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Vulnerability Assessment of Forest Ecosystem to Climate Change in Korea Using MC1 Model

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ABSTRACT

The objective of this study was to assess the vulnerability of forest ecosystem to climate change in Korea using MAPSS-CENTURY (MC1) model, one of Dynamic Global Vegetation Models (DGVMs). Also, it was to suggest selected and concentrated adaptation strategies for local government on the basis of this assessment. For the MC1 simulation of past years (1971-2000), the climatic data was prepared by the Korea Meteorological Administration (KMA). In addition, for the future simulation, the Fifth-Generation NCAR/Penn State Mesoscale Model (MM5) coupling with atmosphere-ocean circulation model (ECHO-G) provided the future climatic data under the SRES (Special Report on Emission Scenario of IPCC) A1B scenarios. This study predicted the changes in vegetation distribution by climate change, and it analyzed the spatial and temporal variation of the Net Primary Production (NPP) and Soil Carbon Storage (SCS) using the MC1 model simulations. The vulnerability assessment of forest ecosystem can be divided into two categories; 1) the vulnerability of vegetation distribution and 2) the vulnerability of forest ecosystem function, such as the NPP and SCS. In addition, the sensitivity and adaptation capacity were evaluated for each category. As results of the vulnerability assessment, relatively vulnerable areas were situated in the western coastal part and south eastern inland of Korea. Based on the spatial variation in vulnerability, we could suggest that the central and local governments need to prepare concentrated adaptation strategies for climate change based on the vulnerability assessment.

Keywords: climate change, forest ecosystem, vulnerability, MC1 model, Dynamic Global Vegetation Model

INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC), mean annual global temperature has been inclined by 0.74°C over the past 100 years, and it may be increased by 1.1-6.4°C in the future 2090s (IPCC, 2007a). With the recent global warming, the IPCC (2007b) has considered that the climate change effect on forest ecosystem is one of major issues. The forest vegetation plays an important role in climate processes by its contribution to heat and moisture fluxes throughout the ecosystem. Therefore, it is important to evaluate the changes in forest ecosystem resulting from cli-

mate change (ARRIS and EAGLESON, 1989; OHSAWA, 1993; MATSUI *et al.*, 2004a; 2004b; LAURENT *et al.*, 2004; HORIKAWA, 2009). Previously, many studies on dynamic global vegetation models (DGVMs) were conducted to understand the climate change effects on the ecosystem (PRENTICE *et al.*, 1992; LENIHAN and NEILSON, 1993; BRZEZIECKI, 1995; CAO and WOODWARD, 1998; OSBORNE *et al.*, 2000; BACHELET *et al.*, 2001; WATANABE *et al.*, 2004). The DGVMs simulate the changes in potential distribution of vegetation and its associated biogeochemical and/or hydrological fluxes due to climate change. The DGVMs simulate the annual or monthly dynamics of ecosystem processes. Their temporal and spatial resolutions depend on the time series of climate data and the given characteristics of latitude,

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topography, and soil data, respectively (BACHELET *et al.*, 2001). Especially, United States Department of Agriculture (USDA) has developed the MAPSS-CENTURY (MC1) model to assess the climate change effects on the ecosystem of California, USA (LENIHAN *et al.*, 2003; 2008). Also, in China, the Carbon Exchange between Vegetation, Soil, and Atmosphere (CEVSA) model predicted the potential vegetation distribution changes due to climate change (YU *et al.*, 2006).

Many researchers have tried to apply previous DGVMs, such as the Holdridge (KIM and LEE, 2006), CEVSA (LEE *et al.*, 2007a), and MC1 (CHOI *et al.*, 2009a), to assess the vulnerability of Korean forest ecosystem using the past and future climatic data, even though there were no national vegetation models in Korea (KIM *et al.*, 2008). Practically, these models have limitations to provide accurate results for the regional scale of Korea, because most of them were designed and tested at the global or the continental scale, and Korea has more heterogeneous topography and climate, compared to global level (LEE *et al.*, 2007a; KIM *et al.*, 2009; CHOI *et al.*, 2009a). However, due to the simple and clear processes of the MC1 model and CEVSA model, it is possible to use Geographic Information System (GIS) application and understand the sub-modules related to ecosystem mechanisms. In other words, these models are suitable to scrutinize the ecosystem vulnerability to climate change (BACHELET *et al.*, 2001; YU *et al.*, 2006).

