIFS (2012). In other words, we added the average DBH change rate every 10 years to the average DBH observed in 2018 to obtain the DBH change until 2100.

<Table 3-5> shows a part of basic statistics of the weather data used in the forecast. According to the RCP8.5 data obtained from the KMA, the average seasonal temperature in Korean Peninsula is predicted to increase steadily and reach about 4°C higher in 2100 than the current. Although the precipitation shows the cyclical characteristics of increase and decrease every 10 years, the overall trend shows the increasing trend.

<Figure 3-3> shows the distribution of coniferous and broad-leaved forests in Korea in 2009 through 2017. We assumed that the area of con-

11

iferous forest accounted to 45% of the coniferous forests and mixed forests while the area of broad-leaved forest accounted to 55% of the broad-leaved forests and mixed forests. The domestic forest resource distribution was high in Gangwon, Gyeongnam and Gyeongbuk Provinces and low in the capital region and Gyeonggi Province for both coniferous and broad-leaved forests. It is because the level of urbanization is high in the capital region and Gyeonggi Province. Both coniferous and broad-leaved forests were widely distributed in the Gangwon region while the area of the coniferous forest was larger than the that of the broad-leaved forest in the Gyeongsang region. The area of the coniferous forest was smaller than the that of the broad-leaved forest in the Jeolla region.

<Table 3-5> Change of Seasonal Average Temperature and Precipitation in

| | | | | Unit:°C, mm |
|-----------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Year | Average Spring Temperature | Average Summer Temperature | Average Autumn Temperature | Average Winter Temperature |
| 2009-2017 | 11.21695 | 23.91849 | 13.95125 | -0.2527483 |
| 2018-2050 | 12.33724 | 25.02954 | 15.22681 | 1.151882 |
| 2051-2070 | 13.72032 | 26.5279 | 16.7232 | 2.902606 |
| 2071-2100 | 15.43706 | 28.40163 | 18.82912 | 4.679151 |
| Year | Average Spring Precipitation | Average Summer Precipitation | Average Autumn Precipitation | Average Winter Precipitation |
| 2009-2017 | 115.8985 | 304.518 | 88.0208 | 32.53594 |
| 2018-2050 | 113.8254 | 314.947 | 93.93651 | 44.96347 |
| 2051-2070 | 115.1337 | 356.4433 | 104.6786 | 48.07139 |
| 2071-2100 | 130.0588 | 327.772 | 94.27228 | 61.24678 |

South Korea

Data: Prepared by the authors



<Figure 3-3> Distribution of Coniferous and Broad-leaved Forests

Note: Left: Coniferous forests, Right: Broad-leaved forests Data: Prepared by the authors

A. Pine Wilt Disease

<Figure 3-4> shows the future damage rate from the pine wilt disease as predicted by the model. The map for 2010 through 2017 shows the damage rates calculated with the past observation, and those in other years are the predicted estimations by the model. Although the damage rate is high in Jeju and southern regions currently, that in the northern regions is expected to increase in the future due to the climate . In the late 21st century, the damage rate from the wilt disease is likely to be high countrywide except for some parts in Gangwon Province. In other words, the damage rate is expected to increase in Gyeongbuk, Jeonnam, and Jeonbuk regions also after 2050. The intensely damaged areas are expected to expand to the Chungnam and Gyeonggi regions by 2051-2070, and the damage by the wilt disease is expected to widely spread countrywide except for some parts in Gangwon Province by 2090.

B. Oak Wilt Disease

<Figure 3-5> shows the future damage rate from the oak wilt disease as predicted by the model. The figures for 2011 through 2017 are the damage rates calculated with the past observation, and those in other years are the predicted estimation by the model. The oak wilt disease currently occurs mostly in the capital region and Gyeonggi Province. Although the main affected regions are currently the capital region and Gyeonggi Province, it is likely that they will expand to not only further north but also the east and west coasts.

It is expected that from the 2050s, the affected areas will gradually expand to Gyeongnam, the coastal areas of Chungcheong, and Jeolla regions and some coastal areas of Gangwon Province will be damaged in the 2090s. The damage rate in the coastal areas of Chungcheong and Jeolla regions is also likely to be higher than the inland areas.



<Figure 3-4> Forecast of Damage Rate from the Pine Wilt Disease

Note: The future values are forecasted by averaging the future damage rate for each period. Data: Prepared by the authors



<Figure 3-5> Forecast of Damage Rate from the Oak Wilt Disease

Note: The future values are forecasted by averaging the future damage rate for each period. Data: Prepared by the authors

3.3. Implications

The estimation shows that the damage rate from the pine wilt disease has the positive correlation with the average spring temperature, minimum winter temperature, the first term of the average summer temperature, minimum autumn temperature, relative humidity in spring, and snowfall in winter. The damage rate has a negative correlation with the square of the average summer temperature and the average precipitation in summer. Although the increase in average temperature generally increases the damage rate from the wilt disease, the square term of the average summer temperature has the negative sign, and thus the damage rate from the wilt disease decreases at the too high summer temperature. The marginal effect curve indicates that the average marginal effect of the average summer temperature to the damage rate from the wilt disease gradually decreases as the temperature increases at the average summer temperature of 22°C or higher and approaches 0 at 27°C or higher. It matches the existing study showing that, although the wilt disease mostly breaks out where the average summer temperature is 20°C or higher, the infection rate decreased due to the migration of insect vectors and slowing down of spawning activities at the too high summer temperature.

The decrease in precipitation in summer causes moisture stress and weakens the resistance by host trees, and thus it is likely to increase the damage rate from the wilt disease. The positive correlation between the municipality population and the damage rate from the wilt disease indicates that the damage by the artificial infection is likely to increase in the areas where there are the high population and active flotation. The estimation result of the damage function of the oak wilt disease shows that the minimum winter temperature, maximum spring temperature, and the first term of the maximum summer temperature have the positive correlation with the damage rate. Moreover, the average precipitation in winter, the average precipitation in summer, and the square of the maximum summer temperature have a negative correlation with the damage rate. It is expected that the damage rate from the oak wilt disease will increase when the minimum winter temperature and the maximum spring temperature in the year (t-1) increase. However, the square term of the average summer temperature has a negative sign, and thus the damage rate from the wilt disease decreases at the too high summer temperature. The marginal effect curve indicates that the average marginal effect of the average summer temperature to the damage rate from the wilt disease gradually decreases as the temperature increases at the average summer temperature of 27°C or higher and approaches 0 at 35°C or higher. Compared to the pine wilt disease, the damage rate from the oak wilt disease is closely related to the precipitation. The average precipitation in winter, the average precipitation in summer, and the average precipitation in autumn have a negative correlation with the damage rate from the oak wilt disease. Moreover, the non-climatic factors such as the infected area without control, DBH, and population are also statistically significant to the damage rate from the oak wilt disease. The damage rate from the oak wilt disease increases as the area of infected trees without control increases, as the DHB increases, and as the population increases. The estimation results indicate that, compared to the pine wilt disease, the damage rate from the oak wilt disease is more affected by indirect factors such as the health of host trees and managerial factors than the population of insect vectors. Therefore, it is necessary to improve the health of trees through preventive management to prevent oak wilt disease.

According to the forecast of future damage rate, the damage from the pine wilt disease which is currently concentrated in the southern region is likely to expand to the north due to climate . The intensely damaged areas are expected to expand to the Chungnam 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. Although the main affected regions are currently the capital region and Gyeonggi Province, it is likely that they will expand to not only further north but also the east and west coasts. Although the capital region and Gyeonggi Province will remain the mainly damaged area in the future, the damage rate in the coastal areas of Chungcheong, Gyeongsang, and Jeolla regions is also likely to be higher than the inland areas. Considering the fact that the oak wilt disease expanded from the coastal regions in Japan, it is necessary to pay attention to the damage in the coastal regions in Korea.

Chapter 4. Analysis of Economic Impact of Damage by Disease

1. Theoretical Background

1.1. Pest Damage Function

The economic impact of forest that is the renewable resource should use the model that can reflect the dynamic change of trees and the long-term logging age. The formula first suggested by Faustmann (1849) is considered as the convenient model that reflects such characteristics of the forest. It assumed that it was the most economical when using the given forest for the production of wood material and measures the economic factor by repeating planting and logging indefinitely. Therefore, it can be expressed as the problem of obtaining the logging age (t) that maximizes the profit from the production of timber.

$$Max_t \frac{PV(t)e^{-rt} - C}{1 - e^{-rt}}$$
 Equation (4-1)

Here, P refers to the market price of the log, and V(t) refers to the volume of the log that changes with age. C refers to the cost and is assumed to occur at the beginning of the planting.

Although it is logical to analyze the economic factor related to timber in the form of a discrete function since it uses the annual data, we as-

sumed that it was a continuous function in consideration of the convenience of analysis and the degree of the implication that could be derived from the result. Many previous studies also tended to assume it as a continuous function for the analysis (Macpherson et al. 2016, 2017; Alarvalapati et al. 2007).

The above problem can have the maximum value at the logging when both side of the following Equation (4-2) are the same. In other words, it is the time when the value slightly smaller than the growth rate is the same as the value slightly larger than the discount rate.

$$\frac{V'(t)}{V(t) - C/P} = \frac{r}{1 - e^{-rt}}$$
 Equation (4-2)

Assessing the economic feasibility of the forest with consideration to pests must apply the one forest cutting age model considering rent as follows. The reason is that the disease does not break out in each rotation period.

$$\int_{t}^{Max} PV(t)e^{-rt} - C + \int_{t}^{\infty} ae^{-rs} ds \qquad \text{Equation (4-3)}$$

Here, a refers to the maximum income from the forest each year after logging (after the year t). Assuming that the maximum income can be obtained through continued forest management, the value is the annual unit of the Faustmann objective function.

After first differentiating the above equation with respect to t, the optimal forest cutting age satisfies the following Equation (4-4). In other words, it is optimal to log trees at the time when the value that excludes the discount rate from the growth rate of the tree is the same as the annual rent divided by the income from the trees.

$$\frac{V'(t)}{V(t)} - r = \frac{a}{PV(t)}$$
 Equation (4-4)

Since Equation (4-3) the model for the forest cutting age to the unit

area, we can consider that the area variable (L) is excluded. The change of the timber production following the infection to the pest in the forest of the specific area can include the area variable (Macpherson et al. 2016).

$$\frac{Max}{t}PV(t)L^{i}(t)e^{-rt} - CL + \int_{t}^{\infty} aLe^{-rs}ds \qquad \text{Equation (4-5)}$$

We equally partitioned the total area L into N small areas and assumed that Li(t) refers to the sum of the small areas that reflect the infection to the pest. In that case, Li(t) becomes the area affected by the pest (Macpherson et al. 2016).

$$L = \sum_{i=1}^{N} x_{i} \qquad L^{i}(t) = \sum_{i=1}^{N} \rho_{i} x_{i}, \ 0 \le \rho \le 1 \qquad \text{Equation (4-6)}$$

 ρ i represents the degree of the infection to the pest and can be a value between 0 and 1. The value of 1 means that no infection and that the pest does not affect timber production. The small areas in which the ρ value is 0 means that timber production is impossible in the are due to the disease and thus is excluded from the production area. The ρ value differs according to the type of the disease, and the ρ value can be 0 in the case of the wilt disease since the infected trees are useless.

