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Estimation of the Impact of an Increase of Ozone(O_3) Concentration on the Net Primary Productivity of Forests and its Damage Costs

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by

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■ Abstract

Estimation of the Impact of an Increase of Ozone(O3) Concentration on the Net Primary Productivity of Forest and its Damage Costs

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Forests absorb and store CO_2 through photosynthesis, which prevents global warming and provides numerous benefits to forests. In the past, acid rain was the primary danger to forests; more recently, ozone, nitrogen, and sulfur have been threatening forest ecosystems. In particular, ozone occupies most photochemical products, and because of its high toxicity, it directly damages plants. It is also expected that the concentration of air pollutants will increase as a results of future climate change. Korea is expected to see an increase in the concentration of ozone because of the introduction of ozone and ozone precursors from China.

The purpose of this study is to understand how 1) ozone affects the net primary productivity of forests and 2) estimate the future net primary productivity of forests affected by a change of ozone and to estimate the damage cost of such changes. To do this, we

selected the variables necessary for determining the net primary productivity of forests by classifying variables related to weather, terrain, and atmospheric pollutants and used resources such as satellite images and atmospheric pollution data to measure each variable from 2001 to 2010. Using statistical models, we estimated the difference between the present and future net primary productivity of forests with and without ozone. In order to estimate the extent of future damage, we applied the concept of convenience and the concept of probability. In this study, damage cost is defined by using economic value concept and the definition of ecosystem service; damage cost is estimated for control service, indirect use value, use value, and total economic value.

According to the result of the analysis, the average net primary productivity of forests over the past 10 years averaged around 64 million tC/yr. The non-parametric test confirmed that the net primary productivity of forests, NDVI and ozone concentration differed between regions. Because the NDVI differences were reflected in the analysis, there are no differences reported in the net primary productivity of forests by region in this study' s results. In addition, ozone is responsible for an average of 8.3% of net primary productivity within forests per year. This is expected to range from about 3.2% to about 13.3% in the future. The impact on net primary productivity of forests due to ozone varied depending on the definition utilized for application methodology and measuring damage cost. When the concept of probability is applied only to the regulation service which has a direct relation to the net primary productivity of forests, the minimum value of the damage cost is about 401 billion KRW, and when metric regression is applied to the maximum value by applying the concept of total economic value, the value increases to roughly 4,653 billion KRW. The estimated cost of damage is about 0.3% of the maximum current GDP. The results of this study suggest that there may be a difference of up to 11 times depending on the definition of damage cost and the method used to estimate damage cost.

The significance of this study is that the estimation of net primary productivity of forests in the future is reflected not only in climate data but also in the utilized clinical data through NDVI. It is also important to predict ozone concentration based on the emissions rather than to make assumptions utilizing a simple scenario to determine the prediction of ozone concentration. Furthermore, small-scale research that was conducted at the laboratory level was analyzed using actual observational data. We have found that there is a large variation in the definition of damage cost and the methodology applied to estimate potential future benefits and damage costs. This implies that there is a risk of underestimation or overestimation of the effects of certain variables on climate change.

❑ *Keywords* : *Impact of Climate Change, Air Pollutants, Greenhouse Gas, Emissions, Ecosystem Services, Environmental Valuation, East Asia*
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1. Introduction

1.1 Background and Purpose

Since the Industrial Revolution, mankind has made incredible advancements through the utilization of fossil fuels. Socio-economic activities emerging from this process have greatly increased the prevalence of aerosols, which are both greenhouse gases and airborne dust, resulting in a notable change in the chemical composition of the atmosphere. Recent studies also show that atmospheric chemicals such as ozone, aerosols, black carbon, and soot can play a significant role in climate change alongside CO_2 (Hansen *et al.* 2007; IPCC 2007).

In the IPCC Fifth Report, short-lived climate pollutants (SLCPs) have begun to be mentioned. Among pollutants affecting the climate, there are substances that stay for only a short time in the atmosphere. Black carbon (BC) is the most common of these materials, and other CH_4, O_3, and HFCs are also available. These materials are of interest to researchers for two reasons: The first is because they are present in the atmosphere in the short-term and affect global warming; the second is that these pollutants affect the community, having an impact on human health (IPCC, 2013).

According to measurements taken of the atmospheric environment's standard items (O_3, NO_2, CO, PM_{10}, Pb) by the Ministry of Environment in Korea (2012), most of the materials show similar decreasing trends, but ozone was recorded at 0.1 ppm and lead was recorded at 0.0024 ㎍/㎥, which represented roughly a 5% increase in comparison to previous measurements (Ministry of Environment 2013). In particular, the concentration of NO_2 contributing to ozone formation has remained constant at an annual average level of 0.25 *ppm* since the 1980s and has recently declined slightly (Ministry of Environment 2013). However, ozone concentration has been steadily increasing since the 1980s. This is presumably due to the increase in ozone precursors resulting from the increasing number of automobiles globally, and also as a result of the long-distance movement of ozone and ozone precursors from China and other nations, which is similar to that of Japan (Nagashima *et al.* 2010).

These air pollutants are measured in a urban air monitoring station / national background monitoring station / suburban atmospheric monitoring station. The results gathered from the station located in Ganseong-eup, Goseong-gun are higher than those gathered from the suburban atmospheric monitoring station, and the annual average ozone concentration of the national background monitoring station was about 0.034~0.044 *ppm* in 2010. Especially noteworthy is that the ozone concentration was higher in Taeha-ri station in Ulleung-do than in the other stations. The national background monitoring station area is low in turbidity due to the stability of the ground, so there is more solar radiation recorded with this station than in urban areas, and because the mixed layer is lower to the ground, pollutants from the ground are not likely to spread to the upper layer. In addition, since the concentration of NO_2 that can extinguish ozone is relatively lower than that found in the urban area, and NO_2, which is a precursor of ozone generation, is also sparse, ozone destruction is suppressed. Therefore, the ozone decay phenomenon is reduced in a clean area (Ministry of Environment 2011).

Forests, on the other hand, absorb and store CO_2 through photosynthesis, there-by preventing global warming and affecting temperature and humidity at local sites (Costanza *et al.* 1997; R. S. de Groot, Wilson, and Boumans 2002). These forests provide us with a variety of ecosystem services. In particular, their regulation service, which is a control function, has the effect of reducing greenhouse gas absorption on both a local and global scale (Costanza *et al.* 1997; Daily *et al.* 2000; Millennium Ecosystem Assessment 2003).

As mentioned previously, acid rain was once the preeminent threat to forests; more recently, however, ozone, nitrogen, and sulfur have become the greatest threats to forest ecosystems (S. Lee *et al.* 2011). In particular, ozone occupies the majority of photochemical products and has a higher toxicity than other substances, which directly affects plants and causes considerable damage to forest ecosystems as a whole (Han *et al.* 2006). When ozone enters the plant body, the first damage occurs in the photosynthetic organ by which the plant takes in ozone; the most serious damage occurs at this point with the loss of the photosynthetic organs (Felzer *et al.* 2004; Krupa and Manning 1988). However, studies on the effects of ozone on vegetation have been limited, extending mostly to indoors studies limited to a select group of species or to the study of plants growing on trees located alongside streets (Han *et al.* 2006; Lindroth *et al.* 2001; Noormets *et al.* 2001).

Forests are recognized internationally as carbon sinks (van Kooten, Laaksonen-Craig, and Wang 2009), and the Korean government supports economic activities through the forest carbon offset business in accordance with Article 27 of the "Act on The Management and Improvement of Carbon Sink" (Korea Forest Service, 2013). In addition, the Korean government intends to implement a policy to increase the CO_2 storage of forests in order to establish a new post-2020 climate agreement, as discussed at UNFCCC COP21 in December 2015 (Korea Forest Service, 2015).

The purposes of this study are 1) to determine the effects of ozone on the net primary productivity of forests and 2) to estimate the net primary productivity of forests by ozone and to estimate the damage costs the impact of ozone will incur in the future. For this purpose, I selected the necessary variables to determine the net primary productivity of forests impact assessment, utilizing classified variables related to weather, topography, air pollutants, and data. Pertinent data was collected from 2001 to 2010 using satellite images and studying related variables. Estimates determining the present and future changes in the net primary productivity of forests with and without ozone were made using statistical models. Furthermore, in order to estimate the cost of future damage, I applied the concepts of benefit transfer and probability.

1.2 Study Flow

The flow of this study is shown in Table 1 below. The introduction describes the background, necessity, and purpose of the study; examines the effect climate change has on forests, the impact of air pollution on forests and provides an estimation for the value of the net primary productivity of forests; and explores prior research, both domestic and foreign, on the content of climate insurance. Next, this study defines the content scope, spatial scope, and temporal scope of the research, and describes each research method utilized. For each method, researchers select the impact assessment variables for the evaluation of the net primary productivity of forests, develop the model through the selected variables, estimate the current net primary productivity of forests using the developed impact assessment model, and compare it with these other models. Afterwards, the verification method is described and estimates on future net primary productivity of forests and the damage caused by ozone are provided. In regard to damage cost, after estimating the value of the damage, the damage cost to be used in this study is defined, and then the degree of damage on the net primary productivity of forests by ozone is estimated.

Table 1. Study Flow

Flow		Contents	Methods
Introduction		◦ Background ◦ Study purpose	
Literature reviews		◦ Climate change, air pollutant and NPP ◦ Impact assessment model of NPP ◦ Estimation methods of damage cost	Review
Study scope and methods		◦ Contents scope ◦ Spatial scope ◦ Time scope	
Results and discussion	Impact assessment of NPP on forests by climate change and ozone	◦ Selection variables for NPP of forest impact assessment ◦ Development of NPP of forest impact assessment model ◦ Estimation of current NPP of forest and damage due to ozone ◦ Estimation of current NPP of forest and damage due to ozone	• Review • Panel Analysis -ArcMAP 10.1 -SPSS 23 -Excel 2016 -STATA 10
	Estimation of damage cost of NPP of forest	◦ Definition of damage cost of net primary productivity of forest ◦ Estimation of damage cost using benefit transfer ◦ Estimation of cost of damage to the application of probability	• Review • Statistical Analysis -SPSS 23 -Excel 2016
Conclusion		◦ Conclusion ◦ Significance and limitation	

2. Literature Review

2.1 Effects of Climate Change and Ozone on Net Primary Productivity of Forests

Since the Industrial Revolution, forest ecosystems have been impacted on both a large and small scale as a result of the damage caused by acid rain and air pollutants (Prinz 1987). In the past, the majority of the damage to forests was caused by acid rain, but this is no longer the case. The major threats to forest ecosystems today are ozone, nitrogen, and sulfur (S. Lee *et al.* 2011). According to Felzer *et al.* (2004), 90% of the damage caused by air pollution in forest ecosystem is due to ozone.

Research on the effects of ozone on forests has been actively conducted worldwide. Research has been focused mainly on the experimental and statistical significance of ozone, and experimental studies have been conducted to directly expose ozone to trees or forests on a small scale in controlled environments, such as within chambers (Beyers, Riechers, and Temple 1992; H. S. Kim and Lee 1995; S. Lee *et al.* 2011; Reig-Armiñana *et al.* 2004; Woo *et al.* 2004; Yun and Chevone 2008). These results were reflected in statistical studies. There was found to be a significant negative correlation between tree health and ozone concentration (K. J. Lee *et al.* 1999; Woo, Lee, and Lee 2004) In addition, most studies have shown that ozone degrades photosynthetic ability and that visible damage can be observed as a result of ozone (Beyers, Riechers, and Temple 1992; H. S. Kim and Lee 1995; K. J. Lee *et al.* 1999; S. Lee *et al.* 2011; Reig-Armiñana *et al.* 2004; Woo, Lee, and Lee 2004; Yun and Chevone 2008).

Climate change, in particular, is likely to have a greater impact on the production of air pollutants such as ozone. Changes in wind patterns, the amount and intensity of precipitation, and an increase in temperature all have a direct impact on the frequency and intensity of air pollution and can increase the production of air pollutants through the use of heaters or air conditioners in affected areas (D'Amato and Cecchi 2008; Jang 2011). Urban heat-island effects are likely to produce secondary pollutants such as ozone and increase natural air pollution sources due to soil erosion or fires (Bernard *et al.* 2001; Chen *et al.* 2004; Grambsch 2004; Prather *et al.* 2003). Climate change is also likely to produce air pollutants because oxidation reactions occur more easily at elevated temperatures (Bernard *et al.* 2001). According to Sim *et al.* (2014), the concentration of ozone has been steadily increasing since the 1980s, more than doubling since then. If the long-distance migration of ozone and ozone precursors from China increases, ozone concentration will contribute to increase in the future.

In summary, the current ozone level is clearly affecting the growth of trees and an increase in the amount of ozone can be expected to cause even more damage in the future.

2.2 Impact Assessment Methods of Net Primary Productivity of Forests

The prediction model used to determine the net primary productivity change of forests can be divided into a remote sensing-based model, a process-based model, and an empirical model (Adams, White, and Lenton 2004).

A remote sensing-based model using satellite imagery is based on the correlation between the NDVI (Normalized Difference Vegetation Index) and the LAI (Leaf Area Index) (Jiang *et al.* 1999; D.-K. Lee, Park, and Oh 2010). Many studies use satellite images (Field, Randerson, and Malmström 1995; Gao *et al.* 2013; Kil *et al.* 2016), and the NASA MODIS algorithm is typically used (Heinsch *et al.* 2003). However, it is difficult to predict the future net primary productivity of forests through the use of satellite imagery because it is difficult to predict the future vitality of forests (Gibbs *et al.* 2007).

Another way to calculate the net primary productivity of forests is through process-based models. Process-based biochemical models include the TEM (Terrestrial Ecosystem Model) (Felzer *et al.* 2004; Tian *et al.* 1999) and the FOREST-BGC model (Running and Coughlan 1988). These models simulate the carbon cycle, nitrogen cycle, and water cycle in vegetation, soil, and the atmosphere. The process-based model is advantageous for predicting the changes of forest species as a result of material circulation considering a number of variables comprehensively. However, this type of model is restricted by the high-quality data required to run it and because of the complicated input data associated with it.

Finally, the empirical model is based on global observations of the net primary productivity of forests, temperature, and precipitation. Examples include the Miami model (Lieth 1975), the Montreal model, and the Chikugo model (Uchijima and Seino 1985); in addition, some studies have estimated net primary productivity using variables which affect net primary productivity (Chu *et al.* 2016; Michaletz *et al.* 2014). Studies predicting changes in net primary productivity of forests and changes in temperature and precipitation do not take into account changes in forests due to climate change, and there are limitation to the assumption that changes in forests occur immediately in response to climate change. Nevertheless, because of this model' s simple structure, it can be used as a basis for calculating the net production of complex models (Na *et al.* 2013).

2.3 Estimation Methods of Damage Cost

On the other hand, to determine the impact of climate change on forest ecosystems as an economic value, a methodology for estimating the value of environmental goods not traded in the market is needed. To do this, we must first determine whether the impact of climate change on us is positive or negative, and we should consider the increase or decrease of costs or benefits that arise therefrom. In particular, valuation is a very important issue for policy makers, and to solve this problem, it is necessary to evaluate the value of the services provided by the ecosystem (Acreman *et al.* 2008; Koo and Lee, 2012; Sander and Haight 2012; Vandermeulen *et al.* 2011).