To assess the vulnerability of forest ecosystem to climate change, it requires several of information. Also, the indicators in vulnerability assessment should be comprehensive for each component of the forest ecosystem. The mechanisms of sensitivity and adaptation capacity are not completely clarified and it is hard to quantify the effect of each indicator on the vulnerability of forest ecosystem. However, principal component analysis (PCA) can be applied for vulnerability assessment, which compounds the related indicators and produces the newly synthetic indicators (HAN *et al.*, 2006). According to LENIHAN *et al.* (2008), the MC1 can simulate the potential vegetation distribution, Net Primary Production (NPP) and Soil Carbon Storage (SCS). Also, it can assess the vulnerability of forest ecosystem due to climate change from the understanding of the sensitivity and adaptation capacity, related to the ecosystem structure, i.e. potential distribution, and the function, i.e. NPP and SCS.

For last three decades, the forest management policy pursues the sustainable management in Korea. Recently, corresponding to United Nations Framework Convention on Climate Change (UNFCCC), Korean government has prepared a master plan to expand the forest as a source of carbon sinks, and have constructed related statistical database. Moreover, for more effective conservation and management of the forest ecosystem, it is important to have the systemic monitoring and to designate the long-term ecological research area and special protection area (HAN *et al.*, 2007). In other words, the climate change assessment of vulnerability using the DGVMs is aiming to minimize the negative effects of climate change on

forest ecosystem, and it is required to predict the highly vulnerable area to enhance the adaptation capacity to climate change.

In this study, we analyzed the vulnerability of Korean forest ecosystem using the MAPSS-CENTURY (MC1) model based on the past and future climatic data. The assessment of vulnerability for forest ecosystem was divided into the two categories; the vulnerability of the vegetation distribution and forest ecosystem function, such as NPP and SCS. Also, it evaluated the sensitivity and adaptation capacity for each indicator.

MATERIAL AND METHOD

The MC1 Model

The MC1 model is a DGVM to assess the climate change effects on ecosystem structure and function. It includes three modules, such as the biogeographic module - MAPSS (NEILSON, 1995), biogeochemistry module - modified CENTURY (PARTON *et al.*, 1987), and fire module - MCFIRE (LENIHAN *et al.*, 1998). This model can routinely generate simulations of tens to hundreds of years period on spatial data grids with cell sizes ranging from 900m² to about 2,500km² (BACHELET *et al.*, 2004). As shown on Fig. 1, it simulates 1) the plant life-form and vegetation classes, 2) the movement of carbon, nitrogen, and water fluxes for ecosystem, and 3) fire disturbance, respectively (BACHELET *et al.*, 2001). Also, it has two modes of equilibrium (static) and transient (dynamic) using climatic and soil information. It results in potential vegetation distribution using the life-form interpreter, and the NPP and SCS using the CENTURY model algorithm, respectively. The results of MC1 model simulations were validated at the previous study of BACHELET *et al.* (2008). Compared to the observed data of NPP across the US, the MC1 model results were fairly reasonable to be verified, even though it provided over and/or under-estimated results for some study sites. In this study, it used the default parameters and thresholds of the MC1 model, even though, sometimes, it needs to optimize the model parameters when we apply the DGVMs to simulate the smaller region, such as Korea.

Study Area and Data Preparation

The study area was located in South Korea, 124°54'~131°06' at longitude and 33°09'~38°45' at latitude. Topographical characteristics of study area are shown in digital elevation model (Fig. 2a). The Taebaek Mountain Range elevates to over 1,500 m on the eastern side of Korea. From the Taebaek Mountain Range, the Sobaek Mountain Range runs from northern east to southern west. In the central zone, moderately high mountains dominate the landscape. Elevations are generally low, because these mountain ranges have been subjected to long-term erosion with relatively stable tectonic movements (NATIONAL

Fig. 1 The structure of the MC1 model

source: BACHELET *et al.* (2001).