First differentiating the above Equation (4-5) with respect to time (t) expresses the condition for the optimal forest cutting age as shown in the following Equation (4-7). It is optimal to log the tree when the value that excludes the discount rate from the growth rate becomes the same as the change of the area (Li(t)) that can produce timber and rent (aL) divided the income from the timber and then divided by the area that can produce timber.

$$\frac{V'(t)}{V(t)} - r = \frac{1}{L^{i}(t)} \left(\left| \frac{dL^{i}(t)}{dt} \right| + \frac{aL}{PV(t)} \right)$$
 Equation (4-7)

dLi(t)/dt has a value equal to or less than 0 since the area affected pest damage according to time, i.e., the area where the timber production is possible, decreases.

Equation (4-5) assumes the case that control and prevention of disease are not applied. It is necessary to add the cost of activities and reflect the changed timber production to reflect the control and preventive activities in the model.

$$\begin{split} & \underset{t}{\overset{Max}{t}} PV(t)L^{c}(t)e^{-rt} - CL - \int_{0}^{t} D(I(s))e^{-rs}ds \\ &+ \int_{t}^{\infty} aLe^{-rs}ds \end{split}$$
 Equation (4-8)

Here, D(.) refers to the cost of the control and prevention, and we can assume that this cost is a function of I (t) (infected area) as reviewed above (the relationship between the budget and the disease outbreak).

The following Equation (4-9) shows the optimal condition through differentiation. In other words, if there is no control and prevention (Equation (4-7)), the value in the right-hand side of the equation increases by the cost of control and prevention to the income from the timber.

$$\frac{V'(t)}{V(t)} - r = \frac{1}{L^{c}(t)} \left(\left| \frac{dL^{c}(t)}{dt} \right| + \frac{1}{PV(t)} (aL + e^{rt} \frac{d}{dt} \int_{0}^{t} D(I(s)) e^{-rs} ds) \right)$$
Equation (4-9)

The conditions that yield the optimal solution in the case of the control and prevention and the other case become very similar if we exclude the cost. However, the optimal condition and the objective function differ due to the difference of the areas $(L^{i}(t) \text{ and } L^{c}(t))$ that affect the timber production.

If no measures were performed in the infected areas, the forest area can be divided into the susceptible area (S(t)) and the infected area (I(t)). In other words, the total area L is the sum of S(t) and I(t) (L=S(t)+I(t)). The following Equation (4-10) expresses the case representing the forest $L^{i}(t)$ that is infected by the disease and affects the timber production by the area the produces the same timber under the condition of no disease (Macpherson et al. 2016).

$$L^{i}(t) = S(t) + \rho(L - S(t))$$
 Equation (4-10)

Here, the parenthesized expression (L-S(t)) in the right-hand side represents the infected area (I(t)). S(t) represents the case of the ρ value at time t is 1 in Equation (4-6), i.e., the disease not affecting the timber production at all. If the ρ value is 0, i.e., the timber production is disabled due to the disease infection, Li(t) is the same as S(t). Therefore, the timber production area becomes the same as the area (S(t)) that can be infected by the disease.

On the other hand, the case of applying the control and prevention of disease can divide the forest area into the area (S(t)) that can be infected by the disease, the controlled area (T(t)), and the infected area (I(t)). In other words, L becomes the sum of S(t), T(t), and I(t) (L=S(t)+T(t)+I(t)).

$$L^{c}(t) = S(t) + T(t) + \rho I(t)$$

Here, the controlled area (T(t)) is free from the disease infection and thus assumed that its timber production is not affected. Assuming that the controlled area is linearly proportional to the infected area (T(t)= α I(t)), the

following equation is valid.

$$L^{c}(t) = S(t) + (\alpha + \rho) \frac{L - S(t)}{1 + \alpha}$$
 Equation (4-11)

If ρ is 0, the timber production area is the sum of the susceptible area to the disease and the controlled area.

1.2. Assessment of Timber and Non-timber Economic Impact

We reviewed the theories about considering only timber in the assessment of the economic impact of trees. We then adopted the concept of green payment which adds the non-timber economic impact such as carbon absorption, protection of biodiversity, and providing the habitat for wild animals (Macpherson et al. 2017). The following equation expresses the objective function to analyze the economic impact of forest including the non-timber incomes. We used the one forest cutting age model that includes the rent described above to consider the disease.

$$Max_{t} PV(t)Le^{-rt} - CL + \int_{0}^{t} G(L)e^{-rs}ds$$

+ $\int_{t}^{\infty} aLe^{-rs}ds$ Equation (4-12)

Here, G(L) refers to the green payment and is assumed to be a function of the forest area. The optimal condition of Equation (4-12) can be expressed as follows.

$$\frac{V'(t)}{V(t)} - r = \frac{1}{L} \frac{aL - G(L)}{PV(t)}$$
 Equation (4-13)

In Equation (4-6), the forest area that affects the timber production is

expressed as L^{i} . Here, the area that affects timber production is expressed as L_{TB}^{i} , and the area that affects non-timber economic impact is expressed as L_{NTB}^{i} .

 ${L_{\text{NTB}}}^i$ can be expressed as below when the total area (L) is divided into n small sections.

$$L_{NTB}^{i} = \sum_{i=1}^{n} \sigma_{i} x_{i}, \qquad 0 \le \sigma_{i} \le 1$$
 Equation (4-14)

Therefore, the objective function that considers the impact of the disease and includes the non-timber economic impact can be expressed as follows.

$$\frac{Max}{t} PV(t) L_{TB}^{i}(t) e^{-rt} - CL + \int_{0}^{t} G(L_{NTB}^{i}(s)) e^{-rs} ds + \int_{t}^{\infty} aL e^{-rs} ds \qquad \text{Equation (4-15)}$$

Assuming that the green payment $G(L_{\text{NTB}}^{i}(t))$ is proportional to the area that creates the non-timber income, the value can be calculated by multiplying the payment per unit area by L_{NTB}^{i} . Assuming that g is the green payment per unit area, the total green payment can be calculated by the following equation.

$$G(L_{NTB}^{i}(t)) = g \times L_{NTB}^{i}(t)$$

First differentiating the above equation with respect to time (t), the condition for the optimal forest cutting age can be expressed as Equation (4-16). It is optimal to cut trees at the time when the value that excludes the discount rate from the growth rate is the same as the current value which is the result of the differentiating the change of the area (LTBi(t)) that can produce timber and the rent (aL) divided by the timber income and the total green payment by the forest cutting age and dividing it by

the area of timber production.

$$\frac{V'(t)}{V(t)} - r = \frac{1}{L_{TB}^{i}(t)} \left(\left| \frac{dL_{TB}^{i}(t)}{dt} \right| + \frac{1}{PV(t)} (aL - e^{rt} \frac{d}{dt} (\int_{0}^{t} G(L_{NTB}^{i}(s))e^{-rs} ds))) \right|$$
Equation (4-16)

Lastly, the objective function in the case of including the control and prevention of disease is expressed by Equation (4-17). Its purpose is to find the forest cutting age (t) that has the best current value for the cost of the control and preventive measures following the disease outbreak, the non-timber value provided annually, and the value of the timer in the logging period.

$$\int_{t}^{Max} PV(t) L_{TB}^{c}(t) e^{-rt} - CL + \int_{0}^{t} [G(L_{NTB}^{c}(s)) - D(I(s))] e^{-rs} ds + \int_{t}^{\infty} aL e^{-rs} ds$$
 Equation (4-17)

The following required condition satisfies the above equation.

$$\frac{V'(t)}{V(t)} - r = \frac{1}{L_{TB}^{c}(t)} \left(\left| \frac{dL_{TB}^{c}(t)}{dt} \right| + \frac{1}{PV(t)} (aL - e^{rt} \frac{d}{dt} (\int_{0}^{t} [G(L_{NTB}^{c}(s)) - D(I(s))] e^{-rs} ds))) \right|$$
Equation (4-18)

The forest areas $L_{TB}^{i}(t)$ and $L_{NTB}^{i}(t)$ that are affected by the disease as shown in Equation (4-10) can be expressed by the area to produce the same timber in the forest without disease and the area that produces the same non-timber.

$$L_{TB}^{i}(t) = S(t) + \rho(L - S(t))$$
 Equation (4-19)

$$L_{NTB}^{i}(t) = S(t) + \sigma(L - S(t))$$
 Equation (4-20)

Likewise, the area can be expressed like Equation (4-11) if the control and prevention are included.

$$L_{TB}^{c}(t) = S(t) + (\alpha + \rho) \frac{L - S(t)}{1 + \alpha}$$
 Equation (4-21)

$$L_{NTB}^{c}(t) = S(t) + (\alpha + \sigma) \frac{L - S(t)}{1 + \alpha}$$
 Equation (4-22)

2. Assessment of Economic Impact

We selected Equation (4-12) to include the timber and non-timber incomes as the baseline for assessing the economic impact. We plan to use Equation (4-15) that includes the impact of the disease and Equation (4-17) that includes the cost of pest control and prevention to estimate the change of forest management income affected by the disease and compare it with the baseline. The data needed for the numerical analysis using these models include the volumetric production function, the change of the infected area according to time, the infection rate, the cost of control and prevention, the annual rent, wood price, and the cost of planting and logging. We can use the data provided from the outside for the analysis and obtain the disease infected area using the susceptible-infected (SI) model that is mostly used in the disease problem. Assuming that the susceptible area to be S(t) and the infected area to be I(t) of the total forest area (L), the SI model can be expressed as follows (Macpherson et al. 2016).

$$\frac{dS}{dt} = -\beta S(t)(I(t) + p)$$
Equation (4-23)
$$\frac{dI}{dt} = \beta S(t)(I(t) + p)$$
Equation (4-24)

Here, p refers to the area infected from outside initially⁴⁹, and β refers to the secondary infection rate, i.e., the rate of the disease that spreads within the forest. As the theory explains, the total forest area (L) is expressed as the sum of S(t) and I(t) if no countermeasures to the disease have been carried out, and the change of S(t) according to time is expressed as follows.

$$\frac{dS}{dt} = -\beta S(t)(L - S(t) + p)$$
 Equation (4-25)

Applying the variable separation model to obtain the solution of the above differential equation, S(t) can be expressed as the following Equation (4-26).

$$S(t) = \frac{(L+p)}{\frac{p}{L}e^{(L+p)\beta t} + 1}$$
 Equation (4-26)

We must calculate the Lⁱ(t) and dLⁱ(t)/dt values to obtain the optimal forest cutting age in Equation (4-7). It is expressed as $L^{i}(t) = S(t) + \rho(L - S(t))$ in Equation (4-10), and we can obtain Lⁱ(t) and dLⁱ(t)/dt by substituting S(t) and ρ calculated in Equation (4-26). If $\rho =$ 0,⁵⁰ Lⁱ(t) and dLⁱ(t)/dt are the same as S(t) and dS(t)/dt. To obtain the

⁴⁹ It refers to the infection rate when calculating with the unit area and can be multiplied by the given area to represent the infected area.