There are three ways to estimate social benefits, including market methods, revealed preference methods, and stated preference methods (Freeman III, Herriges, and Kling 2010; Kwon 2007). But although it is best to conduct direct research to estimate non-market values, it is almost impossible to conduct direct research on individual issues in a situation constrained by time and budgetary considerations. For the purpose of this study, the benefit transfer method of estimating benefits based on existing research results has been utilized. The general definition of a benefit is that the economic information from existing research is appropriately applied and transferred to similar resources or environments that have not yet been studied (Boutwell and Westra 2013; Randall and Loomis 2000).

The benefit transfer method can be divided into two methods: the value transfer method and function transfer method. The value transfer method can be further divided into Single Point Estimate, Measure of Central Tendency, and Administratively Approved Estimate, and the function transfer method can be divided into Benefit/Demand Function Transfer and Meta-Regression Analysis (Rosenberger and Loomis 2000).

The function transfer method shows the correlation between the benefit measure and the characteristic variables of a population, which is the evaluation subject, or the resource under evaluation, unlike the value transfer method, which directly transfers the benefit measure, such as the amount of payment or compensation demand (Boyle and Bergstrom 1992; Downing and Ozuna 1996; Loomis and Santiago 2013; Rosenberger and Loomis 2000). Meta-regression analysis is a method of summarizing the correlation between the benefit measure and quantifiable research characteristics using statistical techniques. In the meta-regression analysis, the summary statistic derived from the previous study is set as the dependent variable, and the regression analysis is performed by setting the characteristics of the population, the resource characteristics of the site, and the value estimation technique utilized (Brouwer 2000; Plummer 2009; Ready *et al.* 2004; Ready and Navrud 2006; Wilson and Hoehn 2006). Meta-regression analysis can quantify the impact of the selection of a particular technique, the design of the study, the nature of the data, etc. on the summary statistics, and the difference between the results of previous studies. There are advantages to this type of analysis. In particular, we can explain the variation among the summary statistics resulting from external factors, as well as the characteristics of the research itself included in the analysis. Another advantage of the meta-regression analysis function is that the function can be adjusted to reflect the characteristics of the target area, as in the case of the benefit function, and thus more accurate estimates can be transferred. However, the meta-regression analysis is different from the demand function transfer in that the factors affecting the benefit measure can be controlled.

2.4 Conclusion

Through the literature reviews, it was confirmed that net primary productivity of forests is affected by air pollution. Several studies have recently confirmed that forests are affected by ozone. However, this research is being performed for the present state of affairs, and research on the long-term effects of ozone on forests is insufficient. The primary reason for the lack of research estimating the future state of forests impacted by ozone is the difficulty in securing reliable and meaningful data and forecasting future variables.

The model for assessment of the net primary productivity of forests can be divided into a remote sensing-based model, process-based model, and empirical model. The empirical model is limited by its simplicity in relation to the other models, but has the advantage of being able to provide a base for a number of predictions to be made. Therefore, this study aims to estimate the effects of ozone and its effects on the net primary productivity of forests using an empirical model after determining variables affecting forests.

The damage caused by climate change and air pollution is steadily increasing. To better prepare for future damage, it is important to determine what that damage might be. In particular, the carbon sequestration function of forests is more cost-effective than reduction through technological development. However, due to the uncertainty of the future, deviations from the predicted outcomes will be significant. In this case, this uncertainty must be considered simultaneously with the value assigned to future damages. Therefore, this study first defines the damage of ozone to forests and estimates damage cost accordingly. The damage cost is estimated by transferring the value of previous studies to benefit of ecosystem services from forests and applying the concept of probability of ozone generation.

3. Study Scope and Methods

3.1 Study Scope

3.1.1 Content Scope

The scope of this study is to estimate the damage on the net primary productivity of forests from ozone, to analyze the economic impact of such damage, and to estimate the damage cost. For this purpose, this study can be roughly divided into the evaluation of the impact of net primary productivity of forests resulting from the change in ozone concentration and the estimation of damage cost according to the values determined by the impact evaluation.

Net primary productivity is defined in this study as the amount of production used for vegetation growth, minus forest respiration in gross primary productivity. The net primary productivity is the unit of mass per unit time per unit area, and the ecosystem mainly uses the carbon mass per unit area per year ($gC/m^2/yr$) as the main unit of measurement (Amthor and Baldocchi, 2001).

In order to assess the impact of the net primary productivity of forests on climate change and ozone concentration, we first selected the variables necessary for impact assessment through relevant theories, previous studies, and expert advice, and developed a net primary productivity of forests impact model that considers ozone using selected variables. The developed impact assessment model compares the results of domestic and international studies with other models. Furthermore, the model estimates the future net primary productivity of forests using derived models and estimates the degree of damage to the net primary productivity of forests as climate change progresses and ozone concentration increases.

To estimate damage cost according to the results of the impact assessment, damage cost is defined through the related theory and prior studies, and is estimated by applying the concept of benefits and the concept of probability.

For the estimation of the future net primary productivity of forests in this study, the RCP (Representative Concentration Pathways) 8.5 scenario was used as the climate variable and the emission of the SSP (Shared Socio-economic Pathways) 2 scenario was used to predict the air pollution variable.

3.1.2 Spatial Scope

The spatial range of this study covers the forests of South Korea (Figure 1). To wit, the forests in this study are composed of broadleaf forests (classification code: 310), coniferous forests (classification code: 320) and mixed forests (classification code: 330) in the land use map provided by the Environmental Spatial Information Service. The land use map was prepared in 2007, and it is written at a scale of 1:25,000. The area of the forests of South Korea decreased by 0.73% from 6,415,920 ha in 2001 to

6,368,843 ha in 2010 (Korea Forest Services, 2016), but since there is no annually-distibuted land use map, this study assumes that there is no change in forest area from 2001 to 2010.

The ozone concentration data were obtained from the National Institute of Environmental Research. The National Institute of Environmental Research is operating the air pollution observation station. It is equipped with an air pollution monitoring station, an urban air pollution monitoring system, a roadside air pollution monitoring system, a national background concentration observation system, a suburban air pollution monitoring system, an atmospheric heavy metal pollution monitoring system, and a photochemical pollution monitoring system; 480 observation stations are distributed through out the study area. This was intentional, as the observation stations can assist in this study's exploration of the relationship between the net primary productivity of forests and ozone.

Data were gathered over a period of ten years between 2001 and 2010 from 11 stations in the forest and 52 stations within 100m of the forest. (See Appendix 7.1)

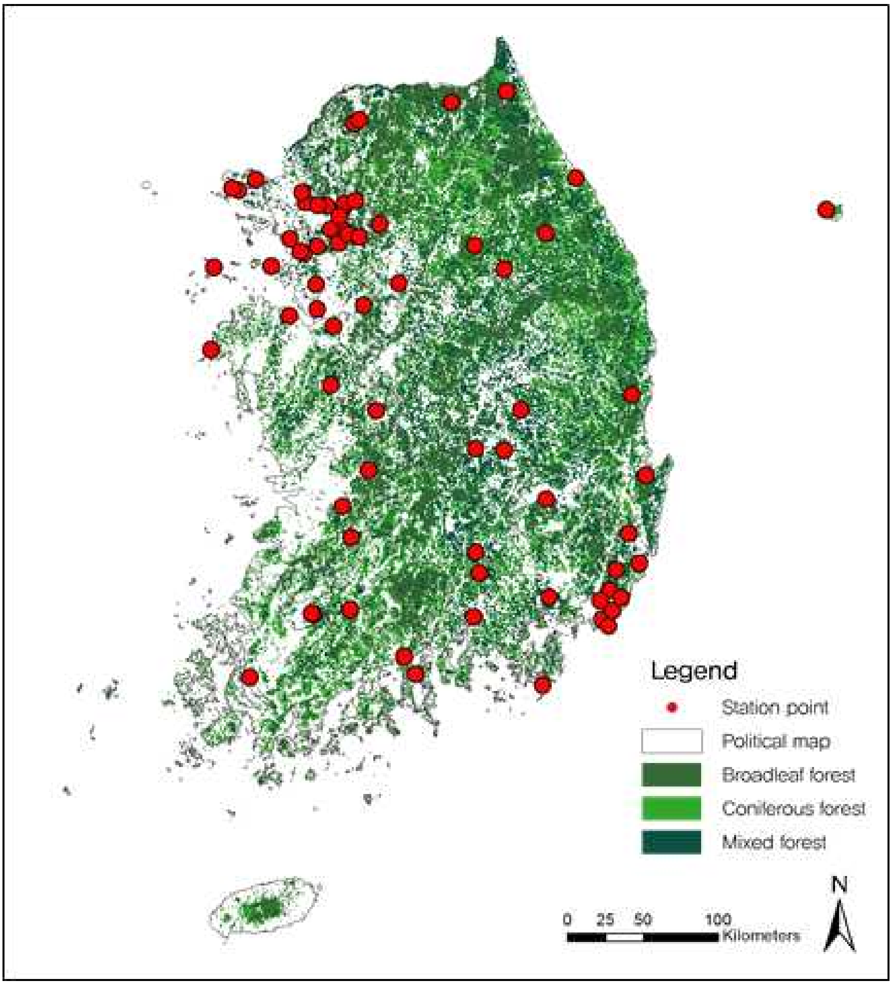


Figure 1. Study Site

3.1.3 Time Scope

The temporal range of this study was set from 2001 to 2010, with 2010 serving as the present, this was the range used for model development. The future target periods are set in the 2050s (2051~2060) and 2090s (2091~2100).

3.2 Methods

3.2.1 Impact assessment of net primary productivity on forests by climate change and ozone

3.2.1.1 Selection variables for net primary productivity of forest impact assessment

The net primary productivity of forests and changes in the net primary productivity of forests over time are considered to be key characteristics of forest ecosystems (Cannell 1982; Reichle *et al.* 1982). In addition, the amount of carbon stored in biomass is gaining interest (Somogyi *et al.* 2007) as a result of the recent Kyoto Protocol and the Paris Protocol at the United Nations Framework Convention on Climate Change (UNFCCC). Therefore, in this study, variables are selected to carry out impact assessment considering the effects of climate change and ozone on forests. The dependent variable used was the net primary production variable of the forest, and the independent variables were selected from the literature review of domestic and foreign countries.

The results of the NASA-CASA (Carnegie Ames Stanford Approach) NPP model were derived from the discrepancy between the air pollution observation point and the MODIS NPP and were used as the dependent variables used in this study. The NASA-CASA NPP model is one of the fastest and most accurate models for estimating the net primary production of crops (Amthor *et al.* 2001; Na *et al.* 2013; C. Potter *et al.* 2007; C. S. Potter *et al.* 1993). The algorithm of the NASA-CASA NPP model used in this study is as follows:

$$NPP = \epsilon \times Sr \times NDVI \times T_1 \times T_2 \times W \qquad \text{Equation (1)}$$

ϵ is a constant, indicating the degree of light efficiency. In this study, the maximum possible efficiency is assumed and a single value of 0.389 $gCMJ^{-1}$ is applied.

Sr is solar radiation, $NDVI$ represents the normalized vegetation index. T_1 and T_2 are variables related to vegetation growth temperature, and can be expressed as $0.8 + 0.02\,T_{opt} - 0.0005\,(T_{opt})^2$ and $1.1814/(1 + e^{(0.2\,T_{opt} - 10 - T)})/(1 + e^{(0.3(-T_{opt}) - 10 + T)})$. In this equation (1), T_{opt} is the mean temperature of the month with the highest NDVI value. Finally, W is the water stress factor, $0.5 + 0.5 \times \frac{EET}{PET}$. EET is the evapotranspiration, and PET is the potential evapotranspiration. In order to create dependent variables, the annual data provided by the Korea Meteorological Administration were used for climate variables such as solar radiation, temperature, etc., and data of slope, altitude, and aspect were constructed using the DEM data provided by the National

Geographic Information Institute. For the LAI and NDVI, we used MODIS satellite image data provided by NASA.

The net primary productivity of forests is based on plant photosynthesis. Therefore, in this study, micro factors that affect the photosynthesis of plants and macroscopic factors that affect the net primary productivity or the gross primary productivity of forests were identified. For the climate factors, the highest average temperature of the warmest month, the lowest average temperature of the coldest month, and the range of annual temperature using the two variables were selected as the annual warmth, annual precipitation and bioclim parameters. Slope, altitude and aspect were selected as topographical factors. Leaf Area Index (LAI), Normal Distribution Vegetation Index (NDVI), evapotranspiration and potential evapotranspiration were considered as factors related to forests.

According to previous research, SO_2 and ozone are typical air pollutants affecting plant growth. However, in the case of SO_2, the concentration is gradually decreasing due to various environmental regulations and it is assumed that the concentration will continue to decrease in the future. In this study, ozone was selected as the air pollution factor and measured quarterly. The concentration of ozone was maintained from early spring to late summer (Logan 1989; Singh, Ludwig, and Johnson 1978) and the average concentration in the second and third quarters was used because during that period the increase in the net primary productivity of forests was the most significant.

Among the selected variables, climate parameters, vegetation factors, and air pollution factors are variables that change with time according to the RCP 8.5 scenario in the past as well as the future.

The selected independent variables were constructed as spatial data, including the variables used in the NASA-CASA NPP estimation. Spatial data for each variable was constructed with a grid of 1㎞×1㎞ resolution. The annual data provided by the Korea Meteorological Administration were used for climate variables such as solar radiation, temperature, etc., and data of slope, altitude, and aspect were constructed using the DEM data provided by the Geographical Information Service. For the LAI and NDVI, MODIS satellite image data provided by NASA was used.

The point data were extracted using the spatial data constructed to develop the impact assessment model reflecting the influence of ozone. The point data extraction point for the development of the impact assessment model was constructed based on data gathered from 63 air pollution stations. The net primary production of forests is determined by the volume of forests and should be approached with the concept of flow rather than stock, and the annual output varies according to climatic conditions. Therefore, to clarify the relationship between unsteady climatic conditions, ozone concentration, and net primary production, panel data was constructed and used instead of using the 10-year average value when building point data.

Table 2. Selected dependent variables for impact assessment

Category	Variables	Sources
Climate factor	Annual mean temperature	AWS DB from KMA (2006) / Build RCP 8.5 scenario variables
	Mean temperature of June	
	Annual precipitation	
	Monthly mean temperature	
	Solar Radiation	
	Average annual max / min temperature	
	Monthly average max / min temperature	
	Min temperature of the coldest month	
	Max temperature of the warmest month	
	Temperature annual range	
Topographical factors	Altitude	Ministry of Environment (2008) WAMIS(2006)
	Slope	
	Aspect	
Vegetation factors	LAI	MODIS
	NDVI	
	Evapotranspiration	
	Potential evapotranspiration	
Air pollution factors	Average concentration of ozone	KMA and NIER / Build SSP2 Scenario variables
	Average concentration of ozone in second and third quarters	
	Sum of average concentration of ozone above 0.04 *ppm*	

*KMA: Korea Meteorological Administration, NIER: National Institute of Environmental Research

3.2.1.2 Development of net primary productivity of forest impact assessment model

There are three methods for estimating the net primary productivity of forests. Using remote sensing-based satellite imagery has the advantage of predicting the net primary productivity of forests on a large scale and can be applied to inaccessible areas. However, there is a limit to the accuracy of producing input data for estimating future net primary productivity of forests (Gibbs *et al.* 2007). The process-based model is a model for the simulation of vegetation, soil, carbon circulation in the atmosphere, nitrogen circulation, and water circulation. This is advantageous in terms of predicting the change within forests when considering material circulation by utilizing different variables, but it is disadvantageous in that input data is very complicated. Furthermore, it is very difficult to predict future changes from data gathered by satellite images. Finally, the empirical model estimates the net primary productivity of forests based on factors such as evapotranspiration, age, biomass, and more as a result of temperature and precipitation. However, the disadvantage of the empirical model is that the assumption that changes in forests occur immediately in response to climate change is flawed. Nevertheless, empirical models have a simple structure and can be used as a basis for calculating net primary productivity (Na *et al.* 2013).