Fig. 2 (a) The Digital Elevation Model of Korea derived from National Geographic Information Institute and (b) the Actual forest type map from Korean Forest Service

GEOGRAPHIC INFORMATION INSTITUTE, 2007). As shown in Fig. 2b, evergreen needle-leaved forests (mainly *Pinus densiflora*) and deciduous broad-leaved forests (mainly *Quercus* spp.) occupy approximately 42% and 26% of the total forest area in 2008, respectively (KOREA FOREST SERVICE, 2009). These species are major tree species in Korea and they are important in terms of ecological, economical, and socio-cultural values (LEE *et al.*, 2006).

For the overall simulations, the MC1 needed two categories of input data, such as climatic and ancillary data. In terms of climatic dataset, seven climatic factors were needed to be prepared; they were cumulative precipitation, monthly mean temperature, mean daily maximum and minimum temperature, vapor pressure, wind speed, and solar radiation. Ancillary dataset included general geographical information, such as elevation, latitude, absolute area, and soil information, such as

soil bulk density, soil texture, mineral depth, and rock fragment.

The temporal ranges of this study were assigned into three periods of 1) the past (1971-2000), 2) near future (2021-2050), and 3) far future (2071-2100). Korea Meteorological Administration (KMA) provided climatic data obtained by 75 weather stations across South Korea for the past years between 1971 and 2000. These data were interpolated with Inverse Distance Squared Weighting (IDSW), one of the spatial statistic methods, regarding the absolute temperature lapse rate by altitude (LEE *et al.*, 2007b). In addition, the anomalies of the future climatic data were predicted by the Fifth-Generation NCAR / Penn State Mesoscale Model (MM5) model coupling with atmosphere-ocean circulation model (ECHO-G) by A1B scenario (Special Report on Emission Scenario of IPCC) from National Institute of Meteorological Research (NIMR) in 0.2432° (about 27km) of

grid size (MIN *et al.*, 2006; CHA *et al.*, 2007). To construct the ancillary data, the elevation, latitude, and absolute area data were achieved from the digital map of the National Geographic Information Institute (NGII). Also, soil information, i.e. soil bulk density, soil texture, mineral depth, and rock fragment, were provided by the Food and Agriculture Organization (FAO) and International Soil Reference and Information Centre (ISRIC). These datasets were rescaled to fit on 0.01° (about 1km) spatial resolution in the World Geodetic System (WGS-84) co-ordination system and applied to produce the future climate data based on the past climatic data (LEE *et al.*, 2007b).

Assessment of Vulnerability

The vulnerability was defined as the range or scope of damage to nature or society system by climate change (IPCC, 2007b). This was estimated by relations between sensitivity and adaptation capacity as the indicators for the vulnerability assessment. The high sensitivity means the high vulnerability; reversely the low adaptation capacity means the high vulnerability (YU *et al.*, 2006; YU, 2006; LEE *et al.*, 2007a). This could be represented as following function (Eq. (1));

$$V = S - A, \quad (1)$$

where V is the vulnerability, S is the sensitivity, and A is the adaptation capacity.

Assessment of vulnerability-potential vegetation distribution

In the MC1 model, the vulnerability of vegetation distribution and forest ecosystem functions, i.e. NPP and SCS, were estimated and integrated into the indicator of vulnerability of Korean forest. Each of them was estimated with sub indicators, such as the sensitivity and adaptation capacity in Eq. (1). In the vulnerability assessment of the potential vegetation distribution, the sensitivity to climate change was decided by the changing frequency of vegetation classes (or types) in each grid. For example, the changing frequency will increase, if there is once vegetation type change in a grid when the certain type of vegetation is not suitable for the provided climate condition (YU *et al.*, 2006; YU, 2006; LEE *et al.*, 2007a; HAN *et al.*, 2007). The high changing frequency was assumed as the high sensitivity. The adaptation capacity could be estimated using the changing direction which was defined as two directions, such as positive (+) and negative (-) direction (YU *et al.*, 2006; YU, 2006; LEE *et al.*, 2007a; HAN *et al.*, 2007). The positive changing was assumed to array from the mixed forest to the broad-leaved and needle-leaved forest in terms of maintenance of species diversity, because the needle-leaved forest has been reported to be likely to reduce the area by increase of temperature (KONG, 2005; KIM and LEE, 2006). The positive changing was assumed to be the high adaptation.