 $^{^{50}}$ In that case, the timber production in the infected area becomes 0.

value of the non-timer (NTB) income area, we just substitute ρ with σ .

In the case of the SI model for the control and prevention (dividing the forest area (L) into S(t), T(t), and I(t)), the change of S(t) according to time can be expressed by Equation (4-27).

$$\frac{dS}{dt} = -\beta S(t)(\frac{L-S(t)}{(1+\alpha)} + p)$$
 Equation (4-27)

Likewise, applying Equation (4-27) to the variable separation model to obtain S(t) yields the following equation.

$$S(t) = \frac{L + p(1 + \alpha)}{\frac{p(1 + \alpha)}{L}e^{(L + p(1 + \alpha))\frac{\beta t}{1 + \alpha}} + 1}$$
 Equation (4-28)

We can obtain $L_{TB}^{c}(t)$ and $dL_{TB}^{c}(t)/dt$ by substituting S(t) (Equation (4-28)) and ρ in Equation (4-21). If $\rho = 0,51 L_{TB}^{c}(t)$ and $dL_{TB}^{c}(t)/dt$ are expressed by the following equations.

$$L_{TB}^{c} = S(t) + \alpha \frac{L - S(t)}{1 + \alpha}$$
$$\frac{dL_{TB}^{c}(t)}{dt} = (1 - \frac{\alpha}{1 + \alpha}) \frac{dS(t)}{dt}$$

To obtain the non-timber income (NTB) area, we substitute ρ with σ as shown in Equation (4-22).

We applied the volume according to tree age in "Timber Biomass and Harvesting Table" published by NIFS (2012) using the surveyed data instead of the volume production function.⁵² We used the data by

⁵¹ In that case, the timber production in the infected are becomes 0.

⁵² The volume (m³/ha) published every 5 years is converted to annual volume using the normal average growth (m³/ha) and used it for the calculation.

Gyeongtaek Min et al. (2017) for the timber price (KRW 1,000/m³), planting cost (KRW 1,000/ha) and planting cost (KRW 1,000/ha). The subject area was set to 100ha which corresponds to the minimum area owned by excellent planters among the members of the Korea Forest Managers Association.

We assumed that the disease occurs to 10 years or older trees. Trunk injection is applied to the trees with 10 cm or larger DBH to prevent the wilt disease, and the trees are about 15-20 years old in that case.⁵³ The insect vectors of the oak wilt disease tend to prefer with the large trunk as described above. Moreover, the impact of the prevention and handling cost decreases as the time of the cost is far from the time of calculating the current value. Therefore, setting the tree age as 10 years for the disease to occur is realistic and suitable to examine the impact of the pest control and prevention cost.

2.1. Pine Wilt Disease

We selected pine trees in the Gangwon region, pine trees in the central region, and nut pine trees and used the forest harvest table for the analysis of the wilt disease. <Table 4-1> shows the parameters for setting the baseline. The discount rate is set 3%, and the green payment is assumed to be KRW 100,000/ha. As described in the section on the SI model, p refers to the area initially infected from the outside, and β refers to the secondary infection rate, i.e., the rate of disease spread within the forest. We then calculated the p (p/L) value per area (ha) based on the 2010 data

⁵³ KFS. 2017. "Control Guidelines on Pine Wilt Disease"; NIFS. 2012. "Timber Biomass and Harvesting Table"

of the areas infected by the wilt disease, and the value was estimated to be 0.00054. We calculated the β value using the SI model (Equation (4-24)) with the infected area (I(t)) and susceptible area (S(t)) data of the region affected by the wilt disease in 2011 through 2017. The average was 0.002. ρ and σ shown in Equations (4-19) - (4-22) refer to the possibility rate of using the timer in the infected area and the possibility rate of using the non-timber. We assume that both coefficients were 0 for the calculation convenience. In other words, we assumed that the infected trees were useless as timber or non-timer.

| | Unit | Pine Trees in the Gangwon Region | Pine Trees in the Central Region | Nut Pine Trees |
|------------------------------------|--------------|-------------------------------------|-------------------------------------|----------------|
| Market price of timer | KRW 1,000/m³ | 109.1 | 109.1 | 89.1 |
| Planting cost | KRW 1,000/ha | 7,415 | 7,415 | 6,066 |
| Logging cost | KRW 1,000/ha | 16,109 | 16,109 | 16,109 |
| Green payment | KRW 1,000/ha | 100 | 100 | 100 |
| Discount rate | % | 3 | 3 | 3 |
| р | | 0.00054×L | 0.00054×L | 0.00054×L |
| β | | 0.002 | 0.002 | 0.002 |
| ρ | | 0 | 0 | 0 |
| Ø | | 0 | 0 | 0 |
| Cost of controlling | KRW 1,000/ha | 900 | 900 | 900 |
| Cost of handling withered trees | KRW 1,000/ha | 3,500 | 3,500 | 3,500 |
| Area (L) | ha | 100 | 100 | 100 |

<Table 4-1> Parameters for the Analysis of Forest Cutting Age

Data: Prepared by the authors

<Table 4-2> shows the forest cutting age and the objective function value using the above data. If there is no disease, the forest cutting age considering the timer and non-timber value was 55-80 years. When the disease breaks out, the forest cutting age was 49-61 years if the control and preventive measures were taken and 32-34 years if no control and

preventive measures were taken. It shows that the forest cutting age shortens if the disease breaks out. In other words, the period in which the decline in timber and non-timber income due to the forest pests is greater than the increase of income due to the extension of the logging period is faster than the case without the forest disease. However, the forest cutting age increases if the control of the disease is applied.

The forest management income expressed as the objective function value under the given condition (parameters) has a negative value in all cases. The objective function value significantly declines when the disease breaks out. Moreover, the current value of the objective function declines even further if no countermeasures of the disease are carried out compared to the case of pest control and prevention.

<Table 4-2> Change of Forest Cutting Age According to the Infection of the Pine Wilt Disease

| | Timer + Non-Timber Value | | Disease Outbreak | | Pest Control | |
|----------------------------------|-----------------------------|----------|------------------|----------|--------------|----------|
| | Forest | Current | Forest | Current | Forest | Current |
| | Cutting Age | value | Cutting Age | value | Cutting Age | value |
| Pine trees in the Gangwon region | 64 | -225,283 | 32 | -771,220 | 54 | -302,395 |
| Pine trees in the central region | 55 | -308,987 | 32 | -810,831 | 49 | -422,267 |
| Nut pine trees | 80 | -334,826 | 34 | -919,456 | 61 | -444,521 |

Unit: Year, KRW 1,000

Data: Prepared by the authors

2.2. Oak Wilt Disease

We used the forest harvest table (NIFS 2012) and selected Quercus acutissima, Quercus variabilis, and Quercus mongolica for the analysis of

the oak wilt disease. <Table 4-3> shows the parameters for setting the baseline. As described in the section on the SI model, p refers to the area initially infected from the outside, and β refers to the secondary infection rate, i.e., the rate of disease spread within the forest. We then calculated the p-value per area (ha) based on the 2010 data of the areas infected by the oak wilt disease, and the value was estimated to be 0.00087. We calculated the β value using the SI model (Equation (4-24)) with the infected area (I(t)) and susceptible area (S(t)) data of the region affected by the oak wilt disease in 2012 through 2017, and the average value was 0.0017. ρ and σ shown in Equations (4-19) - (4-22) refer to the infected area with the possible use of the timber and the infected area with the possible use of non-timber. We assume that both coefficients were 0.5 for the calculation convenience. In other words, the trees infected to the oak wilt disease are assumed to have lost half of timber and non-timber values.

| | Unit | Quercus acutissima | Quercus variabilis | Quercus mongolica |
|------------------------------------|--------------|--------------------|--------------------|-------------------|
| Market price of timber | KRW 1,000/m³ | 83.5 | 83.5 | 83.5 |
| Cost of planting | KRW 1,000/ha | 8,339 | 8,339 | 8,339 |
| Cost of logging | KRW 1,000/ha | 16,109 | 16,109 | 16,109 |
| Green payment | KRW 1,000/ha | 100 | 100 | 100 |
| Discount rate | % | 3 | 3 | 3 |
| р | | 0.00087×L | 0.00087×L | 0.00087×L |
| β | | 0.0017 | 0.0017 | 0.0017 |
| ρ | | 0.5 | 0.5 | 0.5 |
| Ø | | 0.5 | 0.5 | 0.5 |
| Cost of control | KRW 1,000/ha | 980 | 980 | 980 |
| Cost of handling withered trees | KRW 1,000/ha | 2,200 | 2,200 | 2,200 |
| Area (L) | ha | 100 | 100 | 100 |

<Table 4-3> Parameters for Forest Cutting Age Analysis

Data: Prepared by the authors

Under the given condition, the forest cutting age decreases from 44-70 years, which is the forest cutting age when the disease does not break out, regardless of whether the control and preventive measures to the oak wilt disease were carried out. Moreover, the forest cutting age when the control and preventive measures were not carried out was 33-44 years, indicating the decrease is even wider.

The objective function value is negative in all cases. Therefore, it is difficult to expect income through forest management under the current condition. Despite that, the objective function value is much higher if the control and preventive measures are carried out than otherwise when the disease breaks out. In other words, the cost of losing timber and non-timber values is higher than the cost of pest control and preventive measures.

<Table 4-4> Change of Forest Cutting Age According to the Infection of the Oak Wilt Disease

| | | | | | Unit: Year, | KRW 1,000 |
|--------------------|--------------------------|----------|-------------|----------|-------------|-----------|
| | Timer + Non-Timber Value | | Disease | Outbreak | Pest C | ontrol |
| | Forest | Current | Forest | Current | Forest | Current |
| | Cutting Age | Value | Cutting Age | Value | Cutting Age | Value |
| Quercus variabilis | 44 | -352,830 | 33 | -462,166 | 41 | -378,795 |
| Quercus acutissima | 70 | -383,332 | 44 | -658,351 | 59 | -478,286 |
| Quercus mongolica | 67 | -382,364 | 36 | -575,852 | 54 | -436,174 |

Data: Prepared by the authors

3. Simulation

We were able to deduce the policy implication by analyzing the impact of the change of model parameters on the forest cutting year and the objective function value based on the analysis results. We performed the simulation on pine trees in the Gangwon region for the pine wilt disease and the Quercus variabilis in the case of the oak wilt disease.