The purpose of this study is to predict the future net primary productivity of forests based on the current net primary productivity of forests and to understand how ozone affects the current and future net primary productivity of forests. However, most of the aforementioned models do not reflect the effects of ozone, and even if they did, it remains difficult to construct input data for estimating the future net primary productivity of forests. Therefore, in this study, a statistical model is developed using the variables that affect the net primary productivity of forests, which were gathered in the study performed by Michaletz *et al.*(2014). Choi *et al.* (2014) compared and analyzed domestic and global carbon stock prediction models. The results of the net primary productivity of forests show that the accuracy of the results is limited by spatial scale, the availability of data, and the availability of alternative data. Rather, using statistical models improves the linkages with other ecosystem services and valuation.

On the other hand, the net primary productivity of forests varies depending on vegetation. This implies that the net primary productivity of forests should be estimated by considering the change in vegetation distribution as a result of future climate change. Generally, The meaning of LAI (Leaf Area Index) is leaf area per unit area, and LAI' s value varies according to vegetation. In previous studies, LAI and NDVI were recorded as highly as 90% (Goswami *et al.* 2015; Johnson 2003) in 70-80% (Fan *et al.* 2009; Turner *et al.* 1999; Wang *et al.* 2005) of the total population. Therefore, in this study, the difference in vegetation was reflected by using NDVI instead of LAI as a variable.

For this purpose, a two-step statistical model was constructed. In order to reflect the difference in the vegetation found in the forests, the model for predicting the NDVI was constructed first and the impact assessment model was developed to predict the net primary productivity of forests.

The data used in this study are multidimensional data with temporal and spatial characteristics covering a period of 10 years at the 68 stations. This can be viewed as panel data with multiple observations obtained over a plurality of times from the same observatory (Han 2017; Lee and No 2012; Min and Choi 2009). Therefore, an impact assessment model using panel analysis was developed to estimate the net primary productivity of forests. Panel analysis is an analysis that can complement the limitations of regression and time series analysis, which provides more sophisticated modeling and more accurate predictions because it provides more information than cross-sectional and time series data, respectively (Abrigo and Love 2016; Bierens 2004; Han 2017). The basic panel analysis can be expressed as Equation (2) below:

$$y_{i,t} = \alpha + \beta X_{i,t} + \epsilon_{i,t} \text{ (단, } \epsilon_{i,t} = \mu_i + \lambda_t + \nu_{i,t}\text{)} \qquad \text{Equation (2)}$$

In the error term of Equation (2), μ_i is the unobserved individual effect, λ_t is the unobserved time effect, and $\nu_{i,t}$ is the remainder stochastic disturbance term. In this study, an individual effect model with a random effect model was set up to study only the individual effect.

3.2.1.3 Estimation of current net primary productivity of forests and damage due to ozone

The national forest data gathered from 2001 to 2010, which we constructed earlier, were input into the derived model to determine the current net primary productivity of the forests studied. The model was verified by statistical methods, and the model was verified by comparing the results of the NASA-CASA NPP model and the results of the MODIS NPP model. In addition, non-parametric tests were conducted to verify regional differences and clinical differences in the results.

3.2.1.4 Estimation of the future net primary productivity of forests and damage due to ozone

Based on the derived model, the future net primary productivity of forests was estimated by applying an RCP 8.5 scenario and determining future ozone concentration. In the estimation of the future net primary productivity of forests, the future ozone concentration variables are divided into a case where the current concentration is maintained and a case where the concentration is changed. The future ozone concentration change estimation is performed by two methods.

The first method which can be utilized to estimate a future change in ozone concentration is to estimate the future ozone concentration based on NOx emissions proposed from the study data gathered by (National Institute of Environmental Research, 2011) which analyzed the relationship between ozone concentration and the factors reflecting the characteristics of the country. According to the National Institute of Environmental Research (2011), ozone concentration is reduced by 40% in scenarios in which 60% of NOx is removed. In addition, the National Institute of Environmental Research (2015) says that the effect of domestic emissions on the concentration of ozone is about 43.6% on average, and that the amount of overseas emissions affects an average of roughly 56.4%. In this study, the effect of ozone concentration on the increase of NOx emissions in China and the effect of NOx emissions in China was analyzed and applied. Korea's NOx emissions are based on the forecasts of Park *et al.* (2015), and the NOx emissions of China are based on the emission data from the National Institute of Environmental Research (2016).

Table 3. NOx emission of SSP scenarios (Unit: Mt)

Year	Korea			China		
	SSP2	SSP3	SSP5	SSP2	SSP3	SSP5
2010s	1.06	1.06	1.06	21.21	21.21	21.21
2050s	1.252	1.174	1.388	26.244	17.78	28.25
2090s	1.23	0.754	1.868	26.95	9.638	28.984

(Sources: Park *et al.* 2015;
National Institute of Environmental Research 2016)

Another ozone concentration estimation method is ozone concentration data derived from the GEOS-Chem model. The GEOS-Chem model is a three-dimensional global atmospheric chemical transport model developed by Harvard University. It is useful for calculating the spatial and temporal distribution of various types of aerosols and gaseous chemicals, including atmospheric ozone (Bey *et al.* 2001; R. J. Park 2004). The GEOS-Chem model has been applied to global atmospheric chemistry problems related to tropospheric chemical composition, air pollution, and climate change, and is used by more than 30 research teams worldwide (National Institute of Environmental Research, 2015).

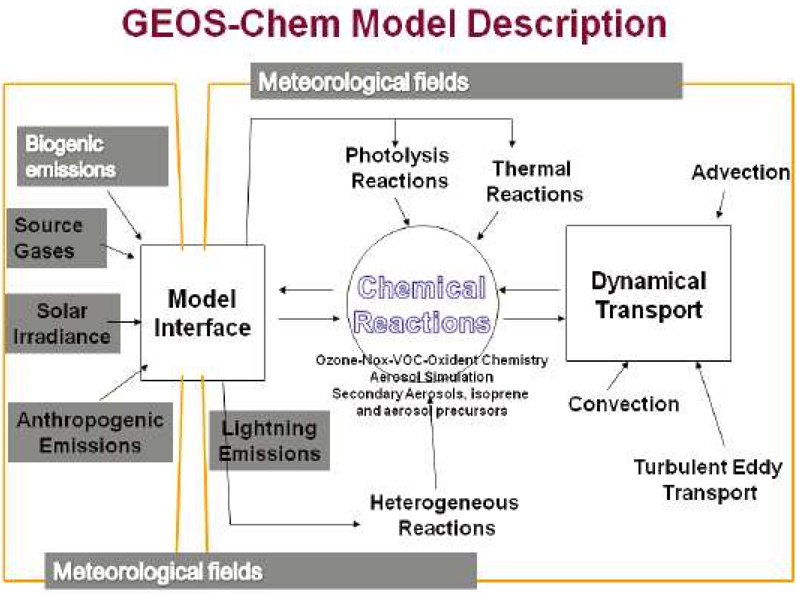


Figure 2. Structure of Global Chemical Transport Module in the GEOS-Chem Model

(Source: National Institute of Environmental Research, 2015)

The GEOS-Chem model consists of detailed modules such as the transport module, convention module, dry deposition module, emission module, chemistry module, and wet deposition module, and is intertwined with around 300 different algorithms (Figure 2) (Kim *et al.* 2015). Among these, the ozone generation algorithm is installed in the transport module, and the concrete formula is as follows:

$$y(t) - \overline{y} = \beta_0 + \beta_1 (x_1 - \overline{x_1}) + \beta_2 (x_2 - \overline{x_2}) + \cdots + \beta_n (x_n - \overline{x_n}) + \epsilon$$

Equation (3)

y and $\bar{y}$ represent the surface ozone concentration, and x_k represents the meteorological variable derived from the CESM model.

Using the GEOS-Chem model, the annual mean concentrations of future ozone concentration were derived. The average concentration of ozone was then applied to the future using the average concentration difference between the second and third quarters in the predicted future concentration of ozone compared with the current annual average concentration of ozone.

In addition, in this study the damage to the net primary productivity of forests was defined as the damage due to climate change and the damage caused by ozone, respectively.

3.2.2 Estimation of the damage cost to the net primary productivity of forests

3.2.2.1 Definition of damage cost to the net primary productivity of forests

The damage caused by the current climate change is summarized by combining preceding studies. In general, damage caused by climate change is short-term damage caused by natural disasters like typhoons, but this study focuses on long-term damage and defines the damage cost to the net primary productivity of forests.

It is necessary to distinguish between carbon stocks and carbon sequestration before defining the damage costs relating to the net primary productivity of forests. The former is the total amount of carbon stored in forest ecosystems, such as wood and soil, and is a kind of stock concept. The latter, on the other hand, is a kind of flow concept with the amount of carbon absorbed from the atmosphere by the wood over the course of a year. At this time, carbon sequestration is measured through the net primary productivity, which limits organic consumption by respiration in the gross primary production of wood by absorbing carbon dioxide through photosynthesis (Richmond *et al.* Al., 2007). In particular, the net primary production share of forest ecosystems is known to be higher than the NPP of other types of land cover (Field *et al.*, 2004; Shividenko *et al.*, 2003). The net primary productivity of forests in this study is determined by net primary production, which can vary from year to year depending on climatic conditions and the status of forests or trees. Since ozone is a short-term persistent climate change-inducing substance in the atmosphere, this study defines short-term effects and the net primary productivity of forests as impacted by the concept of flow that varies according to each year's characteristics. In addition, the damage to the net primary productivity of forests is defined as the damage resulting from ozone due to changes in the amount of future production and the presence or absence of ozone parameter, which is decreased over time with respect to the present production amount.

The net primary productivity of forests is a basic component of forest growth. In a narrow sense, it has direct functions such as carbon sequestration and carbon storage, but in a broader sense it provides many indirect functions, impacting all ecosystem services provided by forests. Estimation of the cost of damage to forests is performed to prevent the secondary and tertiary damages caused by ozone loss due to ozone depletion. Therefore, this study estimates the cost of damage not only to estimate the damage cost for the function in a narrow sense but also for the function in a broad sense.

The definition of damage cost from an economic point of view can be defined as the cost of damage due to climate change. An estimation of damage cost according to a variety of scenarios, can be done by estimating the decrease in benefits in the target year compared to the base year. Also, in one possible scenario, the difference in benefits according to the application of a specific policy can also be defined as the damage cost. Therefore, this study defined the value of production or the amount of production reduced by ozone as the damage cost.

This study used both direct and indirect use values, including damages and ecosystem services. The indirect use values included damage and control services using the value of control service related to net production amount. Damage cost was estimated according to the range of the value setting using the total economic value, including direct or indirect use value, use value, and non-use value (Figure 3).

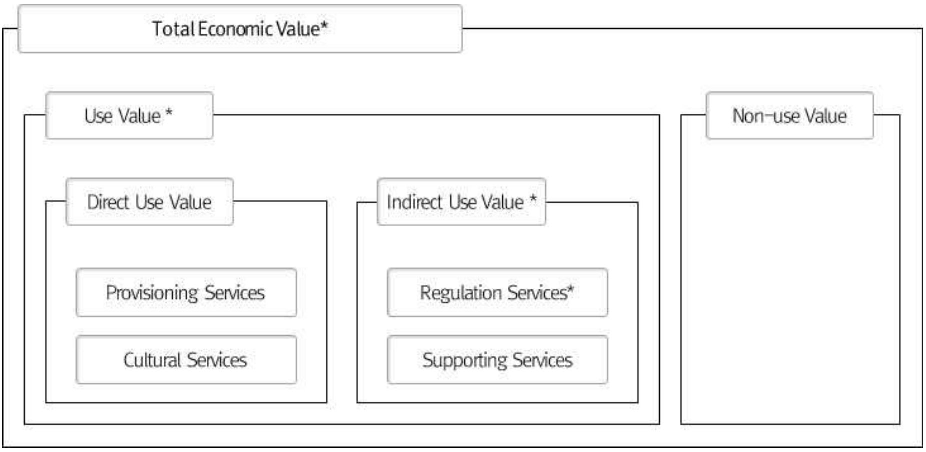


Figure 3. A range of values for estimating damage cost in this study (Source: Ahn(2006) and R. de Groot(2006) modified)

3.2.2.2 Estimation of damage cost using benefit transfer

Benefit transfer can be divided into value transfer and function transfer. Value transfer is a method of transferring benefits, such as the amount of payment, directly, and function transfer is a method of transferring the relationship between explanatory variables of benefits, as well as benefits through a function (Figure 4).

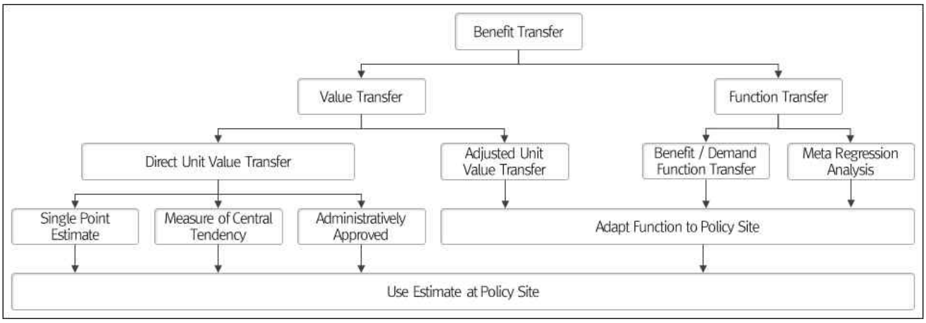


Figure 4. Classification of benefit transfer methods
(Source: Kwak, An, and Bae(2013) and Rosenberger and Loomis(2000) modified)

In this study, mean transfer method and meta-regression method were used in the transfer of value between methods. The OLS (Ordinary Least Square) multiple regression method was used for the meta-regression analysis.

To apply the benefit transfer method, the results of the evaluation of various values of forests and explanatory variables were collected through a literature review. When collecting explanatory variables, the longevity variable, different for each document, was reset to fit the four ranges of ecosystem services, and the range of ecosystem services was reset with reference to R. de Groot (2010) and Koo *et al.*(2012). In estimating value, assuming that the value is estimated for the entire forest without specifying services or items, it is assumed that the all four use values are calculated.