Assessment of vulnerability-forest ecosystem function (NPP and SCS)

According to the assessment of vulnerability for the forest ecosystem function variables, such as the NPP and SCS, the sensitivity and adaptation were respectively described as the variability and changing trend (YU *et al.*, 2006; LEE *et al.*, 2007a; HAN *et al.*, 2007). The variability of forest ecosystem functions was estimated with the average values for the study period and whole period (1970-2100). The variability of each period implied as the differences between the values of study year and the average value for whole simulation term. It was described below (Eq. (2));

$$D_n = \frac{\sum_{i=1}^j |V_{ni} - \bar{V}_n|}{\bar{V}_n}, \quad (2)$$

where D is the variability of forest ecosystem functions for whole period (years), V_i is the value of forest ecosystem function variable in study year i , $\bar{V}$ is the average value of the forest ecosystem function variable for whole period (years), and n is a grid of the study site.

The adaptation capacity of forest ecosystem functions was estimated with the change trend of variability of forest ecosystem function variables, such as the NPP and SCS (YU *et al.*, 2006; YU, 2006; LEE *et al.*, 2007a; HAN *et al.*, 2007). Decreasing of the trend of variability means that the system is apt to be stabled to climate change, which can be described as the more adaptive (Eq. (3)). On the other hand, the increase of the trend means the forest ecosystem function variables were less stable and much more vulnerable to climate change. The trend of the forest ecosystem annual variability was represented as the slope of the linear trend lines fitting to the variability of the forest ecosystem functions in the study period (YU *et al.*, 2006; YU, 2006; LEE *et al.*, 2007a; HAN *et al.*, 2007).

$$Y = aX + b, \quad (3)$$

where Y is the variability of the study period, X is the study period, and a is the change trend of forest ecosystem function variables.

As shown in Fig. 3, this method can explain the sensitivity and adaptation capacity of forest ecosystem function. For example, in comparison of two test sites, such as A (Fig. 3a) and B (Fig. 3b), we assumed that a temporary variable of ecosystem function was simulated for 25 years (Hypothetical period). The average values were assumed as 18.6 and 18.24 for the site A and B, respectively. In terms of the sensitivity, the site A was more sensitive than the site B, because the site A (Fig. 3c) had the larger sum of differences between the values for each year and the average for whole years, compared to the site B (Fig. 3d). On the other hands, in terms of the adaptation capacity, the site A was more adaptive than the site B, because the variability trend (slope) of site A (Fig. 3e) was negative (-0.0015:

Fig.3 Examples of sensitivity and adaptation capacity for a temporary variable of ecosystem function

decrease of the variability for each year) and the trend of site B (Fig. 3f) was positive (0.0028: increase of the variability for each year).

Integrated vulnerability of forest ecosystem distribution and function

To assess the vulnerability of Korean forest ecosystem, using the above indicators, the overall vulnerability of forest ecosystem was assessed by integrated indices, e.g. the vulnerability of both forest ecosystem distribution and functions. In the integration of indicators, we normalized the values of vulnerability for forest ecosystem distribution and forest ecosystem function (Eqs. (4) and (5)). In this study, we classified the

vulnerability, sensitivity, and adaptation capacity into five categories, depending on their normalized ranges, such as “very high: 0.8–1.0”, “high: 0.6–0.8”, “moderate 0.4–0.6”, “low: 0.2–0.4”, and “very low: 0.0–0.2”. Also, the vulnerability of forest ecosystem was assessed with Principal Component Analysis (PCA) to calculate the degree of vulnerability (Table 1).

$${}_nV = \frac{X - X_{mn}}{X_{mx} - X_{mn}}, \quad (4)$$

where ${}_nV$ is the normalized vulnerability, X is the estimated vulnerability, X_{mn} is the minimum value of vulnerability, and X_{mx} is the maximum value of vulnerability.