3.1. Market Price of Timber

The forest age for cutting decreases in all cases when the market price of timber increases from KRW $90,000/m^3$ to KRW $160,000/m^3$. It decreases from 33 years to 30 years as the timber price increases when there are no countermeasures to the wilt disease. It decreases from 57 years to 48 years as the timber price increases when the control and preventive measures are carried out. This phenomenon is typical as the forest owners tend to realize the income through the timber earlier as the price increases.

Although the objective function value, i.e., the income from forest management, increases when the timber price goes up, it has the positive value only when there is no infection of the disease when the price is about KRW 160,000/m³ (forest cutting age of 53 years). The result indicates that it is difficult to make up the loss by the diseases despite the increase of the timber price.


<Figure 4-1> Change of Management Income of Pine Trees in the Gangwon Region According to the Change of Timber Market Price

Data: Prepared by the authors

In the case of Quercus variabilis also, the forest cutting age decreases from 45 years to 31 years if there is no infection of disease and from 33 years to 28 years if there are no countermeasures carried out after the infection of the disease as the timber market price increased (KRW 80,000-200,000/m3). The change of the forest cutting age when the control and preventive measures are carried out is similar to when there is no disease, and the forest cutting ages in the two cases are similar at the timber price of KRW 180,000/m³ or higher.

The simulation result shows that forest management income decreases when there is a disease infection. However, the objective function increases when applying the control and preventive measures and becomes similar to the value in the case of no disease. The objective function value has a positive value in all three cases when the timber price is around KRW $160,000/m^3$.



<Figure 4-2> Change of Management Income of Quercus variabilis According to the Change of Timber Market Price

Data: Prepared by the authors

3.2. Green Payment

This analysis assumed that the payment of the forest was paid to the forest owners, and the amount was KRW 100,000/ha. The results of the baseline case analysis using the price showed the forest cutting age of 64 years, 32 years (disease infection), and 54 years (control and preventive measures after the infection).

<Figure 4-3> shows the change of the forest cutting age and the forest management income when the green payment increases gradually.⁵⁴ It indicates that the forest cutting age increases when the payment increases.

⁵⁴ The reason that the forest cutting age remains constant if there is no infection to the pine wilt disease after the green payment of KRW 400,000/ha is because there is no data after the tree agee of 80 years.

The reason is that the forest owners have the incentive to preserve the forest and increase the income when the green payment is higher. It also shows that there is a significant difference in the forest cutting age between the case of the countermeasures being carried out and otherwise after the infection of the disease.

The forest management income also showed a significant difference between the case of the countermeasures being carried out and otherwise after the infection of the disease. Although the forest management income changed to a positive value at the payout amount of around KRW 300,000/ha when the control and preventive measures are carried out, the positive income occurs at about KRW 500,000/ha if no countermeasures are carried out.

The change of the forest cutting age according to the change of the green payment in the case of Quercus acutissima is similar to pine trees. The forest cutting age can increase with the control and preventive measures of the disease, and thus the forest management income increases.

If there is no disease, the payout of about KRW 300,000/ha is needed for the forest management income including the green payment to have a positive value. The forest owners can expect a positive income with a similar amount of payout if the control and preventive measures to the disease are carried out <Figure 4-4>.



<Figure 4-3> Change of Management Income of Pine Trees in the Gangwon Region According to the Green payment

Data: Prepared by the authors

<Figure 4-4> Change of Management Income of Quercus acutissima According to the Green payment



Data: Prepared by the authors

3.3. Climate

Chapter 2 describes the relationship between climate change and the breakout of forest disease presented in previous studies. It predicted that the pine wilt disease and oak wilt disease would break out more often due to climate change as the inhabiting environment becomes more favorable to insect vectors, and the health of host trees deteriorates. Chapter 3 predicted the damage rate of the disease using the actual data and the climate change data (RCP8.5). The analysis showed that the damage from the pine wilt disease and the oak wilt disease would spread widely throughout the Korean Peninsula, and thus the damage rate from the disease due to climate change would have a negative impact on the forest economy also.

For this analysis, we can estimate the economic effect of the change of the β value which corresponds to the disease outbreak rate according to climate change. As mentioned above, we estimated the future β value using Equation (4-24) and used the value to deduce the forest cutting age that fulfills the optimization condition and the objective function value, i.e., the current value of the forest management income including the timber and non-timber values, in that case. The data were the damaged area and the forest area estimated in Chapter 3.⁵⁵

<Table 4-5> shows the average of β values for 30 years, which are the period to estimate the normal year value of weather, deduced with Equation (4-24). The result showed that the β value gradually increased as climate change progressed.

⁵⁵ We used the data of the affected regions only.

<Table 4-5> Change of Pine Wilt Disease Breakout Rate (β)

| Period | 2011-2040 | 2041-2070 | 2071-2100 |
|---------------|-----------|-----------|-----------|
| β value | 0.0031 | 0.0046 | 0.0088 |

Data: Prepared by the authors

<Figure 4-5> shows the change of the forest cutting age and the objective function value (income) according to the increase in the β value. The forest cutting age decreases 11 years and 18 years from 32 years (disease infection) and 54 years (pest control), respectively, which are the baseline values. The forest management loss gradually decreases also. In particular, the standard deviation of income when the control and preventive measures are carried out and otherwise after the infection of the disease is KRW 4.84 million and KRW 4.03 million, respectively, indicating that the significant increase from the case of no disease infection.⁵⁶ Therefore, it is necessary to establish measures to stabilize the income and reduce the uncertainties due to the disease infection, and the control and preventive measures to disease can be one of them.

⁵⁶ This study did not consider the change of volumetric growth due to climate change. Therefore, the deviation of income due to climate change when there is no disease outbreak is 0.

<Figure 4-5> Change of Management Income According to the Change of Pine Wilt Disease Outbreak Rate (β)



Data: Prepared by the authors

<Table 4-6> shows the average of β values of the oak wilt disease for 30 years which are the period to estimate the normal year value of weather.

<Table 4-6> Change of Oak Wilt Disease Breakout Rate (β)

| Period | 2011-2040 | 2041-2070 | 2071-2100 |
|---------------|-----------|-----------|-----------|
| β value | 0.0016 | 0.0023 | 0.0044 |

Data: Prepared by the authors

Like the case of the pine wilt disease, the forest cutting age shortens as the β value changes. Although the change of the income is smaller than the pine wilt disease, the deviation increases even more if no countermeasures are carried out (KRW 300 million) than when the countermeasures are carried out (KRW 90 million) after the disease infection. Therefore, the income stabilization can be realized through the control and prevention.





Data: Prepared by the authors

3.4. Change of Utilization Rate (ρ, σ) of Infected Trees

How does the change in the coefficients ρ and σ , which affect the production of timer and non-timer (environmental materials), affect the forest cutting age and income when the disease occurs? While all withered trees infected of the pine wilt disease must be disposed of to prevent the spread of the disease, some trees infected of the oak wilt disease may be useful. Therefore, we analyzed the impact of the change of the above coefficients for the Quercus variabilis. We assumed that ρ and σ values were the same as the baseline case.

As shown in <Figure 4-7>, if the utilization rate of the infected trees is low, i.e., if the impact of the disease on the production of timber and non-timber is high, the decrease of the income when no countermeasures are carried out after the disease infection is much higher than when the

countermeasures are carried out. However, the difference narrows as the utilization rate increases.

<Figure 4-7> Change of Management Income of Quercus variabilis According to the Change of Utilization Rate (ρ , σ) of Infected Trees



Data: Prepared by the authors

3.5. Implications

The income from forest management must have a positive value to preserve the forest permanently. The criterion may be met when the timber price increases significantly or paying for the various values of the forests. However, it is difficult to expect the income from forest management even when we consider the production of both timber and non-timber under the conditions set for this study. The analysis showed that it was more advantageous from the management profit viewpoint not to use the forest after the logging. The difficulties intensified because of disease infection. The analysis emphasized the importance of control and prevention since the economic factors deteriorated when no measures were carried out after the infection.

In the case of the green payment, unlike the timber price, the forest cutting age increased when the payout increased. However, there was no benefit of extending the forest cutting age by paying the green payment if no countermeasures were carried after the disease infection. On the other hand, the effect on extending the forest cutting age if the control and preventive measures were carried out was similar to the case of no disease infection.

The change in utilization rate affects the forest management income significantly if the infected trees can be used. A higher utilization rate is advantageous since it can mitigate deterioration of the forest management income even when no control and preventive measures were carried out.

The probability of disease infection is likely to increase due to climate change. Moreover, the probability of the forest pest outbreak intensifies the decline of the management income and increases the uncertainty. No control and preventive measures, in particular, creates a more severe problem in income stability. The management income assuming climate change (B=0.0088) as shown in <Figure 4-8> is much worse than using the current condition data (B=0.002) as shown in <Figure 4-1>, and the difference between the case of the control and preventive measures after the infection of pine wilt disease and the case of otherwise increases. The forest cutting age shortens when trees are infected due to climate change.

<Figure 4-8> Change of Management Income of Pine Trees in the Gangwon Region According to the Change of Timber Price after Climate Change (2071-2100)



Data: Prepared by the authors

Active control and prevention and the additional income stabilization are necessary to prepare for the increase of pests due to climate change and to ensure a stable income. The analysis indicates that the effect of the economic aid such as the increase in timber price and the green payment decreases even further in the future when the income from forest management related to the disease is expected to decline. Therefore, the policy to increase and stabilize the forest owners' income would be more effective to be applied from the short-term viewpoint before climate change.

Chapter 5. Basic Control Direction and Responses to Pest Control

1. Impact of Climate Change

It is difficult to predict the change from disease accurately since it occurs by the complex interaction of the weather, pathogen, host, and other external factors. Moreover, the effect of climate change does not seem to apply to all pests in the same way since the affecting factors differ according to the type of pest and the target tree. However, the analysis indicates that the effect of pest has the following direction in a large frame.