The statistical value published by Statistics Korea in 2016 was used to unify the units which were set differently in each document. The population was 50,801,405, the number of households was 19,560,503, and the exchange rates were 1,109 KWR/USD, 1,455 GBP/USD and 1,243 EUR/USD, respectively. In order to make use of each year's exchange rate, the GDP deflator published by Statistics Korea was used to convert amounts to reflect 2010 rates, which were used as a standard value.

To determine the value per unit area of forest, the unit value of provisioning service, regulation service, supporting service, cultural service, and non-use value were applied to each average estimation method and to the meta-regression analysis used in this study. The use value was the sum of the value of provisioning services, regulation services, supporting services and cultural services.

3.2.2.3 Estimation of the cost of damage to the application of probability

The reason for introducing probabilities in estimating the cost of damage resulting from climate change is due to future uncertainties. Therefore, it is necessary to calculate the probability of occurrence of the event in advance and to estimate the damage cost accordingly.

In this study, future damage cost is estimated through the future probability of the occurrence of ozone, the damage area of forest, and the value per unit area. The probability of the occurrence of future ozone means the probability of the occurrence of a high concentration of 0.04 *ppm* or more. Ozone is a short-term sojourn climate change-inducing material, which causes damage to vegetation when it increases beyond a certain concentration. The damage area of forests was derived by dividing the net primary productivity of a given forest as determined by the impact evaluation in advance into the net primary productivity of said forest per unit area, and the value per unit area was estimated by referring to the existing research literature.

In many studies, damage mitigation measures for climate change disasters include 1) estimating the degree of a disaster and 2) estimating the damage resulting from a given disaster (Mahler and Dean, 2001). Wouter Botzen and Van Den Bergh (2012) estimated the cost of damages using a series of variables, including the probability of flooding and damage. In this study, this methodology is used to estimate the damage cost by applying the concept of probability. The method for estimating damage cost is as follows.

$$\begin{aligned} \textit{Damage Cost} = \; & \textit{Probability of the occurrence of event} \\ & \times \textit{Damage area of forest} \\ & \times \textit{Value per unit area of forest} \end{aligned} \qquad \text{Equation (4)}$$

The probability of occurrence is the probability of high concentrations of ozone due to future climate change. The area of forest damage is calculated by dividing the total amount of the net primary productivity of forests in Korea by the net primary productivity of forests per unit area. The reason for converting the damage to the net primary productivity of forests into the area is to utilize the value per unit area. The value per unit area of forests was found using the value arrived at through the benefit method.

4. Results and Discussion

4.1 Impact assessment of the net primary productivity of forests by ozone

4.1.1 Development of the net primary productivity of forest impact assessment model

The average value of the NASA-CASA NPP model used in model development was 592.53 $tC/km^2/yr$ (SD: 213.72 $tC/km^2/yr$) for the last decade, and the average ozone concentration in the forest area during the last 10years, from 2001 to 2010, was 0.0872 ppm (SD: 0.0395 ppm). (See Appendix 7.2)

First, future NDVI was estimated using a OLS regression model to reflect changes in vegetation over time, such as future forest distribution. The NDVI estimation model was developed using variables that affect vegetation activity. The independent variables used in the NDVI estimation model are the previous year's NDVI, annual precipitation, and annual temperature range. The higher the NDVI value in the previous year, the higher the NDVI value for the year being examined. Higher annual precipitation and higher annual temperature ranges also lead to a higher NDVI value.

Table 4. Model of NDVI estimation

Variables	Coef.	Std. Error	t	Sig.
(Constant)	-574.602	323.551	-1.776	.076
Previous NDVI	.881	.019	46.162	.000
Annual Precipitation	.222	.079	2.820	.005
Annual Temperature range	248.263	82.738	3.001	.003

** Dependent Variable: NDVI*
*** R-sq: 0.816*
**** F-value: 836.813 (Sig. .000)*

In order to establish the most appropriate panel model for the next step, the binary fixed effect mode was tested first. An analysis of the Least Square Dummy Variable (LSDV) model showed, that the one-dimensional effect model was more accurate than the binary fixed effect model and the probability effect of time was more significant when the individual effect fixed (See Appendix 7.4-7.8).

Using these results, a more suitable model was selected among the fixed effect of time and the random effect of time. Both the fixed effect of time and the random effect of time were significant, but the Hausman test was performed for comparison between the two models. As a result, the null hypothesis that there is no difference between the two models was rejected ($p = 0.72$) (See Appendix 7.9). Finally, in this study, a random effect model of individual was used.

As a result of the analysis, it is assumed that the correlation between the variance and the explanatory variables is 0, and that the abstract coefficient of the stochastic model is efficient and the coincident estimator. The rho value, which is the ratio of the individual effects to the total error, is about 0.86, indicating that most of the errors are caused by differences among individuals (See Appendix 7.7). In addition, the Durbin-Watson test value was 1.722, indicating that there was no autocorrelation between the variables.

The independent variables used to develop the net primary productivity of the forest impact model considering the effects of ozone are NDVI, solar radiation, altitude, and average concentration of ozone in the second and third quarters.

Table 5. Model of NPP estimation considering ozone effect

Variables	Coef.	Std. Error	Z	P>|t|
(Constant)	-3548.925	569.9089	-6.23	0.000
NVDI	1.174644	.0619074	18.97	0.000
Solar radiation	1.036475	.0702302	14.76	0.000
Altitude	-4.752429	1.462732	-3.25	0.001
Average concentration of O_3 in 2&3 quarters	-6810.416	3393.694	-2.01	0.045

** Dependent Variable: NPP (Number of obs: 630, Number of groups: 10)*
*** rho: 0.08218871*
**** R-sq: 0.5743*

According to the NDVI, as the net primary productivity tends to increase, and the net primary productivity increases alongside irradiation dose. However, as the altitude increased, the net primary productivity decreased (Table 5). NDVI is an index of vegetation distribution and vegetation activity, ranging from −1 to +1 (Carlson and Ripley 1997). A value of +1 indicates a positive relationship between NDVI and net primary productivity because of the greater activity of vegetation. In most net primary productivity estimation models, solar radiation affects the net primary productivity estimation (Cramer, *et al.* 1999). The results also show that solar radiation has a positive effect on net primary productivity. Altitude has been shown to have a negative impact on net primary productivity, which is due to temperature. On average, as altitude increases by 100m, the temperature decreases by about 0.65℃ (ICAO 1993). The topography of Korea is divided into east and west, and the eastern terrain is more than 800~1,000 m above sea level. For example, the maximum altitude of Mt.Seolak is about 1,700 m. Therefore, it can be inferred that the relationship between altitude and the primary productivity appears to have a negative relationship. However, due to the nature of the terrain in Korea, it is necessary to reflect the altitude, so it was included as a variable in this study.

In particular, the concentration of ozone has a negative effect on net primary productivity. According to Lee *et al.* (2011), damage is expressed when contact is made between 0.06 *ppm* and 0.170 *ppm* for 4 hours and between 0.200 *ppm* and 0.510 *ppm* for 1 hour with susceptible species. In general, it is said that when the concentration of ozone in the air is 0.03 *ppm* or more, damage to trees occurs. It is also known that radish reduces the yield by 50% when exposed for 20 days at −0.05 *ppm* for 8 hours each day. Furthermore, it is known that carnations are affected by the decrease in the flowering rate and the decrease of the production of pollen.

The forest impact assessment model that reflects the concentration of ozone finally developed in this study is shown in Equations (5) and (6). NDVI for the current and previous year, annual precipitation, annual temperature range, solar radiation, altitude, and average ozone concentrations in the second and third quarters were found to be related to vegetation growth.

Step 1)

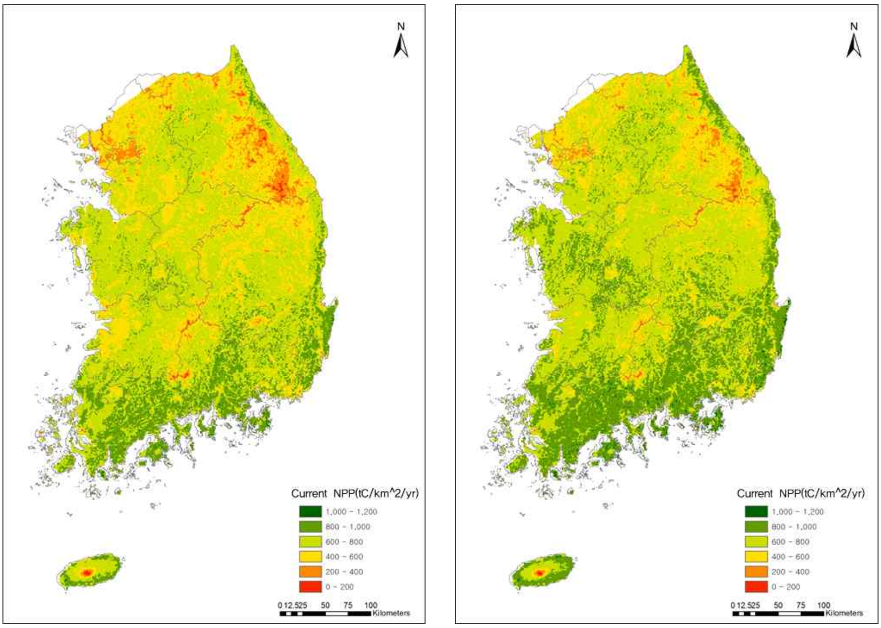
$$NDVI_t = -289.2741 + 0.8999039 \times NDVI_{t-1} + 0.1620896 \times Annual\ precipitation_t + 17.62102 \times Annual\ temperature\ range_t \quad \text{Equation (5)}$$

Step 2)

$$NPP_t = -3548.93 + 1.174644 \times NDVI_t + 1.036475 \times Solar\ radiation_t - 4.752429 \times Altitude - 6810.416 \times O_3\ concentration_t \quad \text{Equation (6)}$$

4.1.2 Estimation of current net primary productivity of forests and damage due to ozone

The net primary productivity of forests is calculated spatially using the derived model, as shown in Figure 5. The net primary productivity of forests in the southern region is higher than that in the central region due to variables such as temperature range, precipitation, and solar radiation, and the net primary productivity of forests in the central inland region is relatively higher. This is because the solar radiation and temperature in the central inland region have an influence on the distribution of the net primary productivity of forests (Kang, Kim, and Kim 2005). The forests area in the central inland area has lower in temperature and light intensity than the plains area, so the amount of energy used for respiration is higher than the amount of carbon accumulation through photosynthesis (Zhang, Yedlapalli, and Lee 2009).



(a) Effect of ozone (b) No ozone effect

Figure 5. Average net primary productivity of forest in 2001~2010

The net primary productivity averaged 573 to 671 $tC/km^2/yr$ from 2001 to 2010, with an average of 628 $tC/km^2/yr$ (SD: 31 $tC/km^2/yr$) for 10 years (Figure 6). According to Lee *et al.* (2010), carbon from 585 $tC/km^2/yr$ to 731 $tC/km^2/yr$ is stored in vegetation each year, which is reflected in the results of this study.

The average net primary productivity of Korea was about 64 million tC/yr on average. The net primary productivity of 2003 was the lowest at about 60 million tC/yr, and the net primary productivity of 2008 was the highest at about 66 million tC/yr. The distribution of input variables in 2003 shows that precipitation, NDVI and temperature range were higher for that year than others, but that solar radiation is especially low then. The low productivity in 2003 was due to this low solar irradiance. In addition, the net primary productivity of forests was highest in 2008 because of an increase in solar radiation during that year, while precipitation and NDVI values remained comparable to the other years observed. Therefore, it can be concluded that the distribution of these input variables affected the result.

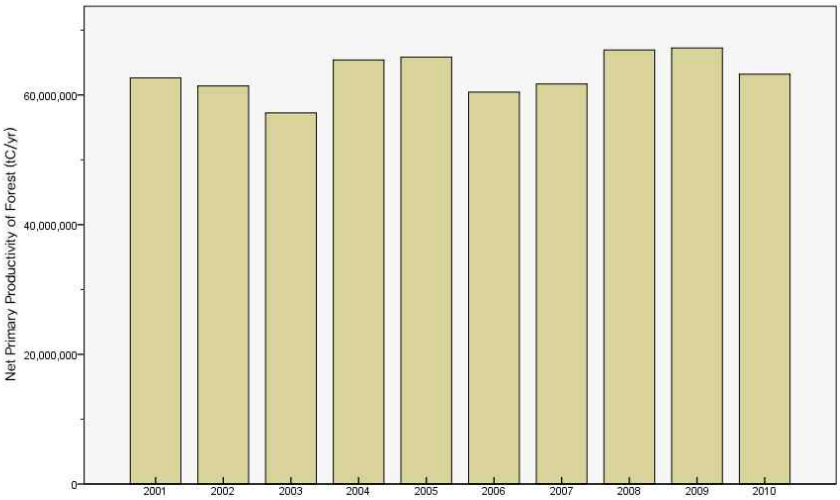
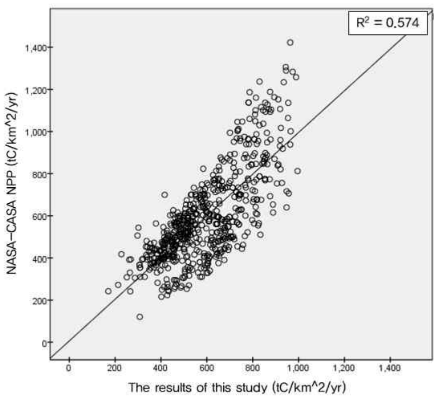


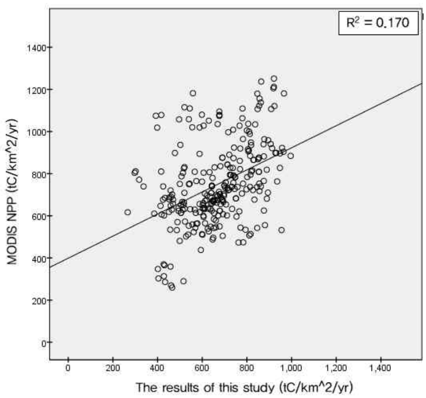
Figure 6. Net primary productivity of forests from 2001~2010

The results of this study are compared with those of other models, and are found to be 60% similar to the results of the NASA-CASA NPP model and almost 17% similar to the MODIS NPP results (Figure 7). In both models, the trends are similar and the range of net primary productivity of forest per unit area is similar.

The dependent variable used in this study is the NASA-CASA NPP model, so the similarities to that model are more prevalent than similarities to MODIS NPP. The primary reason for differences between the results of this study and the results of the NASA-CASA NPP model is that the variables used for each model are different. Because the MODIS NPP uses satellite imagery, its algorithm is different from the one used in this study. Therefore, although the results are similar to those of this study, the accuracy of the results is low.



(a) Comparison with NASA-CASA NPP results



(b) Comparison with MODIS NPP results

Figure 7. Comparing the results

Finally, using the point data gathered, the differences between clinics and regions were evaluated; the Kruskal-Wallis test was used to do this. The results showed that the net primary productivity of forests, NDVI, and ozone concentrations differed significantly by region. However, there was no difference between the two groups when they were classified using the same method. This is because the clinical differences were reflected in the process of deriving the future variables of NDVI.