Table 1 The scheme of vulnerability assessment of forest ecosystem

Categories of vulnerability		Indicators	Sub-indicators	Description
Forest Ecosystem Vulnerability	Vulnerability of vegetation distribution	Changes in forest type	Changing frequency	Sensitivity
			Changing trend	Adaptability
	Vulnerability of forest ecosystem function	NPP	Variability	Sensitivity
			Trend of variability	Adaptability
		SCS	Variability	Sensitivity
			Trend of variability	Adaptability

*From the assessment process of YU *et al.* (2006).

Fig.4 (a) the MC1 Simulation of the potential vegetation distribution of past (1971-2000), (b) near future (2021-2050), and (c) far future (2071-2100)

EN: Evergreen Needle-leaved dominant; *DEB: Deciduous and Evergreen Broad-leaved dominant; **DB: Deciduous Broad-leaved dominant.

Table 2 Proportion of potential vegetation distribution in area (km²) and ratio (%)

Forest types	Past	Near future	Far future
Cool mixed forest	***95,214 (96.06)	92,351 (93.18)	55,117 (55.61)
*Warm mixed forest (EN)	3,252 (3.28)	5,549 (5.60)	38,634 (38.98)
**Warm mixed forest (DEB)	648 (0.65)	1,140 (1.15)	5,348 (5.40)
***Forest hard wood cool (DB)	1 (0.00)	75 (0.07)	16 (0.02)
Total	99,115 (100.00)	99,115 (100.00)	99,115 (100.00)

EN: Evergreen Needle-leaved dominant; *DEB: Deciduous and Evergreen Broad-leaved dominant; **DB: Deciduous Broad-leaved dominant; ***Area in km² (Ratio in %).

Table 3 Changing frequency of each period in area (km²) and ratio (%)

Changing frequency	From past to near future	From near future to far future
Changed	*3,354 (3.38)	40,150 (40.51)
Unchanged	95,761 (96.62)	58,965 (59.49)
Total	99,115 (100.00)	99,115 (100.00)

*Area in km² (Ratio in %).

$${}_nV_E = {}_nV_D + {}_nV_F, \quad (5)$$

where ${}_nV_E$ is the normalized forest ecosystem vulnerability, ${}_nV_D$ is the normalized vulnerability of the forest ecosystem distribution, and ${}_nV_F$ is the normalized vulnerability of the forest ecosystem function.

RESULTS AND DISCUSSION

Vulnerability of the Vegetation Distribution

Potential vegetation distribution of past and future

Fig. 4 depicts the simulated potential vegetation distribution of past (1971-2000), near future (2021-2050), and far future (2071-2100) using the MC1 model.

As results of the predicted potential vegetation distribution of past years (1971-2000), Korean ecosystem was mostly occupied by the cool mixed forest, the needle-leaved dominant (EN) warm mixed forest, and the broad-leaved dominant (DEB) warm mixed forest, and their proportions were 96.06%, 3.28%, and 0.65%, respectively. The cool mixed forests were occupying the most part of Korea and the EN warm mixed forest was existed in southern coast and the Jeju Island. In near future, the composition of forest types were 93.18% of the cool mixed forest, 5.60% of the EN warm mixed forest, and 1.15% of the DEB warm mixed forest. Compared to the past years, the EN warm mixed forests were expanding to northward, and the DEB

warm mixed forests, which existed in only Jeju area, were appeared in southern metropolitan cities, such as Busan, Pohang, and Dae-Gu. In far future, there was no great change in overall composition of vegetation type, but distribution ratio was changed. The cool mixed forests were decreased down to 55.61% and the EN warm mixed forests were increased up to 38.98% (Table 2). This result was correspondent to the result of research by LEE *et al.* (2007a).

Vulnerability of vegetation distribution

To assess the vulnerability of vegetation distribution, it estimated the changing frequency and changing direction in terms of sensitivity and adaptability, respectively. As results of the sensitivity estimation for vegetation distribution, the future climate would not provide the suitable climatic condition for vegetations existed in the past years (Table 3), and 3.38% of the study area was exposed to be changed from past to near future. Also, there were vegetation composition changes in 40.51% of area from near future to far future. As the integrated changing frequencies above, the sensitivity of whole years (1971-2100) was derived in Table 3 and Fig. 5b.