A. Expansion of Areas Suitable for Inhabitation and New Host Trees

The long-term climate change creates the environmental condition favorable to pests, and the pests will adequately adapt to such environments. As the area favorable for inhabitation expands, the damage that has been concentrated in some regions can expand nationwide, and new trees can be damaged. The areas where Monochamus alternatus is currently active are mostly Jeollanam Province and the southern regions of Gyeongsang Province while the areas where Monochamus saltuarius is

active are the northern and central regions such as Gangwon, Gyeonggi, and Chungcheong Provinces. However, the districts that the insect vectors are in cohabitation are increasing as the distribution area of Monochamus alternatus is expanding to the north, and the Monochamus saltuarius is found in southern regions also. Although the migration of Monochamus alternatus to the north was expected to be the inhabitation area expansion due to climate change, Monochamus saltuarius found in southern regions such as Gyeongju is reportedly attributed to artificial factors (Gyeongbuk Daily 2015). As the damage rate in Gyeonggi and Gangwon Provinces is likely to increase due to climate change in the future, the damage to nut pine trees (Pinus Koraiensis⁵⁷) and pine trees concentrated in these regions can increase. Moreover, new trees may be damaged as the areas favorable for inhabitation expands nationwide. Considering that the walnut twig beetle in the United States has damaged 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 new trees.

B. Increase in Insect Vector Population Due to the Decrease in Larva Death Rate and Expansion of Active Period

The analysis results show that the minimum winter temperature that affects the larva death rate and the average spring and autumn temperatures that are related to the early eclosion and active period of larva have a statistically positive correlation with the damage rate.

⁵⁷ 11.5% of Pinus Koraiensis in national forests in Korea inhabit in Gangwon Province while 26.3%, 25.5%, 7.3%, and 5.9% of Pinus Koraiensis in privately owned forests inhabit in Gyeonggi Province, Gangwon Province, Gyeongbuk Province, and Chungbuk Province, indicating the concentration in Gyeonggi and Gangwon regions (Jaewook Kim et al. 2015).

Moreover, the summer precipitation and other factors that affect the health of trees have a significantly negative correlation with the damage rate. As the average spring, autumn, and winter temperatures are likely to increase due to climate change in the future, the insect vector population and active period of insect vectors are expected to increase. The damage rate can increase greatly, in particular, if the climatic factors such as the dry summer and warm winter that are favorable to insect vectors appear simultaneously.

C. Generation of New Damaged Areas

The damage from the pine wilt disease and oak wilt disease was not significant in some regions such as Daegwalleong in Gangwon where the winter temperature is very low. However, the forecasted rise in winter temperature is likely to lead to the expanded damage to bitter cold areas and high mountainous regions where the damage has not occurred until now.

There was a case of three pine trees being suspected of being infected with the pine wilt disease in a straight distance of 10 km from the border of Odaesan National Park and 7 km from the Daegwallyeong pine forest in 2005 (Joongang Daily 2005). Healthy pine trees inhabit the region around Daegwallyeong, and it is necessary to take a particular precaution since an outbreak of the pine wilt disease can lead to catastrophic environmental and economic damage. The pine wilt disease has already expanded to the areas near DMZ. Eight infected trees were found in the north of Paju City, where no pine wilt disease had been found until then, in Gyeonggi in 2017, and the number of infected trees greatly increased to 48 in 2017 after the incidence of six new infections in 2015 in the north of Yeoncheon-gun, Gyeonggi. There is a growing risk that damage will

spread to North Korea following the discovery of the pine wilt disease in civilian controlled areas and some parts of DMZ. If the pine wilt disease spreads to North Korea, where the forests and forestry infrastructure are weak, it could result in the catastrophic annihilation of coniferous forest in North Korea (Euju Yoo 2017).

According to the forecast result of damage rate of the oak wilt disease, new damages are expected on the west coast and the southern region of the east coast after the 2050s. Considering that the oak wilt disease expanded around the west coast in Japan in the 1990s, it is necessary to monitor the disease outbreak in the coastal areas in Korea.

D. Deterioration of Forest Management Income

The income from forest management would be worse when the disease outbreak intensifies due to climate change than when there is no disease. Moreover, the analysis shows that the income from forest management deteriorates faster, and the uncertainty of income increases when no control measures are carried out than otherwise. Therefore, the control and preventive measures are necessary to prepare for the increase of pests and assure the income, and the efforts to stabilize the income is needed. For it, the preventive control, as well as, the follow-up control is necessary.

2. Basic Control Direction and Response

2.1. Basic Direction of Pest Control

The estimate by the damage function and prediction of future damage rate indicate that the damage rate from forest pests would increase, and the damaged area would expand due to climate change in the future. Moreover, the economic analysis indicates that the increased damage of pest caused by climate change deteriorates the forest management income and increases the uncertainty.

Although the government's programs to control forest pests are showing positive outcomes, additional measures to prepare for the increased uncertainty due to climate control are necessary. Until now, pest control has mostly focused on follow-up measures. Instead of allocating stable control budget, the government allocates the budget and personnel after establishing the control plan for the next year based on the forest pest outbreak status this year. As such, the damage from pests has increased or decreased according to the budget. In other words, the positive outcomes follow the concentrated input of the budget temporarily, and then the damage rate increases again due to the decreased budget, causing the cycle of irregular control performance. Since the uncertainty and economic loss are expected to expand due to the increased pests as the result of climate change, it is necessary to strengthen the preventive control measures to secure stable control. Therefore, we should pay attention to preemptive measures as well as suitable follow-up measures.

It requires the cooperation of the government with individual forest owners. However, the problem is that most forest owners do not have the incentive to better manage their forest because of the low economic

efficiency of domestic forests. Although the main subject of forest pest control is forest owners, many of them neglect to manage the forest due to the low economic efficiency, and thus the government is leading the control efforts. However, the government-led control has the limitation in cost and personnel due to the increased uncertainty. Therefore, it is necessary to provide the incentive for forest owners to actively participate in pest control and expand their role as the actual control subject. It is possible to meet the objective efficiently if both regulatory measures and economic incentive are applied.

2.2. Pest Control Response

2.2.1. Strengthening of Preventive Response

A. Understanding of Key Control Targets

It is necessary to focus control on trees that are easy to be the targets of pests. This study has discovered the positive correlation between the DBH and the damage rate, and it confirms the results of the previous study that the insect vectors of the oak wilt disease prefer the trees with a large diameter. Therefore the older trees with large DBH should be the key control targets, and the forests that have many old trees should be monitored more carefully.

Having lost more than 90% of pine trees due to the pine wilt disease in the early 1900s, Japan has practically abandoned the control of the pine wilt disease (Jinseok Son 2014). However, it carries out the methodical and thorough control in historical sites, coastal windbreak forests, and golf courses, and has established the key monitoring regions within 6 km from the northern limit of the pine wilt diseases such as Akita Prefecture (Daily Korea 2007). Korea should also designate the key control districts such as the historical sites to carry out thorough control such as controlling migration of pine trees.

B. Improvement of the Health of Trees

The results of the estimation by the model show that the precipitation that affects the health of host trees has a negative correlation with the damage rate of the oak wilt disease. Compared to the pine wilt disease, the oak wilt disease is less infectious, and the wither rate is also low at less than 20%. The healthy trees can recover from the oak wilt disease through the internal immune function. Therefore, it is necessary to perform preventive control measures such as tree moisture management and forestation programs to improve the self-immunity.

Since moisture stress is one of the key factors to deteriorate the health of trees, it is necessary to pay attention to supplying water during the dry weather. Moreover, it is necessary to increase the health of trees by reducing the moisture stress in the west coast and southern east coast which are the regions that are expected to be new areas vulnerable to the disease outbreak. Moreover, the forestation programs to create healthy forest are also necessary.

C. Improvement of Resistance to Pests through the Development and Replacement Trees and the Development of Vaccine

The forecast of the future damage rate shows that the damage from the pine wilt disease would occur in wider regions than the damage from the oak wilt disease. Since pine trees may be more vulnerable to climate

change, it is necessary to develop the trees that can withstand pests better and gradually replace existing trees with them.

Most of the forests in Korea are the secondary restored forest established after the 1970s. Therefore, it is presumed that the trees have acquired immunity through coevolution with pests. The currently high outbreak rates of the pine wilt disease in the southern region of the Korean Peninsula and Jeju Island indicate that these areas are no longer the suitable habitat for growth of coniferous trees due to climate change in the 20th century. As the pine tree forests established during a relatively short period have been exposed to unfavorable climate environment, they may be vulnerable to pests.

According to a study by Donggeun Lee (2014), the rate of climate change is faster than the adaptation rate of forest to climate change under the RCP8.5 climate scenario, and thus the evergreen broad-leaved forests and deciduous broad-leaved forests are expected to increase while the coniferous forests and mixed forests are expected to be left behind the competition. Therefore, it is necessary to develop trees that are suitable for future climate change and replace existing pine trees with them beginning in the southern region. The tree replacement in the damaged area,⁵⁸ in particular, would be effective for preventing the spread of the damage. Having experienced the critical damage by the pine wilt disease in 1985, Taiwan planted cedar trees instead of pine trees and converted pine tree forests into tea farms. China, considering that the migration radius of the insect vector Monochamus alternatus is 3 km, created the pine-free belt with a width of 4 km and the length of 100 km (Jinseok Son 2014). Japan also created a pine-tree belt of 3 km in the border between Akita

⁵⁸ The damaged areas are the areas in which the pine wilt disease breaks out and the outskirts to which the disease can spread (KFS 2017).

Prefecture and Aomori Prefecture, which are the northern limit of the pine wilt disease, to prevent the spread of the pine wilt disease (Daily Korea 2007).

The effectiveness of the current program of finding the withered trees and removing them would be limited if the pine wilt disease spreads fast due to climate change. As the case of solving the problem with the pine midge, which incurred the great damage in the 1980s, with finding the predator and advancement of the control technology, the development of the vaccine to the pine wilt disease is necessary for the fundamental treatment. However, there are few related studies in Korea and 70% of all studies on the pine wilt disease were performed in China (Maeil Economic 2018). It is necessary to expand the technical support such as R&D for the establishment of the control policy since it requires long-term research and significant investment to develop the pesticide. Moreover, it is necessary to expand the research exchanges and joint R&D and broaden the interchange of field personnel with countries such as China and Japan which share the common insect vectors and infected trees.

D. Elimination of External Factor Using the Green Payment

Pest management can be explained with the positive external factors. It is because the individual forest owner properly controlling the pests has the positive effect to nearby forests by preventing the spread of the infection, and the creation of healthy forests brings many benefits such as the landscape effect, the emotional effect, and the carbon absorption to the people without extra cost. However, it may cause the problem of "free riding" as people benefiting from such efforts without paying for the additional management cost and the supply shortage due to mismatch of social demand and private demand. The supply shortage problem can

intensify in the case of currently low income from forest management.