The damage to the net primary productivity of forests due to ozone decreased by up to 27.07%, with an average decrease 9.08% in the unit of analysis. The total net primary productivity of forests in Korea is estimated to be about 69 million tC/yr without the 10 years average ozone effect and about 64 million tC/yr considering the effect of ozone. From 2001 to 2010, the net primary productivity of forests decreased by an average of about 8.24% nationwide. According to a study by Ollinger, *et al.*(1997), the decrease in the net primary productivity of forests due to ozone in the United States has decreased by at least 3% to 16%, an average of 7.4% in 64 areas from 1987 to 1992, Felzer, *et al.* (2004) found that the annual net primary productivity of forest decreased from 1987 to 1992 by 2.6 ± 0.34%.

In particular, the average concentration of ozone during the second and third quarters, when net primary productivity is in full swing, has the greatest impact on the ecosystem. According to Ollinger, *et al.* (1997) and Felzer, *et al.* (2004), ozone influences the net primary productivity at a mean concentration of 0.04 *ppm* or higher. In fact, the concentration was about 0.05 *ppm*, indicating a concentration that influences the net primary productivity.

4.1.3 Estimation of the future net primary productivity of forests and damage due to ozone

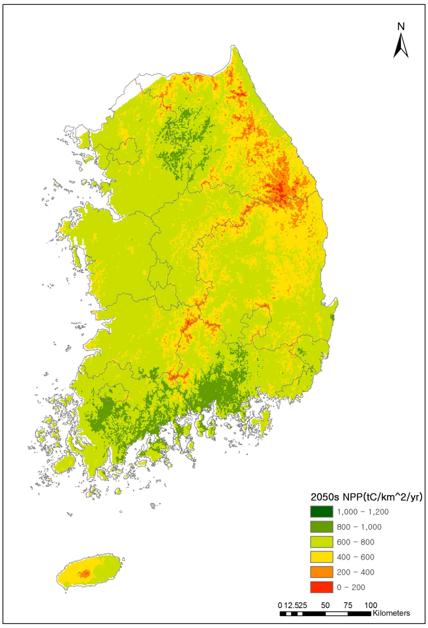
Input data for the estimation of the future net primary productivity of forests is based on the average data collected form 2001-2010 for the variables of solar radiation and this data is used without any correlation between it and the present altitude. The RCP 8.5 scenario was were applied to the temperature- and precipitation-related variables for NDVI estimation.

4.1.3.1 In case the current ozone concentration is maintained

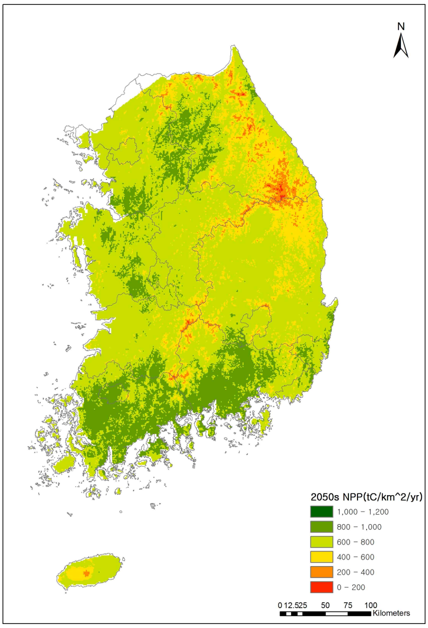
In this instance, the concentration of ozone is assumed to maintain its present level. Table 6 and Figure 8 show the differences and spatial distributions of the net primary productivity of forests and the net primary productivity of forests with and without an impact from ozone in the 2050s and 2090s. The effects of ozone are almost identical in the present and future, and the net primary productivity of forests is expected to increase by about 2.54% in the 2090s due to an increase in temperature and precipitation.

Table 6. Comparing current and future net primary productivity of forest (maintaining current ozone concentration)

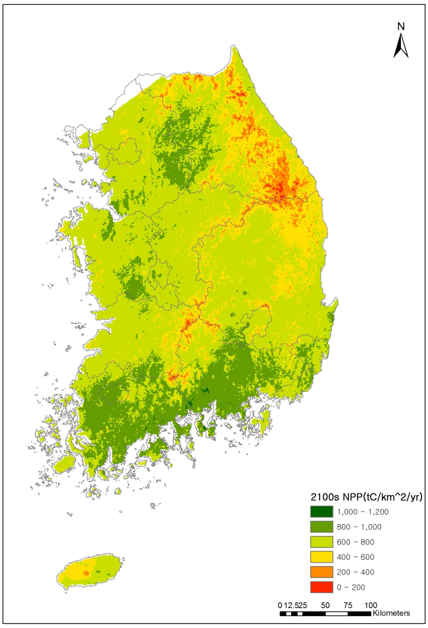
		No ozone effect	Effect of ozone
Current (10 year average)	NPP (tC/yr)	69,341,592	63,627,604
	compared to current value	100.00%	91.76%
2050s	NPP (tC/yr)	66,871,635	61,295,426
	compared to current value	96.44%	88.40%
2090s	NPP (tC/yr)	71,103,777	65,526,158
	compared to current value	102.54%	94.50%



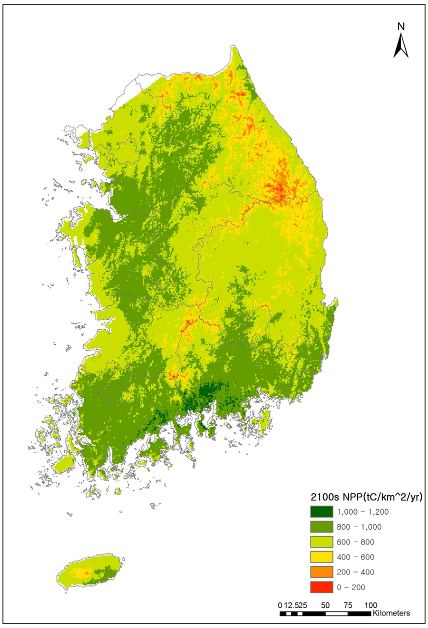
(a) Effect of ozone (2050s)



(b) No ozone effect (2050s)



(c) Effect of ozone (2090s)



(d) No ozone effect (2090s)

Figure 8. Changes in the net primary productivity of forests according to the RCP 8.5 scenario

4.1.3.2 In case of changes in ozone concentration due to emissions

Next, the researcher estimated the concentration of ozone in connection with NOx emissions in Korea and China. At the National Institute of Environmental Research (2011), the emission factor that had the greatest influence on ozone generation in Korea was identified as NOx. Using the relation between NOx emission and ozone concentration, the following Equation (7) was formulated.

$$\begin{aligned}&O_3 \text{ concentration change ratio in the future}\\&\quad = (4/6) \times \{(\text{NOx emissions in Korea} \times 0.436) + (\text{NOx emissions in China} \times 0.564)\}\\&\quad / \text{Base emissions in 2010}\end{aligned} \qquad \text{Equation (7)}$$

Thus, future ozone concentration changes due to NOx emissions from various scenario combinations are expected to decrease by up to 3% or up to 21% compared to current levels in the 2050s and up to either 29% or 36% in the 2090s (Table 7).

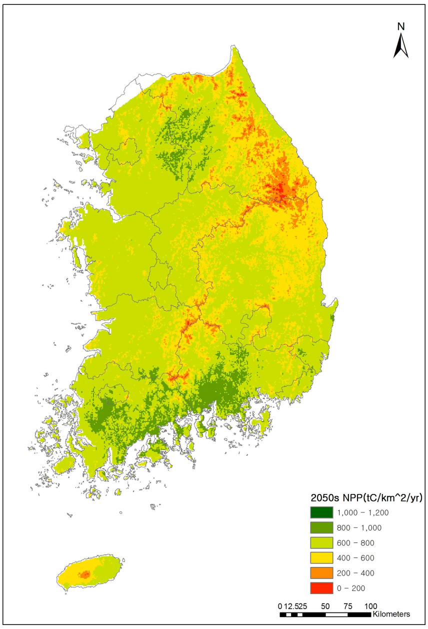
Table 7. Estimation of the change of ozone concentration according to NOx emission by scenarios

KOR	SSP2			SSP3			SSP5		
CHN	SSP2	SSP3	SSP5	SSP2	SSP3	SSP5	SSP2	SSP3	SSP5
2010s	1.00								
2050s	1.14	0.99	1.18	1.12	0.97	1.16	1.18	1.03	1.21
2090s	1.15	0.84	1.18	1.02	0.71	1.05	1.32	1.02	1.36

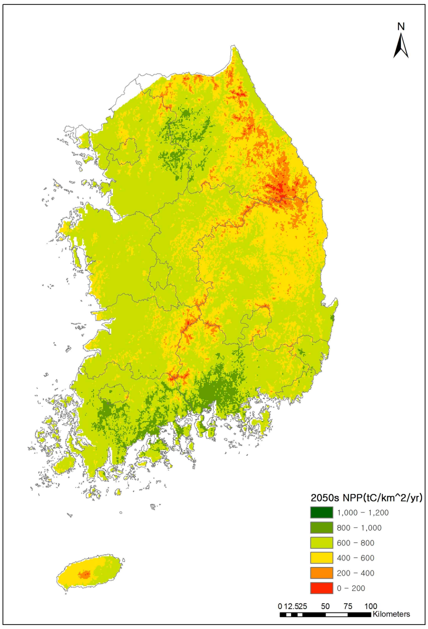
Changes in the net primary productivity of forests due to scenarios predicting changes in ozone concentration are shown in Table 8 and Figure 9 below. When the average ozone concentration decreases by about 3% in the 2050s, the net primary productivity of forests increases by about 0.27%. When the average ozone concentration increases by about 21%, the net primary productivity of forests decreases by about 1.91%. In the 2090s, when the average ozone concentration decreases by about 29%, the net primary productivity of forests increases by 2.47%, and when the ozone concentration increases by about 36%, the productivity decreases by about 3.07%.

Table 8. Comparison of the net primary productivity of forests by ozone concentration change scenarios in the future

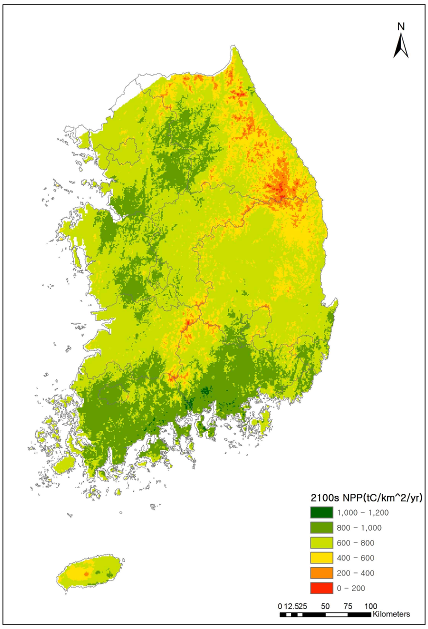
		O_3 concentration decrease	O_3 concentration maintenance	O_3 concentration increase
2050s	NPP (tC/yr)	61,462,854	61,295,426	60,123,123
	compared to concentration maintenance	100.27%	100.00%	98.09%
2090s	NPP (tC/yr)	67,145,028	65,526,158	63,516,382
	compared to concentration maintenance	102.47%	100.00%	96.93%



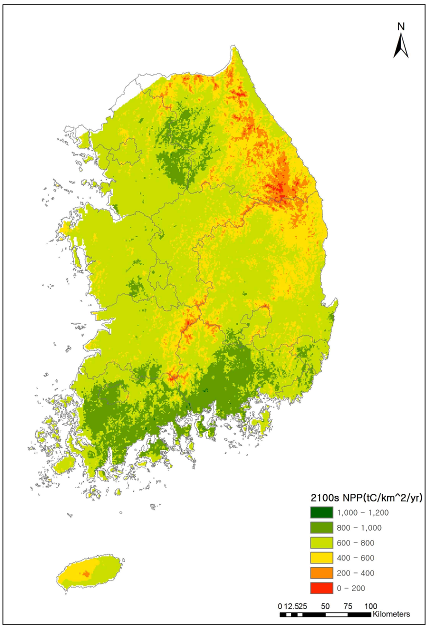
(a) Maximum reduction of ozone concentration (-3%) (2050s)



(b) Maximum increase in ozone concentration (+21%) (2050s)



(c) Maximum reduction of ozone concentration (-29%) (2090s)



(d) Maximum increase in ozone concentration (+36%) (2090s)

Figure 9. Changes in the net primary productivity of forests due to ozone concentration change scenarios in the future

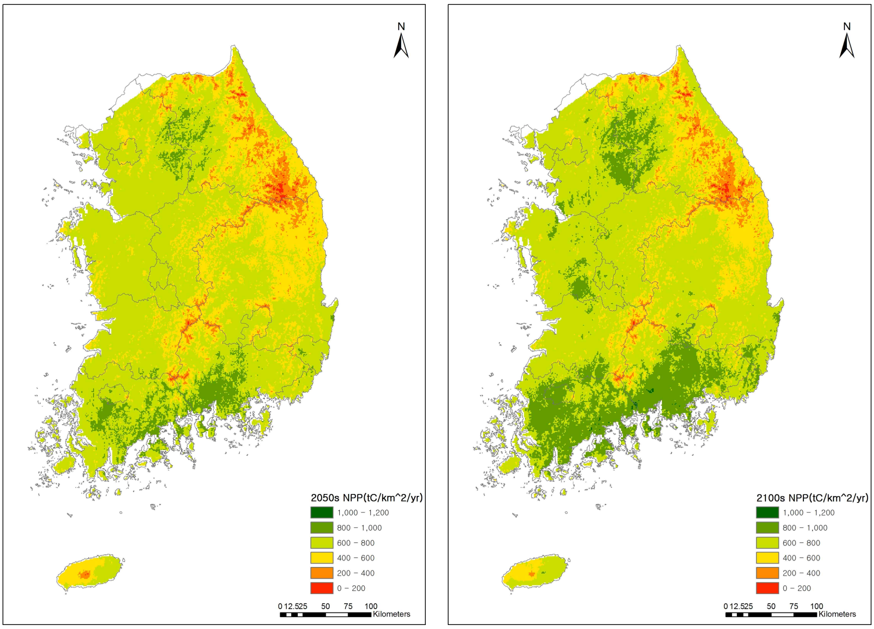
4.1.3.3 In case of changes in ozone concentration according to modeling results

Finally, the results of ozone concentration data from the GEOS-Chem/CESM were utilized. The ozone concentration in the 2050s increased by about 10% compared to the present level, and was then used to estimate the future net primary productivity. The 2090s also showed an increase in concentration similar to that of the 2050s, and had a concentration 10% higher than the value assigned to the 2050s.

Table 9. Comparison of net primary productivity of forests by ozone concentration change scenarios in the future

		O_3 concentration maintenance	O_3 concentration increase
2050s	NPP (tC/yr)	61,295,426	60,737,129
	compared to concentration maintenance	100.00%	99.09%
2090s	NPP (tC/yr)	65,526,158	64,967,846
	compared to concentration maintenance	100.00%	99.15%

The results of the ozone concentration analysis by GEOS-Chem/CESM analysis showed that in the 2050s ozone productivity was reduced by about 0.91% to about 56 million tC/yr, and about 56 million tC/yr by the 2090s, which is about 0.85% (Table 9 and Figure 10).