From the results of predicting adaptation capacity of vegetation distribution, 3.38% of study area was likely to change to negative (-) direction from past to near future and 40.43% was changed to negative direction from near future to far future. Especially, some of region (1.30%) will be exposed to two steps of negative direction (-2) - from the cool mixed to the DEB

Table 4 Changing direction of each period in area (km²) and ratio (%)

Changing direction	From past to near future	From near future to far future
Positive direction (+1)	-	73 (0.07)
No changes	95,761 (96.62)	58,965 (59.49)
Negative direction (-1)	3,279 (3.31)	38,771 (39.12)
Negative direction (-2)	1 (0.00)	1,292 (1.30)
Negative direction (-3)	74 (0.07)	14 (0.01)
Total	99,115 (100.00)	99,115 (100.00)

*Area in km² (Ratio in %).

Table 5 Sensitivity, adaptation capacity, and vulnerability of vegetation distribution in area (km²) and ratio (%)

Sensitivity	Adaptation Capacity	Vulnerability	Changing frequency	Changing direction	Overall vulnerability
Very High (0.8~1.0)			1,174 (1.18)	1 (0.00)	1,190 (1.20)
High (0.6~0.8)			-	56,785 (57.29)	1,293 (1.30)
Moderate (0.4~0.6)			41,156 (41.52)	39,846 (40.20)	39,846 (40.20)
Low (0.2~0.4)			-	2,467 (2.49)	-
Very Low (0.0~0.2)			56,785 (57.29)	16 (0.02)	56,786 (57.29)
Total			99,115 (100.00)	99,115 (100.00)	99,115 (100.00)

*Area in km² (Ratio in %).

Fig.5 (a) Vulnerability of vegetation distribution, (b) Sensitivity, and (c) Adaptation Capacity of vegetation distribution
 *Vulnerability of vegetation distribution = Sensitivity (Changing frequency) - Adaptation Capacity (Changing direction).

Fig.6 (a) MC1 Simulated potential NPP distribution of past (1971-2000), (b) near future (2021-2050), and (c) far future (2071-2100), and (d) potential SCS distribution of past, (e) near future, and (f) far future

Table 6 Variability and changing trend of NPP and SCS in area (km²) and ratio (%)

Sensitivity Adaptation Capacity	Variability		Changing trend	
	NPP	SCS	NPP	SCS
Very High (0.8~1.0)	-	-	1,252 (1.26)	2,067 (2.09)
High (0.6~0.8)	-	132 (0.13)	3,878 (3.91)	16,746 (16.90)
Moderate (0.4~0.6)	2,271 (2.29)	19,020 (19.19)	50,921 (51.38)	55,202 (55.69)
Low (0.2~0.4)	30,695 (30.97)	62,231 (62.79)	41,023 (41.39)	24,205 (24.42)
Very Low (0.0~0.2)	66,149 (66.74)	17,732 (17.89)	2,041 (2.06)	895 (0.90)
Total	99,115 (100.00)	99,115 (100.00)	99,115 (100.00)	99,115 (100.00)

*Area in km² (Ratio in %).

warm mixed forest (Table 4). From the changing directions, the adaptation capacity of whole year (1971-2100) was estimated in table 5 and Fig. 5c.

The vulnerability of vegetation distribution can be assessed by the integration of the sensitivity and adaptation capacity. The higher changing frequency and the negative trend of changing direction are comprehended as the high vulnerability of vegetation distribution. As results of the integration of above results, some part of southern inland area and western and eastern coastal areas (2.50% of study area) were exposed to the "Very high" or "High" vulnerability (Fig. 5a and Table 5). It is assumed that the mean monthly temperatures would increase by 4.1-4.6°C in far future and the accumulated precipitation in growing season would be 1.5-2.8 times higher in far future than in past (1971-2000). However, other study area was exposed to the "Very low" vulnerability (57.29%) and the "Moderate" vulnerability (40.20%) of vegetation distribution.