However, it is difficult to expect the improvement of income from forest management even when we consider the production of both timber and non-timber under the conditions set for this study. Moreover, the simulation results showed that the disease infection worsened the income. Even though the income from forest management declines faster if no control measures are carried out than otherwise, it is very difficult to motivate forest owners to carry out the preventive measures under the current situation. The reason is that forest owners can hardly expect income from forest management and can expect much larger benefits from the increased appraisal when changing the usage of the forests for other purposes. Therefore, if the forest owners can realize the increased income from forest management through the green payment and other programs, we can expect the increased supply of pest control through the economic incentive of the positive external factor. The social discussion of the suitable green payment and payout method is necessary to increase the effectiveness of the policy.

The detailed strategy such as the amount and method of the green payment is beyond the scope of this study.⁵⁹ However, the basic direction of the green payment should be to minimize the opportunity cost of the forest owners changing the use of forestry and to reduce the payment while meeting the objective. Moreover, the policy of setting the

⁵⁹ Regarding the payout of the green payment, Mendelsohn et al. (2017) conducted a study to propose payment of rent to individual owners as an incentive for enhancing forest carbon uptake. They proposed paying the landlords the rent for the best carbon price calculated on the DICE model and the rent for ten-year storage of carbon and renewing it every ten years. They also argued that an option to pay rent only for carbon stored in trees that exceed the Faustmann optimal age to reduce the government's financial burden.

appropriate damage rate target and paying the green payment only when meeting the target to reduce the government subsidy should be introduced.

2.2.2. Supplementation of Follow-up Measures

A. Strengthening of Handling of Withered Trees

The fact that the area of infected trees without control and the damage rate have a positive correlation in the damage function implies the importance of proper follow-up management to prevent the proliferation of the damage. The delayed disposal of the damaged trees can attract the insect vectors, resulting in the spread of damage to nearby trees, and thus the follow-up measures such as cutting off withered trees and installing the sticky roll trap are necessary. Since the pine wilt disease is highly infectious, the infected trees should be cut off immediately.

B. Prevention of Artificial Expansion

The result of the estimation by the damage function indicates that the population and the damage rate have a positive correlation for both pine wilt disease and oak wilt disease. Since the population is the main surrogate variable of artificial factors, it indicates that the damage can spread through artificial factors for both diseases. The site visits and the review of previous studies confirm that the key artificial factor that causes the spread of the pine wilt disease is the migration of infected trees by humans. It is difficult to mitigate the cause in the case of the spread by climatic factors. However, the policy and schematic support can effectively mitigate the artificial spread.

In the case of pine tree re-infectious disease, a severe punishment (fine

of KRW 10 million or less in case of violation) is imposed on smuggling of trees infected of pine wilt disease according to the Special Act on the Extermination of Pine Wilt Disease. However, some old local residents do not fully understand the regulation and carry out the infected pine trees illegally. Therefore, more education and PR are necessary. Efforts to help residents and the general public to be aware of the risk of transporting infected trees arbitrarily and the severity of punishment are needed.

It is necessary to block the possibility of transporting infected trees by shredding and incinerating them fumigation after logging. The government has designated shredding, not fumigation, as the measures to dispose of infected trees. However, there is a shortage of the equipment, and thus the government should supplement the equipment so that the withered trees are disposed of without delay.

The artificial factors of the spread of the oak wilt disease are not known. Although the phototaxis of insect vectors is mentioned as the main cause based on the fact that the population of the insect vectors is high in road areas, rest areas, and trails, more studies are required to investigate the natural and social cause. The cases of disease spreading through logging and construction have been reported in the overseas studies. The fact that the oak wilt disease is concentrated in the capital region and Gyeonggi Province also indicates that the disease may be related to the logging due to the urbanization.

C. Expansion of Utilization of Infected Trees

According to the simulation in this study, the change of the infected trees significantly affects the income from forest management. Increasing the utilization of infected trees is advantageous in that it can mitigate the deterioration of income from forest management regardless of the pest control measures. As described above, trying to utilize the trees infected of the highly infectious pine wilt disease does more harm than good, and thus the infected trees should be shredded or incinerated. However, it is necessary to actively utilize the infected and withered trees in the case of the oak wilt disease since its infection rate and the withered rate are relatively low. The fumigated withered trees are currently used as the fuel in saunas and the sawdust, but the ways to use them in other purposes such as the wood chip and wood pellets for fuel of new and renewable energy should be considered.

Chapter 6. Summary and Conclusion

This study suggests a way to measure the impact of damage by forest diseases due to climate change. In details, it establishes the damage function with consideration to the direct and indirect factors that affect the damage and measures the damage rate and the economic impact of the diseases due to climate change. To measure the damages inflicted by pests, we implemented the structural damage function used in studies such as Cobourn et al. (2011) and Kim Yongjun et al. (2015) and adopted the nonlinear panel probit model and the GEE estimation method to reflect the characteristics of the damage rate (D) which was the dependent variable. Moreover, we added the mean per panel value to the model according to the method proposed by Mundlak (1978) and Chamberlain (1980) to reflect the fixed effect that had not been observed.

The estimation shows that the damage rate from the pine wilt disease increases as the average spring temperature, minimum winter temperature, relative humidity in spring, and snowfall in winter increase and it decreases as the average precipitation in summer increases. Since the correlation between the average summer temperature and the damage rate from the pine wilt disease is a quadratic function with the negative sign for the square term, it decreases after a certain critical point. The marginal effect curve indicates that the average marginal effect of the average summer temperature to the damage rate from the wilt disease gradually

122 Summary and conclusion

decreases as the temperature increases at the average summer temperature of 22°C or higher and approaches 0 at 27°C or higher. The positive correlation between the municipality population and the damage rate from the wilt disease indicates that the damage by the artificial infection is likely to increase in the areas where there are the high population and active flotation.

The estimation result of the damage function of the oak wilt disease shows that the minimum winter temperature, maximum spring temperature, and the first term of the maximum summer temperature have a positive correlation with the damage rate. The precipitation in winter, the average precipitation in summer, the average precipitation in autumn, and the square of the maximum summer temperature have a negative correlation. It is expected that the damage rate from the oak wilt disease will increase when the minimum winter temperature and the maximum spring temperature in the year (t-1) increase. However, the square term of the average summer temperature has a negative sign, and thus the damage rate from the wilt disease decreases at the too high summer temperature. The marginal effect curve indicates that the average marginal effect of the average summer temperature to the damage rate from the wilt disease gradually decreases as the temperature increases at the average summer temperature of 27°C or higher and approaches 0 at 35°C or higher. Compared to the pine wilt disease, the oak wilt disease has a closer correlation with precipitation. The average precipitation in winter, the average precipitation in summer, and the average precipitation in autumn have a negative correlation with the damage rate from the oak wilt disease. Moreover, the non-climatic factors such as the area of infected trees without control, DBH, and population also have a statistically significant positive correlation with the damage rate from the oak wilt disease. The estimate shows that the damage rate of the oak wilt disease tends to be more affected by indirect factors such as the health of host trees and management than the insect vector population compared to the pine wilt disease.

The forecast of future damage rate indicates that the damage from the pine wilt disease, which is currently concentrated in southern regions, is expected to expand to the north due to climate change. The intensely damaged areas are expected to expand to the Chungnam 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. Although the main affected regions are currently the capital region and Gyeonggi Province, it is likely that they will expand to not only further north but also the east and west coasts.

Although the capital region and Gyeonggi Province will remain the mainly damaged area in the future, the damage rate in the coastal areas of Chungcheong, Gyeongsang, and Jeolla regions is also likely to be higher than the inland areas.

We introduced the concept of the green payment to reflect the economic factors of timer and non-timber in the economic impact assessment. For the economic analysis, we set three scenarios of no disease outbreak-baseline, disease outbreak-no control. and disease outbreak-control and prevention and compared the forest cutting age and the income from forest management including the timber and non-timber production for each scenario. We then performed the simulation to examine the change of the income from forest management according to the change of the timber market price, the green payment, the climate change, and the change of the utilization rate of infected trees based on the analysis result.

According to the analysis result, it is difficult to expect the income from forest management even when both timer and non-timber production

124 Summary and conclusion

is considered under the conditions set for this study. The difficulties intensified because of disease infection. The analysis emphasized the importance of control and prevention since the economic factors deteriorated when no measures were carried out after the infection. The forest cutting age is shortened and the income from forest management increases if the timer price increases in all cases. However, given the same timer price, the income decreases if the disease breaks out, and it decreases even further if no control measures are carried out.

In the case of the green payment, unlike the timber price, the forest cutting age increased when the payout increased. However, there was no benefit of extending the forest cutting age by paying the green payment if no countermeasures were carried after the disease infection. On the other hand, the effect on extending the forest cutting age if the control and preventive measures were carried out was similar to the case of no disease infection.

The Estimate by the damage function and prediction of future damage rate indicate that the damage rate from forest pests would increase, and the damaged area would expand due to climate change in the future. Moreover, the economic analysis indicates that the increased damage of pest caused by climate change deteriorates the forest management income and increases the uncertainty. Although the government's forest disease control programs have shown positive outcomes, they focus on follow-up actions. As such, the positive outcomes follow the concentrated input of the budget temporarily, and then the damage rate increases again due to the decreased budget, causing the cycle of irregular control performance. Since the uncertainty and economic loss are expected to expand due to the increased pests as the result of climate change, it is necessary to strengthen the preventive control measures to secure stable control. Therefore, we should pay attention to preventive measures as well as suitable follow-up measures.

The preventive measures to be strengthened include the understanding of key management targets, improvement of tree health, improvement of resistance to disease by the development and replacement of trees, and elimination of external factors by paying the green payment. The supplementation of follow-up measures can include the control and immediate treatment of trees infected of the oak wilt disease, the strengthening of preventing the artificial spread of the pine wilt disease, and the expansion of utilization of infected trees to increase the income from forest management.

The differentiating factors of this study are that it developed the disease damage function that considers various factors and assessed the economic impact of the disease with consideration to the management factors through the dynamic analysis. However, there are limitations such as the fact that the population variable used in this study to assess the artificial activities does not show the correlation between the detailed activities with the damage rate. Since the proliferation of disease by artificial factors is the subject that has attracted much attention from the academic and policy viewpoint, it is necessary to identify the surrogate variables that represent the detailed activities in future studies and reflect them in the model. In addition, comparing the changes of the control efficiency and the income from forest management according to the control details such as injection to trees and chemical control can be the subject for future studies. Although the pine wilt disease monitoring center currently collects the detailed data of the control measures by city or municipality, this study could not use them because the sampling period was too short. We expect to utilize them fully if the data are sufficiently constructed in the future.