(a) Increased ozone concentration by 10% (2050s)

(b) Increased ozone concentration by 10% (2090s)

Figure 10. Changes in the net primary productivity of forests in ozone concentration change scenarios in the future

4.1.3.4 Conclusion

Combining the results of the prediction regards the future net primary productivity of forests, productivity as a whole declined in the 2050s, but increased in the 2090s. It is believed that this was caused by the increase of the NDVI value, and the reason for the increase of the NDVI is presumably due to the increase of the precipitation amount. The average annual precipitation of RCP 8.5 in the 2050s is about 1,300 mm, and productivity in the 2090s is about 1,600 mm.

It is estimated that the net primary productivity of forests will be higher in the southern and central inland areas in the future. In high altitude areas along the Mt. Taebaek and Mt. Sobaek ranges, it is estimated that the net primary productivity of forests will be lower due to temperature differences. According to Lee *et al.* (2010), it is predicted that the amount of carbon stored in vegetation will increase with future temperature increases. In particular, it is predicted that carbon stocks in the southern region will increase, which is similar to the results of this study.

The damage caused by ozone is estimated to be at least 11.36% to 13.29% in the 2050s and at least 3.17% to 9.40% in the 2090s. This reflects the SSP 2 scenario for estimating concentration, but the deviations between the high-growth and low-growth scenarios become greater as numbers are calculated farther into the future.

Table 10. Comparison of the net primary productivity of forests by ozone concentration change scenarios in the future

	No ozone effects NPP (tC/yr)	Effect of ozone NPP (tC/yr)	
2010s (compared to current no ozone effect)	69,341,592 (100.00%)	63,627,604 (91.76%)	
2050s (compared to current no ozone effect)	66,871,635 (96.44%)	Application of ozone concentration change scenarios	
		▼ 3%	61,462,854 (88.64%)
		–	61,295,426 (88.40%)
		▲ 10%	60,395,582 (87.59%
		▲ 21%	60,123,123 (86.71%
2090s (compared to current no ozone effect)	71,103,777 (102.54%)	▼ 29%	67,145,028 (96.83%)
		–	65,526,158 (94.50%)
		▲ 10%	64,606,965 (93.69%)
		▲ 36%	63,516,382 (91.60%)

4.2 Estimation of the damage cost to the net primary productivity of forests

4.2.1 Estimation of damage cost using benefit transfer

In order to derive the benefit function, 50 forests had values assigned to them based on 17 papers and reports from national and international sources. The total usage value was 53, with 21 regulation services, 19 cultural services, 7 supporting services, 6 provisioning services, and 7 non-use values making up that number. The average value of DB was 72.87 million KRW/㎢. The value per unit area of ecosystem service items estimated based on this is shown in Table 11 below.

Table 11. Value per unit area of forests

Services / Value Type		Estimated Unit Cost (10,000KRW/㎢)	
		Measure of Central Tendency	Meta-Regression Analysis
	Provisioning Services	4,722	5,616
	Regulation Services	7,523	8,139
	Supporting Services	6,069	7,750
	Cultural Services	3,027	2,876
Use Value		21,341	24,381
Non-use Value		17,636	18,747

In the case of applying the meta-regression method to all items, the meta-regression method is applied to about 19% of provisioning services, about 8% of regulation services, about 28% of supporting services, and about 14% of cultural services. The results of this study are as follows: First, it is estimated that the method of estimating the average value of cultural services is about 5% larger than that of meta-regression analysis. In addition, the values of provisioning services, regulation services, and supporting services are relatively greater than cultural services that people actually use, and usage value is relatively higher than non-use values, such as those attributed to heritage and existence.

As of 2010, the total net primary productivity of the forests of Korea was about 69 million tC/yr without considering ozone, and about 64 million tC/yr if the effect of ozone is taken into consideration. In other words, the damage to the net primary productivity of forest due to ozone was about 5.7 million tC/yr, which is similar to the loss of 9,099 ㎢ of forests when converted into the area using the value of net primary productivity of forest per unit area. Applying the same methods to the future predictions, when considering the effects of ozone, the average of the net primary productivity in 2010, around 64 million tC/yr is reduced to between 60 million tC/yr and 61 million tC/yr in the 2050s. This number reflects a decrease in forestation of approximately 3,262~5,205 ㎢. The net primary productivity of forests in the 2090s is expected to range from 63 million tC/yr to 67 million tC/yr, or, in other words, to represent as much as 6,304 ㎢ to 12,082 ㎢ of deforestation.

Table 12. Estimation of forest damage area in the future

Target year	Forest damage area (㎢)
2050s	8,879
	8,613
	9,768
	10,746
2090s	8,882
	6,304
	9,771
	12,082

Based on the above table, multiplying the value per unit area of each ecosystem service item and the area of future forest damage is a viable means of estimating the damage cost of ozone concentration into the future. In the range of total economic value, it is expected that the damage will range from 4,133 billion KRW to 2,977 billion KRW in 2050s, which is about 0.14~0.27% of Korea's GDP and about 0.21% on average. In the 2090s, it is expected to incur a maximum of 4,662.6 billion KRW down to 2,153.9 billion KRW. This is about 0.15~0.30% of Korea's annual

GDP, which is about 0.23% on average. The maximum damage cost and the average cost of damages are expected to increase in the 2090s compared to the 2050s, and the minimum damage cost is expected to decrease further in the 2090s (Table 13, Table 14).

Among the ecosystem service items, only the control services related to the carbon absorption function are expected to suffer, ranging from 780 billion KRW in damages to 574.8 billion KRW in the 2050s, and from a maximum of 878 billion KRW to a minium of 412.5 billion KRW in the 2090s. The estimated cost of indirect use, including control services, was between 1,524.2 billion KRW and 1,384 billion KRW in the 2050s and 1,714 billion KRW and 751 billion KRW in the 2090s. The estimated cost of damages resulting from use in the 2050s was approximately 1,630.5 billion KRW to 2,364.4 billion KRW, and 1,193.9 billion KRW to 2,630.2 billion KRW in the 2090s; it can be seen that the change in damage cost is larger in the 2090s than it is in the 2050s.

Table 13. Estimation of damage costs to forests in the future

(Unit: one hundred million KRW)

Target Year	Services / Value Type			Estimated Damage Cost	
				Measure of Central Tendency	Meta-Regression Analysis
2050s			Provisioning Services	3,608	4,291
				3,798	4,517
				4,180	4,971
				4,525	5,382
			Regulating Services	5,748	6,218
				6,051	6,546
				6,659	7,205
				7,209	7,800
			Supporting Services	4,637	5,921
				4,881	6,233
				5,372	6,860
				5,816	7,427
			Cultural Services	2,313	2,197
				2,435	2,313
				2,680	2,546
				2,901	2,756
		Use Value		16,305	18,627
				17,165	19,610
				18,891	21,582
				20,451	23,364
		Non-use Value		13,474	14,323
				14,185	15,078
				15,611	16,595
				16,901	17,965
	Total Economic Value			29,778	32,950
				31,349	34,688
				34,502	38,177
				37,352	41,330

Table 14. Estimation of damage costs to forests in the future

(Unit: one hundred million KRW)

Target Year	Services / Value Type	Estimated Damage Cost: Measure of Central Tendency	Estimated Damage Cost: Meta-Regression Analysis
2090s	Provisioning Services	2,609	3,103
		3,797	4,516
		4,158	4,945
		5,094	6,059
	Regulating Services	4,157	4,498
		6,049	6,545
		6,624	7,166
		8,116	8,780
	Supporting Services	3,354	4,283
		4,880	6,232
		5,344	6,824
		6,547	8,361
	Cultural Services	1,673	1,589
		2,434	2,313
		2,665	2,532
		3,266	3,103
	Use Value	11,793	13,473
		17,160	19,605
		18,791	21,467
		23,023	26,302
	Non-use Value	9,746	10,360
		14,181	15,074
		15,528	16,507
		19,026	20,224
	Total Economic Value	21,539	23,833
		31,341	34,679
		34,319	37,974
		42,048	46,526

4.2.2 Estimation of the cost of damage by application of probability

In order to estimate the damage cost by using the probability of high future concentrations of ozone, the probability of the occurrence of ozone, the area of occurrence of forest damage, and the value per unit area of forest are required.

The probability of higher concentrations of ozone was used only by the results of the GEOS-Chem/CESM model. Using the monthly data, the probability of ozone concentration of 0.04 *ppm* or more can be calculated as 98.33% in the 2050s and 96.67% in the 2090s. This is roughly 11~13% higher than 85.00%, which is the current probability of modeling results.

Table 15. Probability of a high concentration of ozone in the future

Target year	Probability (%)
2050s	98.33
2090s	96.67

The damage area of the forest is estimated to be 8,613~10,746 ㎢ in the 2050s, and 6,304~12,082 ㎢ in the 2090s.

Table 16. Estimation of forest damage area in the future

Target year	Forest damage area (㎢)
2050s	8,879
	8,613
	9,768
	10,746
2090s	8,882
	6,304
	9,771
	12,082

The value per unit area of the forest was also used as a result of the previous survey. According to the estimation method and the utilized range of values, these value ranges from 28.76 million KRW/㎢ to 243.81 million KRW/㎢.

Table 17. Value per unit area of forest

Services / Value Type		Estimated Unit Cost (10,000KRW/㎢)	
		Measure of Central Tendency	Meta-Regression Analysis
	Provisioning Services	4,722	5,616
	Regulating Services	7,523	8,139
	Supporting Services	6,069	7,750
	Cultural Services	3,027	2,876
Use Value		21,341	24,381
Non-use Value		17,636	18,747

Based on this information, the cost of damage is estimated by applying the concept of probability as shown in Table 18 and Table 19 below. In the 2050s, it is estimated that the damage will reach a maximum of about 4.639 billion KRW down to 2,928.1 billion KRW, which is between 0.19 and 0.26% of Korea's GDP and about 0.22% on average. In the 2090s, it is expected to incur a maximum of 4,977.7 billion KRW down to 2.82 trillion KRW in damages. This is about 0.13~0.29% of Korea's annual GDP, which is about 0.21% on average. The maximum damage cost and the average cost of damages are expected to increase in the 2090s compared to the 2050s, and the minimum damage cost is expected to decline further in the 2090s.

Similar to the results from the estimation of damage cost by benefit transfer, it is believed that the control service related to the carbon absorption function among the ecosystem service items is predicted to decline between 565.2 billion KRW and 766.9 billion KRW in the 2050s; about 848.8 billion KRW in damage is expected. The estimated cost of indirect use, including control services, was about 1.497 trillion KRW, but may range as low as 1 trillion 21.1 billion KRW in the 2050s, and is estimated to range from 726.1 billion KRW to 1.6 trillion KRW in the 2090s. The cost of damages estimated from the value of use in the 2050s ranged from 1.6332 trillion KRW to 2.2974 trillion KRW, and in the 2090s the number increased to 2.15 trillion KRW, a significant increase in the damage cost. Although the dollar amount is greater, the tendency of the damage cost is not significantly increased from the tendency of the damage cost by the method of benefit transfer.

Table 18. Estimation of the damage costs to forests in the future

(Unit: one hundred million KRW)

Target Year	Services / Value Type	Estimated Damage Cost: Measure of Central Tendency	Estimated Damage Cost: Meta-Regression Analysis
2050s	Provisioning Services	3,547	4,219
		3,734	4,442
		4,110	4,888
		4,450	5,292
	Regulating Services	5,652	6,114
		5,950	6,437
		6,548	7,084
		7,089	7,669
	Supporting Services	4,559	5,822
		4,800	6,129
		5,283	6,746
		5,719	7,303
	Cultural Services	2,274	2,161
		2,394	2,275
		2,635	2,503
		2,852	2,710
	Use Value	16,032	18,316
		16,878	19,282
		18,576	21,222
		20,110	22,974
	Non-use Value	13,249	14,084
		13,948	14,826
		15,351	16,318
		16,618	17,665
	Total Economic Value	29,281	32,400
		30,826	34,109
		33,926	37,539
		36,728	40,639

Table 19. Estimation of damage costs to forests in the future

(Unit: one hundred million KRW)

Target Year	Services / Value Type	Estimated Damage Cost: Measure of Central Tendency	Estimated Damage Cost: Meta-Regression Analysis
2090s	Provisioning Services	2,522	3,000
		3,671	4,365
		4,019	4,780
		4,924	5,857
	Regulating Services	4,019	4,348
		5,848	6,327
		6,403	6,928
		7,846	8,488
	Supporting Services	3,242	4,140
		4,718	6,024
		5,166	6,597
		6,329	8,082
	Cultural Services	1,617	1,536
		2,353	2,236
		2,577	2,448
		3,157	2,999
	Use Value	11,400	13,024
		16,589	18,952
		18,165	20,753
		22,256	25,426
	Non-use Value	9,421	10,015
		13,709	14,572
		15,011	15,957
		18,392	19,551
	Total Economic Value	20,821	23,039
		30,298	33,524
		33,176	36,710
		40,648	44,977

4.2.3 Damage cost to the net primary productivity of forests due to future ozone effects

In this study, the damage cost to the future net primary productivity of forests was derived using two methods. In the range of total economic value, the damage cost estimated by the transfer of benefits was expected to range from approximately 2,997.8 billion KRW to 4,133 billion KRW in the 2050s and from 2,153.9 billion KRW up to 4,662.6 billion KRW in the 2090s. This accounts for approximately 0.23% of Korea's GDP. In the case of regulated services, it is estimated that the damage cost will range from 574.8 billion KRW to 780 billion KRW in the 2050s and from 415.7 billion KRW to 878 billion KRW in the 2090s. If this value is extended to include indirect use values, it will be between 1 trillion 384 billion KRW and 1 trillion and 226 billion KRW in the 2050s and 751.1 billion KRW and 1,714.1 billion KRW in the 2090s. In the 1990s, damages were estimated to be between 1,639 billion KRW and 1,193 billion KRW.

When estimating the cost of damage by applying the concept of probability, it seems to generate lower totals than the benefit transfer method. This is because the probability of occurrence is considered based on the benefit transfer method. Likewise, in the range of total economic value, it is estimated that about 4.29 trillion KRW will be devastated, up from 2.9218 billion KRW, which accounts for about 0.13-0.29% of GDP, up to 4,497.7 billion KRW from about 2.821 trillion KRW. In the case of regulated services, about 565.2 billion KRW to 766.9 billion KRW in the 2050s and about 409.1 billion KRW in the 2090s are expected to see damages in the amount of 848.8 billion KRW. Likewise, the cost of damages estimated from the indirect use value is predicted to com in between 1.121 billion KRW and 1.4972 trillion KRW, and from 726.1 billion KRW to 1.657 trillion KRW in the 2090s. It is estimated that about 2,454.6 billion KRW of damage will occur, ranging from 1 trillion 603.2 billion KRW to 2 trillion 297.4 billion KRW and about 1 trillion 140 billion KRW.