REFERENCES

- 강동원·차진열·김태근·정종철·박기현. 2010. 『북한산국립공원 내 참나무시들음병 발생현황 및 확산예측 분석』. 국립공원연구원.
- 경북일보. 2015. 2. 9. "솔수염·북방수염하늘소 분포도 급변…방제당국 비상." <http://m. kyongbuk.co.kr/?mod=news&act=articleView&idxno=679703>. 검색일: 2018. 10. 7.
- 고명찬·이승호. 2013. "한국의 도시 규모별 습도 변화에 관한 연구." 『대한지리학회』 48(1): 19-36.
- 국립공원연구원. 2010. 『북한산국립공원 참나무시들음병 발생현황 및 확산예측』.

_____. 2012. 『국립공원(계룡산덕유산)내 참나무시드름병 발생현황 및 확산예측 분 석』 연구보고 12-30.

국립산림과학원. 2010. 『참나무시들음병 발병생태 및 방제 연구』연구보고 10-23. _____. 2012. 『임목재적·바이오매스 및 임분수확표』.

태 및 방제연구』. 9788981766863. 국립산림과학원

- 기상청 국립기상연구소 기후연구팀. 2008. 『기후변화의 이해와 기후변화 시나리오 활용』.
- 김용준·정진교·안동환. 2017. "병해충의 공간자기상관을 고려한 인삼 피해함수 추정." 『농촌경제』 40(4): 75-95.
- 김용준·안동환·김관수. 2015. "기상요인을 고려한 인삼의 탄저병 피해 추정." 『농업경 제연구』 56(3): 105-128.
- 김재욱·정휘철·박용하. 2016. "기후변화에 따른 솔수염하늘소 잠재적 분포 변화 예측." 『한국응용곤충학회지』 55(4): 501-511.
- 김재욱·정휘철·전성우·이동근. 2015. "앙상블 기후 시나리오 자료를 활용한 우리나라 잣나무림 분포 적지 전망." 『한국환경기술복원학회지』 18(2): 79-88.
- 김호준. 2014. 그린과학기술원. 병해충관리「참나무시들음병과 광릉긴나무좀」. <http://www.landtree.co.kr/index.php?document_srl=30855&mid=disease&so rt_index=title&order_type=desc>. 검색일: 2018. 5. 10.

- . 2011. 그린과학기술원. 병해충관리「나무좀과 그리스 신화」.
 - <http://www.landtree.co.kr/index.php?mid=disease&page=2&document_srl=3 272>. 검색일: 2018. 5. 10.
- . 2012. 그린과학기술원·「참나무시들음병과 광릉긴나무좀」. <http://www.landtree.co.kr/index.php?mid=disease&listStyle=gallery&order_t ype=desc&document srl=12165>. 검색일: 2018. 4. 20.
- 남영우·최원일·고상현·이승규. 2016. 『산림병해충 발생조사 및 예측 연구 보고서』연 구보고 16-24. 국립산림과학원.
- 남영우·최원일·이차영·이수진·고상현·이승규. 2017. 『2016년도 산림병해충 발생예찰 조사연보』 연구보고 17-01. 국립산림과학원.
- 네이버 백과. <https://terms.naver.com/>. 검색일: 2018. 2. 16.
- 뉴스와이드. 2012. 7. 10. "서울시, 참나무시들음병 '선택과 집중' 방제 실시." http://www.newswire.co.kr/newsRead.php?no=636913>. 검색일: 2018. 6. 15.
- 데일리 대한민국. 2007. 6. 20. "일본 중국 재선충병 분석." < http://www.dailykorea.kr/sub read.html?uid=3150>. 검색일: 2018. 9. 5.
- 매일경제. 2018. 4. 30. "MK News 소나무재선충병, 국가적으로 백신 개발해야.. 원시적 방법으론 안돼!" < http://news.mk.co.kr/newsRead.php?no=274842&ye ar=2018>. 검색일: 2018. 9. 13.
- 민경택·석현덕·최준영. 2017. 『산림경영의 수익성 개선을 위한 정책과제』 R817. 한국 농촌경제연구원.
- 산림청. 2017a. "소나무재선충병 방제지침."

_____ 2017b.『2018년도 산림병해충 예찰 방제 계획』.

- 「산지관리법 시행규칙」(농축산식품부령 제34호., 2018. 12. 4., 일부개정) 제4조의 2. <http://www.law.go.kr/법령/산지관리법시행규칙>. 검색일: 2018. 5. 2.
- 선정민. 2014. "[비전 2015 공공기관] 이상기후에 확산된 소나무재선충, 앞으로 5년 내 완전 박멸한다." http://biz.chosun.com/site/data/html_dir/2014/11/24/2014 112402774.html>. 검색일: 2018. 1. 23.
- 소나무재선충병 2014. Daum블로그. <http://blog.daum.net/philook/15721003>. 검색 일: 2018. 1. 24.
- 손진석. 2014. "[전국 재선충 비상] 日 사실상 방제 포기, 대만 소나무 아예 없애, 中 '無松 벨트'로 방어." 조선닷컴. < http://news.chosun.com/site/data/html_dir/ 2014/03/06/2014030600169.html>. 검색일: 2018. 9. 7.

- 안현진·조성주·오새라·정재민. 2018. "기후변화에 따른 미발생 병해충 피해 경제적 영향분석: Lycorma delicatula의 사례를 중심으로." 『한국산학기술학회 논문지』 19(7): 415-22.
- 유의주. 2017. 10. 17. "소나무재선충병, 민통선 가까이 확산. 북한으로 번질 우려." 연합뉴스. http://www.yonhapnews.co.kr/bulletin/2017/10/17/0200000000A KR20171017102800063.HTML>. 검색일: 2018. 10. 17.
- 윤태중·조기종·이미경·정명섭·배연재. 2010. "기후변화와 식품해충." 『곤충연구지』 26: 27-30.
- 이동근. 2014. 『한국 기후변화 평가보고서 2014』. 11-1450523-002031-01. 환경부·국 립환경과학원
- 이상웅·엄태원. 2014. "기후변화에 따른 참나무시들음병 발생현황 및 대책에 관한 연구: 치악산국립공원 지역을 중심으로." 상지대학교 산림과학과 석사 학위 논문.
- 이승규. 2009. "주요 산림병해의 발생 동향과 기후변화." 『Forest Information 기후변 화와 산림』 pp. 71-75.
- 이영근·성주환·천정화·신만용. 2014. "기후변화가 신갈나무의 적지분포에 미치는 영향." 『한국임학회지』103(4): 605-12.
- 이요한·석현덕·구자춘. 2014. "소나무재선충병과 방제정책 과제." 『KREI 농정포커스』 제87호. 농촌경제연구원.
- 임재은·권필용·권경훈·이상웅·최영환·전미현. 2016. "포항시 소나무재선충병 기본설 계 용역." 포항시청.
- 임종환. 2015. "산림병해충의 발생/확산 예측 및 대응방안 연구." 『기후변화에 따른 산림생태계 영향평가 및 적응 연구(2009-2014)』. 국립산림과학원
- 정병헌·배재수·주린원. 2017. 『산림자원의 변화, 임산물 및 산림서비스 수급 장기전망 과 정책적 시사점』. 국립산림과학원
- 중앙일보. 2005. 10. 20. "소나무 에이즈 '재선충' 백두대간까지 번졌다." < https://new s.joins.com/article/1705197>. 검색일: 2018. 9. 17.
- 채여라·강상인·이상엽·김동현·공현숙·박종철·김미진·이주형·제갈운·송슬기. 2017. "신기후체제와 기후안전사회로의 전환."『미래사회 협동연구총서』17-20-21. 경제·인문사회연구회.
- 최광식. 2009. "조경수에 문제를 야기하는 돌발해충의 발생원인과 종류." 조경수 병해 충 관리 워크숍 발표자료. 한국조경수협회.

- 최원일. 2013. "광릉긴나무좀, Platypus koryeonsis (Coleoptera:Curculionidae)의 생활 사 및 개체군 특성."『한국응용곤충학회 학술대회논문집』2013(4): 28-28.
- 파이낸셜뉴스. 2015. "일본도 포기한 소나무 재선충병 한국은 2017년 '완전방제' 목표." <http://www.fnnews.com/news/201503111723419052>. 검색일: 2018. 10. 31.
- Alarvalapati, Janaki R. R., Shibu Jose, George A. Stainback, Jagannadha R. Matta and Douglas R. Carter. 2007. "Economics of Cogongrass Control in Slash Pine Forests." *Journal of Agricultural and Applied Economics* 39(s1): 61-68.
- An, Hyunjin, Jianbang Gan and Sung Ju Cho. 2015. "Assessing Climate Change Impacts on Wildfire Risk in the United States." *Forests* 6(8): 3197-3211.
- Bale, Jeffery S., Gregory J. Masters, Ian D. Hodkinson, Caroline Awmack, T. Martijn Bezemer, Valerie K. Brown, Jennifer Butterfield. 2002. "Herbivory in Global Climate Change Research: Direct Effects of Rising Temperature on Insect Herbivores." *Global Change Biology* 8(1): 1-16.
- Bentz, Barbara J., Jacques Regniere, Christopher J. Fettig, E. Matthew Hansen, Jane
 L. Hayes, Jeffrey A. Hicke, Rick G. Kelsey, Jose F. Negron and Steven J.
 Seybold. 2010. "Climate Change and Bark Beetles of the Western United
 States and Canada: Direct and Indirect Effects." *BioScience* 60(8): 602-13.
- Chamberlain, Gary. 1980. "Analysis of Covariance with Qualitative Data." *The Review* of *Economic Studies* 47(1): 225-238.
- Ciesla, William. 2011. "Forest Entomology: A Global Perspective." John Wiley & Sons.
- Cobourn, Kelly M., Hannah J. Burrack, Rachael E. Goodhue, Jeffrey C. Williams and Frank G. Zalom. 2011. "Implications of simultaneity in a physical damage function." *Journal of Environmental Economics and Management* 62(2): 278-289.
- Dangerfield, C. E., Whalley, A. E., Hanley, N., Gilligan, C. A. 2017. "What a Difference a Stochastic Process Makes: Epidemiological-Based Real Options Models of Optimal Treatment of Disease." *Environmental and Resource Economics Open Access.* 21 June 2017.
- Davis, Andrew J., Linda S. Jenkinson, John H. Lawton, Bryan Shorrocks and Simon Wood. 1998. "Making Mistakes When Predicting Shifts in Species Range in Response to Global Warming." *Nature* 391(6669): 783-786.