The cost of damage to forests by ozone varies depending on the definition used of the damage cost and the method of estimating the damage cost (Figure 11). If the definition of damage costs for forests is only the adjustment service that is directly related to the carbon absorption function, the damage cost is 188~409 billion KRW, but when damage cost estimated as indirect use value including control services is determined to be between 726.1 billion KRW and 1,714.1 billion KRW. The cost of damage to forests estimated by total economic value plus use value and non-use value was roughly 2,821~4,665.2 billion KRW. That is, according to the definition of the damage range, a minimum of about 409.1 billion KRW and a maximum of about 4,662.6 billion KRW were obtained, a difference of 11.6 times. The reason for this result is that the deviation of the damaged area varies depending on the deviation from the value per unit area and the concentration of ozone.

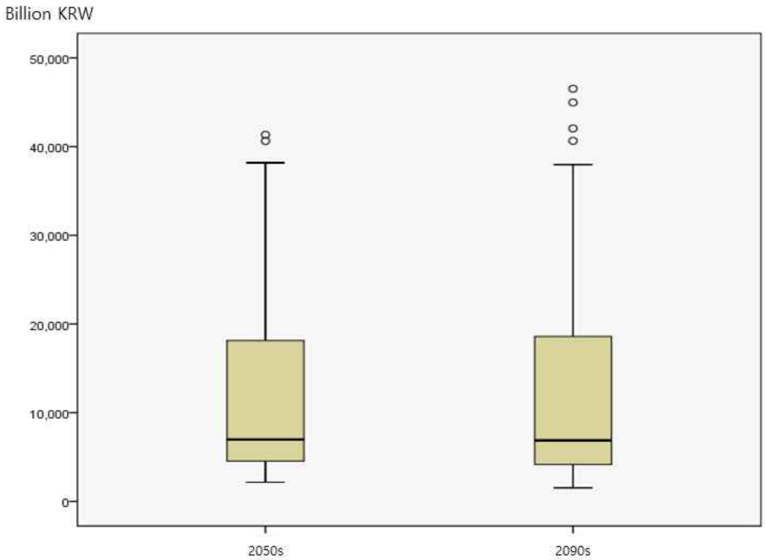
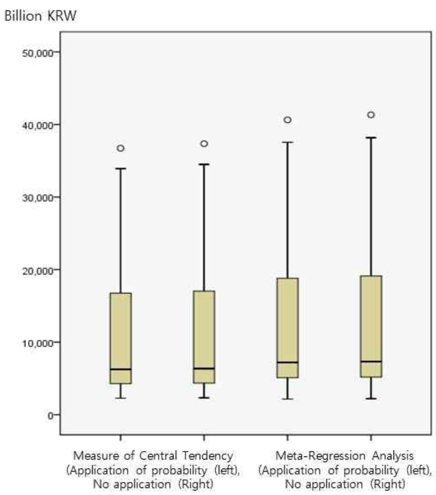


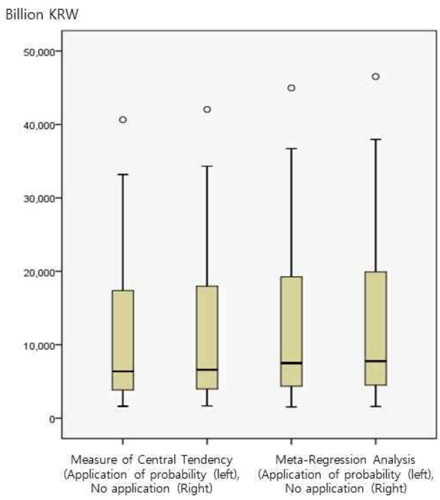
Figure 11. Comparing future damage cost

Looking at the total cost of damages in the 2050s and 2090s, the average cost of damages was 1,268.3 billion KRW (SD: 1,834.4 billion KRW) and 1.2224 trillion KRW (SD: 1,097.3 billion KRW), respectively. The average cost of damage in the 2050s was high, but the cost of damage in the 2090s was greater. This is due to the uncertainty of models and scenarios that attempt to make predictions about conditions further in the future. As a result, when the cost of damage in the 2050s and the 2090s is compared, the minimum damage cost has a smaller value in the 2090s, but the maximum damage cost is simultaneously larger.

The results of the damage cost estimation method show that the damage cost of the meta-regression method is slightly larger than that of the average estimation method, which is the same in both the 2050s and 2090s (Figure 12). Similarly, when considering only the damage cost of the regulatory services, the average transfer method suffered damages from a minimum of about 409.9 billion KRW to a maximum of about 4.284 trillion KRW. In the meta-regression method, a minimum was determined of about 4,348 KRW up to close to 4,665.6 billion KRW. In both methods, the difference between the maximum value is around 10 times greater than the minimum value. The methodological difference is about 8% for the minimum value and 11% for the maximum value when using the meta-regression analysis.



(a) 2050s



(b) 2090s

Figure 12. Comparing future damage cost according to different methods

As a result of this study, the damage cost to forests varied according to method and definition. According to Kim *et al.* (2012), as of 2008, the value provided by all forests in Korea is about 73,179.9 billion KRW, which is about 11,480,000 KRW/㎢/yr when the total forest area is determined to be 6,374,875ha. According to a study by Park *et al.*(2014), the value provided by the forests is about 34.94 million KRW/㎢/yr. The value of use is about 13.12 million KRW/㎢/yr and the non-use value is 21.82 million KRW/㎢/yr. In 2011, the average land price was 39,900,000 KRW/㎡ at a minimum of 39 KRW/㎡ in the case of forests, and the average was about 77,181,000 KRW/㎢. In order to compare the results with the results of this study, the GDP deflator was applied with a value of 11.18 million KRW/㎢, 13.66 million KRW/㎢, 22.71 million KRW/㎢, 36.37 million KRW/㎢ and 78.41 million KRW/㎢ in 2010. The value of forests derived from this study was found to be between 28.76 million KRW/㎢ and 24.38 million KRW/㎢. The results of this study are similar to those of other studies except for the perceived values for use and non-use (Figure 13).

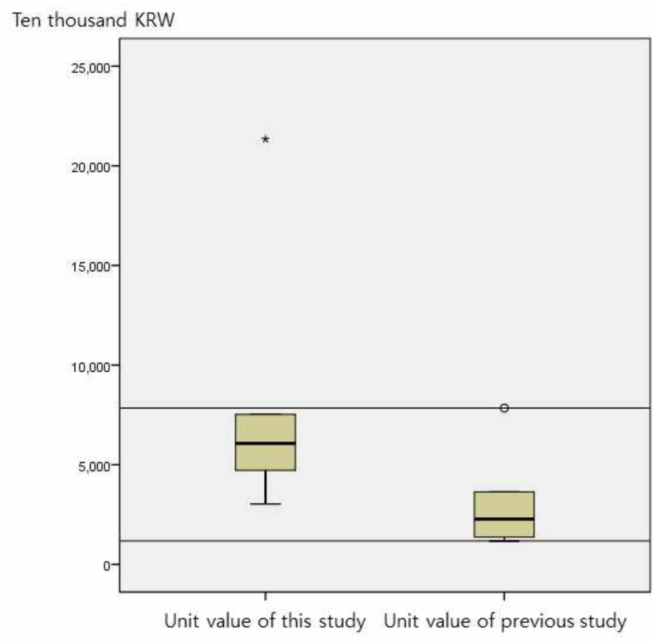


Figure 13. Comparing value per unit area of forest

5. Conclusion

In this study, the effect of ozone concentration on the net primary productivity of forests during the second and third quarters was estimated and the damage caused by ozone was estimated considering changes in ozone concentration into the future. In addition, the damage cost to the net primary productivity of forests was predicted based on the measure indicated by the central tendency method, meta-regression analysis, and the application of probability concept. Furthermore, the researcher estimated a range of damage costs based on the concepts of ecosystem services and economic value.

To do this, 1) an empirical model was developed that can represent the current net primary productivity of forests, reflecting the effects of ozone; 2) the effects of ozone on the current net primary productivity of forests was analyzed; and 3) estimates of the future net primary productivity of forests and the impact of future ozone concentrations on forest fertility were made using the future ozone concentration data derived by using the temperature and precipitation data of the RCP 8.5 scenario and the NOx emissions of the SSP 2 scenario. In order to predict future damage cost, 4) the term ‘damage’ and the damage cost of net primary productivity of forests in this study were defined using the economic value classification and ecosystem service concept, and 5) an estimation of the damage cost to net primary productivity of forests based on the effects of potential future ozone concentrations was determined by applying three methods; the central tendency method, meta-regression analysis and the concept of probability.

The results of the study are summarized below.

First, as a result of the analysis, the average net primary productivity of forests in the past 10 years was about 64 million tC/yr. As a result of the non-parametric test, it was confirmed that the net primary productivity of forests, NDVI and ozone concentration differed by region. Because NDVI reflects forests type, there was no difference in the net primary productivity of forests between broadleaf forests, coniferous forests, and mixed forests.

Second, when the effect of ozone on the net primary productivity of forests was examined, there was a decrease in the net primary productivity of forests of up to 27.1% when analyzed by unit area, and productivity decreased by about 9.1% on average. If these results are applied nationwide, it is estimated that the net primary productivity of forests was affected by about 8.3% per year by ozone from 2001 to 2010 on average. The impact of future ozone concentration on the net primary productivity of forests is expected to range from a minimum of about 3.2% to a maximum of about 13.3%, depending on the scenario, compared to the current net primary productivity undisturbed by the effects of ozone. It is expected that future ozone concentration scenarios will include scenarios that decrease compared to the present ozone concentration, which will lead to a decrease in damage below current levels. However, in both national and international studies, it is suggested that future ozone concentration is likely to increase due to climate change. Therefore, future damage is expected to increase beyond the level of current damage.

Third, the future damage cost of the net primary productivity of forests due to ozone varied according to the definition of application method and damage cost. When the concept of probability is applied only to the regulation service which has a direct relation to the net primary productivity of forests, the minimum value of the damage cost is about 401 billion KRW, and when metric regression is applied to the maximum value by applying the concept of total economic value, the value was determined to be roughly 4,653 billion KRW. The estimated cost of damage is about 0.3% of the maximum current GDP. In addition, the results of this study suggest that there may be a difference of up to 11 times depending on the definition of the damage cost and the method used to estimate the future damage cost.

The significance of this study is that the estimation of the net primary productivity of forests in the future is reflected not only in the climate data but also in the forest type through NDVI. It is also important to predict the concentration based on emissions rather than to make assumptions based on a simply scenario to calculate future ozone concentrations. Furthermore, similar studies performed in the past were done on a small scale, primarily in laboratories, but the scope of this study was much larger and analyzed a large geographic area using actual observational data. The researcher confirmed that damage to forests can increase as a result of the impact of current ozone concentration, as well as changes in said concentration over time. This can be taken into account when developing future plans for introducing policies related to the Korea Forest Services' carbon sequestration promotion plan or local governments' forest carbon offsets program. In addition, when carrying out forest conservation projects through the renewal of species, it is important to consider species that are resistant to pollution. Based on the results of this study, it is expected that doing so will help to establish countermeasures for climate change through adaptation to ozone in future forest sectors. In addition, we have found that there is a large variation in the definition of damage cost and the methodology applied to estimate future benefit and damage cost. This implies that there is a risk of underestimation or overestimation in estimating the benefits or costs of damage to climate change. In addition, we can estimate the cost of damages by using the concept of probability, which was limited to existing natural disasters.

The actual photosynthesis and growth mechanisms of forests are very complex, but this study has intrinsic limitations arising from the application of empirical models and predictable variables. In order to further advance the net primary productivity of forests estimation model, it will be necessary to supplement it. In addition, the ozone concentration used in this study is not determined by the amount of NOx emissions, but rather is caused by a photochemical reaction involving other materials such as VOC, and thus has a limitation in that it cannot accurately reflect the prediction. It is necessary to cooperate with other research institutes that can perform atmospheric modeling based on energy consumption in the future. In particular, the problem of air pollution in Korea can be regarded as a problem across East Asia, including China. For more accurate forecasting, cooperation among domestic and international researchers will be needed.

Finally, the introduction of the concept of probability in the estimation of damage cost is significant because it helps predict the possibility of a future event, but there is a limit to whether any event other than a natural disaster can see equal application through this method. However, this is the limit of the monthly average data used in this study, and further study is necessary to make hourly data of ozone concentration available.

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7. Appendix

7.1 Station Coordinate

Table A1. Station Coordinate

Station Code	X-Coordinate	Y-Coordinate	Station Code	X-Coordinate	Y-Coordinate
111141	127.09920	37.54447	221271	129.10781	35.15270
111162	127.00106	37.60792	238128	129.31452	35.43478
111181	126.93478	37.60861	238141	128.64401	35.24032
111265	127.03368	37.46460	324121	126.88968	35.15665
131120	127.09184	37.38016	324122	126.90764	35.14677
131126	127.13117	37.45719	336126	128.12988	35.39470
131129	127.16450	37.43286	336127	127.65361	34.78779
131191	126.83040	37.32205	336356	128.10977	35.51733
131194	126.80188	37.33155	336441	126.43919	34.76681
131196	126.58530	37.24368	336451	127.17505	35.17694
131211	127.12974	37.59446	422115	128.63156	35.83047
131212	127.13811	37.61856	437116	129.37679	35.96307
131241	127.21619	37.63561	437131	128.11370	36.14032
131342	126.93144	36.98594	437152	128.32778	36.12778
131381	126.84193	37.62491	437371	129.28700	36.44773
131382	126.81344	37.68551	437411	128.45642	36.36884
131391	127.25043	37.41918	525141	127.37385	36.37248
131431	127.40765	37.49494	534341	127.03085	36.52628
131441	127.54716	37.13878	534342	127.05265	36.88372
131451	127.21309	38.10166	534432	126.72342	36.94194
131452	127.25235	38.12383	632132	128.90297	37.76003
131502	126.93364	37.36166	632371	128.66476	37.43023
131552	126.92019	37.13236	632421	128.38521	38.28744
131581	127.27986	37.00759	632431	128.12509	37.36014
132401	127.95856	38.22439	633361	128.34618	37.21935
221132	129.10781	35.15270	735111	127.12176	35.79898
221172	128.08628	35.12955	735351	127.18626	35.61045
221173	129.17536	35.23001	735352	127.31739	36.01791
221182	129.01965	35.21605	735361	127.18626	35.61045
221191	129.08952	35.27548	735374	127.31739	36.01791
221232	129.24057	35.61097	823704	126.72608	37.40669
221252	129.14104	35.39761			

7.2 Descriptive Statistics

Table A2. Descriptive statistics

Variables	N	Range	Minimum	Maximum	Mean		Std. Deviation	Variance
					Statistic	Std. Error		
NPP	630	13024	1203	14227	5925.332	85.15114	2137.277	4567952
NDVI	630	5442	1923	7365	4636.55	54.504	1368.037	1871524
Altitude	630	644	10	654	104.98	4.724	118.569	14058.65
Precipitation	630	2107.1	641.4	2748.5	1388.528	13.09208	328.6086	107983.6
Solar radiation	630	3300	2962.61	6262.61	4870.318	16.46784	413.3395	170849.5
T Range*	630	2	2.7	4.7	3.6605	0.013003	0.326361	0.107
O3 Con.**	630	0.13282	1.72E-05	0.132837	0.087173	0.001574	0.039518	0.002

*Range: Annual temperature range

**O_3 Con.: Average concentration of ozone in quarters 2&3

7.3 Results of Bivariate Correlations

Table A3. Results of bivariate correlations (N=630)

		NPP	NDVI	Altitude	Precipitation	Solar radiation	T Range*	O3 Con.**
NPP	Pearson Correlation	1	.641**	.099*	.141**	.295**	-.280**	-.282**
	Sig. (2-tailed)		0.000	0.013	0.000	0.000	0.000	0.000
NDVI	Pearson Correlation	.641**	1	.463**	.179**	0.012	.238**	-.106**
	Sig. (2-tailed)	0.000		0.000	0.000	0.761	0.000	0.008
Altitude	Pearson Correlation	.099*	.463**	1	.194**	.115**	.294**	0.071
	Sig. (2-tailed)	0.013	0.000		0.000	0.004	0.000	0.075
Precipitation	Pearson Correlation	.141**	.179**	.194**	1	-.173**	-.202**	-.219**
	Sig. (2-tailed)	0.000	0.000	0.000		0.000	0.000	0.000
Solar radiation	Pearson Correlation	.295**	0.012	.115**	-.173**	1	-.226**	-.208**
	Sig. (2-tailed)	0.000	0.761	0.004	0.000		0.000	0.000
T Range*	Pearson Correlation	-.280**	.238**	.294**	-.202**	-.226**	1	.334**
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000		0.000
O3 Con.**	Pearson Correlation	-.282**	-.106**	0.071	-.219**	-.208**	.334**	1
	Sig. (2-tailed)	0.000	0.008	0.075	0.000	0.000	0.000	

*T Range: Annual temperature range

**O_3 Con.: Average concentration of ozone in quarters 2&3

7.4 Results of One-way Fixed Effect Model with Individual Effect

Fixed-effects (within) regression		Number of obs =	630
Group variable: id		Number of groups =	63
R-sq:	within = 0.4652	Obs per group: min =	10
	between = 0.5081	avg =	10.0
	overall = 0.5031	max =	10
		F(3,564) =	163.54
corr(u_i, Xb) = −0.1390		Prob > F =	0.0000

Table A4. Results of One-way Fixed Effect Model (Individual Effect)

NPP	Coef.	Std. Err.	t	P>|t|	[95% Conf. Interval]	
O_3 Con.*	−5250.073	5520.511	−0.95	0.342	−16093.35	5593.199
NDVI	1.176851	.0684168	17.20	0.000	1.042468	1.311234
Solar radiation	1.036475	.0702302	14.76	0.000	.8985307	1.17442
Altitude	(dropped)					
_cons	−4121.505	664.8844	−6.20	0.000	−5427.457	−2815.553
sigma_u	1446.1519					
sigma_e	526.38302					
rho	.88301172	(fraction of variance due to u_i)				

F test that all u_i=0: F(62, 564)= 61.97 Prob > F = 0.0000

*O_3 Con. : Average concentration of ozone in quarters 2&3

7.5 Results of One-way Random Effect Model with Individual Effect

Random-effects GLS regression		Number of obs =	630
Group variable: id		Number of groups =	63
R-sq: within	= 0.4651	Obs per group: min =	10
between	= 0.5796	avg =	10.0
overall	= 0.5679	max =	10
Random effects u_i ~ Gaussian		Wald chi2(4) =	574.22
corr(u_i, X)	= 0 (assumed)	Prob > chi2 =	0.0000

Table A5. Results of One-way Random Effect Model (Individual Effect)

NPP	Coef.	Std. Err.	z	P>|z|	[95% Conf. Interval]	
O_3 Con.*	-6810.416	3393.694	-2.01	0.045	-13461.94	-158.8973
NDVI	1.174644	.0619074	18.97	0.000	1.053308	1.295981
Solar radiation	1.036475	.0702302	14.76	0.000	.8985307	1.17442
Altitude	-4.752429	1.462732	-3.25	0.001	-7.61933	-1.885527
_cons	-3548.925	569.9089	-6.23	0.000	-4665.926	-2431.924
sigma_u	1325.6489					
sigma_e	526.38302					
rho	.86380466	(fraction of variance due to u_i)				

*O_3 Con. : Average concentration of ozone in quarters 2&3

7.6 Results of One-way Fixed Effect Model with Time Effect

Fixed-effects (within) regression		Number of obs =	630
Group variable: year		Number of groups =	10
R-sq: within	= 0.5931	Obs per group: min =	63
between	= 0.1586	avg =	63.0
overall	= 0.5739	max =	63
		F(4,616) =	224.49
corr(u_i, Xb)	= -0.0559	Prob > F =	0.0000

Table A6. Results of One-way Fixed Effect Model (Time Effect)

NPP	Coef.	Std. Err.	t	P>|t|	[95% Conf. Interval]	
O_3 Con.*	-6105.83	1435.126	-4.25	0	-8924.16	-3287.49
NDVI	1.170383	0.045366	25.8	0	1.081292	1.259474
Solar radiation	1.702528	0.150766	11.29	0	1.406451	1.998605
Altitude	-5.00786	0.525954	-9.52	0	-6.04074	-3.97498
_cons	-6735.05	812.5151	-8.29	0	-8330.69	-5139.42
sigma_u	416.06582					
sigma_e	1352.2548					
rho	.0864817	(fraction of variance due to u_i)				

F test that all u_i=0: F(9, 616) = 5.74 Prob > F = 0.0000

*O_3 Con. : Average concentration of ozone in quarters 2&3

7.7 Results of One-way Random Effect Model with Time Effect

Random-effects GLS regression		Number of obs =	630
Group variable: year		Number of groups =	10
R-sq: within	= 0.5931	Obs per group: min =	63
between	= 0.1611	avg =	63
overall	= 0.5743	max =	63
Random effects u_i ~ Gaussian		Wald chi2(4) =	899.96
corr(u_i, X)	= 0 (assumed)	Prob > chi2 =	0

Table A7. Results of One-way Random Effect Model (Time Effect)

NPP	Coef.	Std. Err.	z	P>|z|	[95% Conf. Interval]	
O_3 Con.*	-6202.423	1431.793	-4.33	0	-9008.685	-3396.16
NDVI	1.170724	.0453017	25.84	0	1.081935	1.259514
Solar radiation	1.667839	.1479288	11.27	0	1.377904	1.957775
Altitude	-4.993465	.5252534	-9.51	0	-6.022943	-3.96399
_cons	-6560.78	808.8564	-8.11	0	-8146.109	-4975.45
sigma_u	404.6578					
sigma_e	1352.2548					
rho	.08218871	(fraction of variance due to u_i)				

*O_3 Con. : Average concentration of ozone in quarters 2&3

7.8 The Results of Significance Test of the Random Effect Model

Breusch and Pagan Lagrangian multiplier test for random effects
NPP[year,t] = Xb + u[id] + e[id,t]

Table A8. Results of Breusch-Pagan LM Test

	var	sd=sqrt(var)
NPP	4567952	2137.277
e	277079.1	526.383
u	1757345	1325.649

Test: Var(u) = 0

chi2(1) = 2030.07
Prob > chi2 = 0.0000

7.9 Results of the Hausman Test

Table A9. Results of the Hausman Test

	(b) id_fe	(B) id_re	(b-B) Difference	sqrt(diag(V_b-V_B)) S.E.
O_3 Con.*	-5250.073	-6810.416	1560.343	4354.144
NDVI	1.176851	1.174644	.0022069	.0291254
Solar radiation	1.036475	1.051382	-.0149071	.0097422

*O_3 Con. : Average concentration of ozone in quarters 2&3

b = consistent under Ho and Ha; obtained from xtreg

B = inconsistent under Ha, efficient under Ho; obtained from xtreg

Test: Ho: difference in coefficients not systematic

chi2(2) = (b-B)'[(V_b-V_B)^(-1)](b-B)

= 0.13

Prob>chi2 = 0.7201

(V_b-V_B is not positive definite)

7.10 Database for Benefit Transfer Method

Table A10. Database for benefit transfer method (continued)

Value per unit area of forest (KRW/㎢)	Year	R.S.*	C.S.**	S.S.***	P.S.****	N.V.*****
9,957,129	1996	0	1	0	0	0
18,121,130	1996	0	1	0	0	0
29,097,122	2012	0	0	0	1	0
97,640,969	2012	1	0	0	0	0
211,760,598	2012	0	0	1	0	0
74,548,862	2012	0	0	1	0	0
264,357,278	2012	1	0	0	0	0
183,526,270	2012	0	1	0	0	0
26,224,543	2012	0	0	1	0	0
50,618,339	2010	1	0	0	0	0
48,607,561	2010	0	1	0	0	0
41,675,032	2010	1	0	0	0	0
18,943,512	2016	0	1	0	0	0
97,336,066	2011	0	0	0	1	0
239,344,262	2011	1	0	0	0	0
7,377,049	2011	1	0	0	0	0
54,918,033	2011	1	0	0	0	0
74,521,858	2011	1	0	0	0	0
1,137,704,918	2011	0	0	0	0	1
14,645,746	2012	1	1	1	1	0
7,561,771	2012	0	0	0	0	1
4,348,018	2012	0	0	0	0	1
29,781,253	2010	0	1	0	0	0
3,330,210	2012	0	0	0	0	1

*R.S.: Regulation Services
**C.S.: Cultural Services
***S.S.: Supporting Services
****P.S.: Provisioning Services
*****N.V.: Non-use Value

Table A11. Database for benefit transfer method

Value per unit area of forest (KRW/㎢)	Year	R.S.*	C.S.**	S.S.***	P.S.****	N.V.*****
20,700,747	2010	0	1	0	0	0
15,511,202	2010	0	1	0	0	0
43,409,192	2010	0	1	0	0	0
4,099,566	2013	0	1	0	0	0
5,290,049	2008	1	1	1	1	0
89,636,375	2007	1	1	1	1	1
465,301	2000	0	0	0	0	1
675,992	1998	0	1	0	0	0
4,203,376	2009	0	1	0	0	0
136,536,114	2013	1	0	0	0	0
111,074,915	2015	1	0	0	0	0
77,170,769	2015	1	0	0	0	0
96,487,842	2015	1	0	0	0	0
148,113,819	2015	1	0	0	0	0
64,576,009	2015	1	0	0	0	0
46,116,856	2016	0	0	0	1	0
22,540,135	2016	1	0	0	0	0
32,667,349	2016	1	0	0	0	0
16,817,787	2016	1	0	0	0	0
3,976,062	2016	1	0	0	0	0
1,917,807	2016	0	0	1	0	0
10,544,831	2016	0	1	0	0	0
23,162,832	2016	0	1	0	0	0
778,060	2016	0	0	0	0	1
12,746,983	2014	0	1	0	0	0
12,921,122	2014	0	1	0	0	0

*R.S.: Regulation Services
**C.S.: Cultural Services
***S.S.: Supporting Services
****P.S.: Provisioning Services
*****N.V.: Non-use Value

■ 국문초록

오존 농도의 증가가 산림의 순일차생산성에 미치는 영향 및 피해 비용 추정

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산림은 광합성작용을 통하여 CO_2를 흡수, 저장하여 지구온난화를 방지함과 동시에 많은 혜택을 주고 있다. 과거에는 산성비 등이 산림에 영향을 주었다면, 최근에는 오존, 질소, 황 등이 산림생태계에 위협이 되고 있다. 특히 오존은 광화학산물의 대부분을 차지하고 있으며, 독성이 높아 식물에 직접적인 피해를 준다. 또한 미래 기후변화로 인하여 대기오염물질의 농도가 증가할 것으로 예상되며, 특히 한국은 중국으로부터 유입되는 오존 및 오존 전구물질에 의해서 오존의 농도는 더욱 증가할 것으로 예상된다.

이에 본 연구의 목적은 1) 오존이 산림생산성에 얼마나 영향을 미치는지 파악하고, 2) 오존에 의한 미래 산림생산성 변화 예측과 그에 따른 피해비용을 추정하는 것이다. 이를 위해서 문헌 고찰을 통하여 기상관련 변수, 지형관련 변수, 대기오염 변수 등으로 구분하여 산림생산성 영향평가에 필요한 변수를 선정하고, 각 변수에 대해서 위성영상, 대기오염 연보 등의 자료를 이용하여 2001년부터 2010

년까지 자료를 구축하였다. 통계 모형을 이용하여 오존의 유무에 따른 현재와 미래의 산림생산성의 변화를 추정하였다. 미래 피해비용 추정을 위해서는 편익이전의 기법과 확률의 개념을 적용하였다. 또한 본 연구에서는 경제가치의 개념과 생태계서비스의 정의를 활용하여 피해비용을 정의하였으며, 조절서비스, 간접사용가치, 사용가치, 총경제가치에 대해서 피해비용을 추정하였다.

분석 결과 과거 10년간 평균 산림생산성은 평균 약 6천4백만 tC/yr로 나타났으며, 비모수검정 결과, 산림생산성과 NDVI, 오존의 농도는 지역별로 차이가 나타나고 있음을 확인하였고, NDVI에 임상의 차이를 반영하였기 때문에 임상별 산림생산성은 차이가 없는 것으로 나타났다. 또한 오존으로 인하여 평균 매년 약 8.3% 정도의 산림생산성이 오존에 의한 피해를 입은 것으로 나타났다. 이는 미래에는 약 3.2%에서 최대 약 13.3% 까지 나타날 것으로 예상된다. 오존으로 인한 산림생산성의 미래 피해비용은 적용 방법론과 피해비용의 정의에 따라 다양하게 나타났다. 피해비용의 최솟값은 산림생산성과 직접적인 관계가 있는 조절서비스만을 대상으로 확률을 개념을 적용하였을 때 약 4,019억 원이 발생하였으며, 최댓값은 총경제가치의 개념을 적용하여 메타회귀분석을 실시하였을 때, 약 4조 6,526억 원으로 나타났다. 연구 결과 추정한 피해비용은 최대 현재 GDP의 약 0.3% 수준이다. 본 연구 결과는 미래 피해비용 추정에 있어서 피해비용의 정의와 피해비용 추정에 사용되는 방법에 따라 최대 11배 이상의 차이가 발생할 수도 있음을 시사한다.

본 연구의 의의는 미래 산림생산성 추정 시 기후 자료뿐만 아니라 임상에 따른 차이를 NDVI를 통해 반영하였으며, 미래 NDVI까지 추정을 하여 산림생산성을 예측하였다는 점에서는 의의가 있다. 또한

오존 농도 예측에 있어서도 단순한 시나리오로 가정을 세운 것이 아니라 배출량에 근거한 농도를 예측하였다는 점에서는 의의가 있다. 또한 실험실 수준에서 진행되던 소규모의 연구를 실제 관측 자료를 이용하여 전 국토 단위로 분석하였다는 데 있다. 또한 미래 편익 및 피해비용 추정에 있어서는 피해비용의 정의와 적용하는 방법론에 따른 편차가 크게 존재한다는 것을 밝혔다. 이는 기후변화에 대한 편익 혹은 피해 비용을 추정함에 있어 과소추정하거나 과대추정 할 위험성을 내포하고 있으므로 이에 대한 주의가 필요함을 의미한다.

❑ *주요어 : 기후변화, 대기오염물질, 온실가스, 배출량, 생태계서비스, 가치평가, 동아시아*

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