- Davis, E.E, E.M Alberch and R.C Venetee. 2008. "Monochamus alternatus. In: Venette, R.C. Exotic Pine Pests: Survey Reference." USDA Forest Service.
- David, G., B. Giffard, D. Piou and H. Jactel. 2014. "Dispersal Capacity of Monochamus Galloprovincialis, the European Vector of the Pine Wood Nematode, on Flight Mills." *Journal of Applied Entomology* 138(8): 566-576.
- Dropkin, V.H, Foundin, Kondo, Lint and Smith. 1981. "Pinewood nematode: a threat to US forests?" *Plant Disease* 65: 1022-1027.
- Enda, N. 1980. "Period from pupation to emergence of the pine sawyer." presented at the Trans. 32nd Ann. Meet, For. Soc.. 91-92. Kanto Branch Jpn.
- Evans, H. F., D. G. Mcnamara, H. Braasch, J. Chadoeuf and C. Magnusson. 1996. "Pest Risk Analysis(PRA) for the Territories of the European Union(as PRA Area) on Bursaphelenchus Xylophilus and Its Vectors in the Genus Monochamus." *EPPO Bulletin* 26(2): 199-249.
- Evans, Sam, Hugh Evans and M. Ikegami. 2008. "Modeling PWN-Induced Wilt Expression: A MechanisticApproach." In Pine Wilt Disease: A Worldwide Threat to Forest Ecosystems. editor: Manuel M. Mota and Paulo Vieira. pp. 259-278. Dordrecht: Springer Netherlands.
- Feder, Gershon. 1979. "Pesticides, Information, and Pest Management under Uncertainty." *American Journal of Agricultural Economics* 61(1): 97-103.
- Gan, Jianbang. 2004. "Risk and Damage of Southern Pine Beetle Outbreaks Under Global Climate Change." *Forest Ecology and Management* 191(1-3): 61-71.
- Gaylord, Monica. 2014. "Climate Change Impacts on Bark Beetle Outbreaks and the Impact of Outbreaks on Subsequent Fires." ERI working paper 31. Ecological Restoration Institute and Southwest Fire Science Consortium, Northern Arizona University.
- Hartman, Richard, 1976. "The harvesting decision when a standing forest has value." *Economic Inquiry* 14: 52-58.
- Hamrick, Kelley and Gallant Melissa. 2017. "Unlocking Potential: State of the Voluntary Carbon Markets, Ecosystem Marketplace, Forest Trends' Ecosystem Marketplace."
- Hart, Sarah J., Thomas T. Veblen, Karen S. Eisenhart, Daniel Jarvis and Dominik Kulakowski. 2014. "Drought Induces Spruce Beetle (Dendroctonus Rufipennis) Outbreaks across Northwestern Colorado." *Ecology* 95(4): 930-939.
- Jung, C.S. 2009. "Study on the ecological characteristic of pine wilt disease." No. 9-21. Research Report of National Institute of Forest Science.
- Kamata, N., N. Kamata, K. Esaki, K. Kato, Y. Igeta and K. Wada. 2002. "Potential Impact of Global Warming on Deciduous Oak Dieback Caused by Ambrosia Fungus Raffaelea Sp. Carried by Ambrosia Beetle Platypus Quercivorus (Coleoptera: Platypodidae) in Japan." *Bulletin of Entomological Research* 92(2): 119-26.
- Kingsolver, Joel G., H. Arthur Woods, Lauren B. Buckley, Kristen A. Potter, Heidi J. MacLean and Jessica K. Higgins. 2011. "Complex Life Cycles and the Responses of Insects to Climate Change." *Integrative and Comparative Biology* 51(5): 719-732.
- Kobayashi, F., A Yamane and T Ikeda. 1984. "The Japanese Pine Sawyer Beetle as the Vector of Pine Wilt Disease." *Annual Review of Entomology* 29(1): 115-135.
- Kong Weina. 2006. "The effects of temperature and humidity on the longevity of Monochamus alternatus Hope(Coleoptera: Cerambycidae)." Journal of Shanxi Agricultural University.
- Kroll, James and Hershel C. Reeves. 1978. "A Simple Model for Predicting Annual Numbers of Southern Pine Beetle Infestations in East Texas." Southern Journal of Applied Forestry 2(5): 62-64.
- Lawton, J. 1994. "Something new under the sun?" Oikos 69: 177-178.
- Lee, Jung-Su, Robert A. Haack and Won Il Choi. 2011. "Attack pattern of Platypus koryoensis(Coleoptera: Curculionidae: Platypodinae) in relation to crown dieback of Mongolian oak in Korea." *Environmental entomology* 40(6): 1363-1369.
- Lee, Sanghyun, Seungkyu Lee, Jaeyoung Kim, ChongKyu Lee, Kyunghee Kim and Yongsub Yi. 2012. "Antifungal Property of Microorganisms against Korea Oak Wilt Pathogen, Raffaelea quercus-mongolicae." *The Korean Society for*

Applied Microbiology 40(1): 66-69.

- Macpherson, Morag F. Kleczkowski Adam, Healey John R. and Hanley Nick. 2017. "Payment for multiple forest benefits alters the effect of tree disease on optimal forest rotation length." *Ecological Economics* 134: 82-94.
- Macpherson, Morag F., Kleczkowski, Adam, Healey John R. and Hanley Nick. 2016. "The Effects of Disease on Optimal Forest Rotation: A Generalisable Analytical Framework." *Environ Resource Econ(2018)* 70: 565-588.
- Ma, F., Gong, G., He, Y and Qiu, G., Wang. 2014. "The potential geographic distribution of Phytophthora hibernalis Carne based on the CLIMEX in China." *Plant Protection* 40: 138-142.
- Naves, Pedro and Edmundo de Sousa. 2009. "Threshold Temperatures and Degree-Day Estimates for Development of Post-Dormancy Larvae of Monochamus Galloprovincialis (Coleoptera: Cerambycidae)." Journal of Pest Science 82(1): 1-6.
- Mamiya, Yasuharu. 1975. "The Life History of the Pine Wood Nematode, Bursaphelenchus Lignicolus." *Japanese Journal of Nematology* 5(10): 16-25.
- Mendelsohn, Robert, Brent Sohngen and Hyunjin An. 2017. An optimal control model of forest carborn sequestration for Korea forest sector. 연구자료-1 R853. 한국 농촌경제연구원.
- Meurant, Gerard. 2012. Insect-Fungus Interactions. Academic Press.
- Mundlak, Yair. 1978. "On the Pooling of Time Series and Cross Section Data." *Econometrica* 46(1): 69-85.
- Nam, Youngwoo, Sang-Hyun Koh, Dae-Sung Won, Jong-Kuk Kim and Won Il Choi. 2013. "An Empirical Predictive Model for the Flight Period of Platypus Koryoensis (Coleoptera: Platypodinae)." *Applied Entomology and Zoology* 48(4): 515-524.
- Neuvonen, S. and T. Virtanen. 2015. "Abiotic Factors, Climatic Variability and Forest Insect Pests." *In Climate Change and Insect Pests.* pp. 154-172. Wallingford: CABI.
- OKuda. 1973. "Development and growth of pine sawyer larvae under different temperature conditions. Trans. 24th Ann. Meet. Kansai Branch Jpn." presented at the Trans. 24th Ann. Meet. Kansai Branch Jpn. For. Soc.

- Papke, Leslie E. and Jeffrey M. Wooldridge. 1996. "Econometric Methods for Fractional Response Variables with an Application to 401(k) Plan Participation Rates." *Journal of Applied Econometrics* 11(6).
- Papke, Leslie E. and Jeffrey M. Wooldridge. 2008. "Panel data methods for fractional response variables with an application to test pass rates." *Journal of Econometrics, The use of econometrics in informing public policy makers* 145(1): 121-133.
- Ripa, Jorgen. 2000. "Analysing the Moran Effect and Dispersal: Their Significance and Interaction in Synchronous Population Dynamics." *Oikos* 89(1): 175-187.
- Robinet, Christelle, Alain Roques, Hongyang Pan, Guofei Fang, Jianren Ye, Yanzhuo Zhang and Jianghua Sun. 2009. "Role of Human-Mediated Dispersal in the Spread of the Pinewood Nematode in China." *PLOS ONE* 4(2): 4646.
- Robinet, Christelle, and Alain Roques. 2010. "Direct Impacts of Recent Climate Warming on Insect Populations." *Integrative Zoology* 5(2): 132-142.
- Robinet, Christelle, Nico Van Opstal, Richard Baker and Alain Roques. 2011. "Applying a Spread Model to Identify the Entry Points from Which the Pine Wood Nematode, the Vector of Pine Wilt Disease, Would Spread Most Rapidly across Europe." *Biological Invasions* 13(12): 2981-2995.
- Roques, Alain, L Zhao, Jianghua Sun and Christelle Robinet. 2015. "Pine wood nematode, pine wilt disease, vector beetle and pine tree: How a multiplayer system could reply to climate change." *In Climate change and insect pests*. pp. 220-234. Wallingford: CABI.
- Rutherford, T. A., and J. M. Webster. 1987. "Distribution of pine wilt disease with respect to temperature in North America, Japan, and Europe." *Canadian Journal of Forest Research* 17(9): 1050-1059.
- Stark, Nellie M. 1979. "Nutrient Losses from Timber Harvesting in a Larch/ Douglas-Fir Forest." Res. Pap. INT-RP-231. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 41: 231.
- Sturrock, R. N., S. J. Frankel, A. V. Brown, P. E. Hennon, J. T. Kliejunas, K. J. Lewis, J. J. Worrall and A. J. Woods. 2011. "Climate change and forest diseases." *Plant Pathology* 60(1): 133-49.

- Takemoto, Shuhei. 2008. "Population Ecology of Bursaphelenchus Xylophilusphasis." In Pine Wilt Disease. pp. 105-122. Springer, Tokyo.
- Tisserat, Ned, Whitney Cranshaw, David Leatherman, Curtis Utley and Alexander Kathleen. 2009. "Black Walnut Mortality in Colorado Caused by the Walnut Twig Beetle and Thousand Cankers Disease." Plant Management Network: The American Phytopathologicla Society. https://www.plantmanagement network.org/searchresults.asp?q=Tisserat+2009&sa=Search+PMN>. access: 2018. 9. 25.
- Torii, Masato, Yosuke Matsuda, Sang Tae Seo, Kyung Hee Kim, Shin-ichiro Ito, Myung Jin Moon, Seong Hwan Kim and Toshihiro Yamada. 2014. "The Effect of Raffaelea quercus-mongolicae Inoculations on the Formation of Non-conductive Sapwood of Quercus mongolica." *Mycobiology* 42(2): 210-214.
- Weed, Aaron S., Matthew P. Ayres and Jeffrey A. Hicke. 2013. "Consequences of climate change for biotic disturbances in North American forests." *Ecological Monographs* 83(4): 441-470.
- Wingfield, M. J., R. A. Blanchette, T. H. Nicholls and K. Robbins. 1982. "The pine wood nematode: a comparison of the situation in the United States and Japan." *Canadian Journal of Forest Research* 12(1): 71-75.