Vulnerability of Forest Ecosystem Function

Potential NPP and SCS distribution of past and future

Fig. 6 depicted the simulated NPP and SCS distribution in past, near future, and far future. The potential vegetation production and carbon storage in soil were simulated by the MC1 using soil temperature and moisture derived from the climatic information, and nitrogen availability derived from the soil information. The NPP of past was ranged from 430.93 to 796.28 gC·m⁻²·yr⁻¹ and the average was 647.90 (std. dev. 73.99) gC·m⁻²·yr⁻¹. Compared to the past, the range of the overall estimated NPP would be changed in near future (376.33-827.27 gC·m⁻²·yr⁻¹) and far future (498.53-901.59 gC·m⁻²·yr⁻¹). Also, the average of NPP would decrease to 609.02 gC·m⁻²·yr⁻¹ in near future and 599.70 gC·m⁻²·yr⁻¹ in far future. On the other hands, the average of SCS in past was 6,810.5 (std. dev. 784.0) gC·m⁻². The SCS was ranged from 4,720.5 to 9,478.2 gC·m⁻² in past. As similar as the NPP, the average value of the SCS would decrease to 6,008.8 gC·m⁻² in near future (range: 4,432.0-9,042.4 gC·m⁻²) and 5,154.5 gC·m⁻² in far future (range: 3,930.5-8,493.9 gC·m⁻²) due to climate change.

Vulnerability of forest ecosystem function

To assess the vulnerability of forest ecosystem function, it estimated variability and changing trend of the NPP and SCS in terms of sensitivity and adaptation capacity, respectively. As results of sensitivity estimation for forest ecosystem function, overall variability of the NPP and SCS was relatively low. More than 80% of study area was classified as the "Low" or "Very low" of variability (e.g. 97.71% for the NPP and 80.68% for the SCS). In other words, the forest ecosystem functions did not respond to climate change sensitively, compared to the sensitivity of vegetation distribution. Conversely, in terms of adaptation capacity, the change trends of variability for the NPP and SCS were likely to be "Moderate" or "Low" adaptability (e.g. 92.77% for the NPP and 80.11% for the SCS) (Table 6).

The vulnerability of forest ecosystem function could be assessed by the integration of sensitivity and adaptation capacity of the NPP and SCS. The higher variability and the positive changing trend were comprehended as the high vulnerability of forest ecosystem function. As results of integration of above results, western coastal and inland areas were exposed to the "Very high" or "High" vulnerability (0.92% of study area). However, 85.14% of study area was exposed to the "Very low" or "Low" vulnerability (Fig. 7 and Table 7). This is assumed that mineral depth of the vulnerable area was deeper than 40cm and the bulk density of the vulnerable area was greater than 1.09 g/cm³, compared to other area. The characteristics could be combined with precipitation and they are related to soil moisture and hydrological values which highly affect on the NPP and SCS (BACHELET *et al.*, 2001).

Vulnerability of Forest Ecosystem

With the integration of vulnerability for vegetation distribution and forest ecosystem function, the overall vulnerability of forest ecosystem was evaluated for forest ecosystem in Korea. As shown Fig. 8 and table 8, 50.61% of Korea was exposed to the "Very low" vulnerability of forest ecosystem. However, some part of Korean ecosystem would be exposed to the "Very high" or "High" vulnerability in southern west and east coastal area and southern east land area due to climate change

Fig.7 (a) Vulnerability of forest ecosystem function (NPP+SCS), (b) NPP and (c) SCS vulnerability

*Vulnerability of forest ecosystem function = NPP vulnerability + SCS vulnerability.

Table 7 Vulnerability of forest ecosystem function - NPP and SCS in area (km²) and ratio (%)

Vulnerability of forest ecosystem function	NPP	SCS	Integrated NPP and SCS
Very High (0.8~1.0)	*349 (0.35)	205 (0.21)	106 (0.11)
High (0.6~0.8)	2,770 (2.79)	4,354 (4.39)	806 (0.81)
Moderate (0.4~0.6)	15,416 (15.55)	37,637 (37.97)	13,817 (13.94)
Low (0.2~0.4)	35,326 (35.64)	41,431 (41.80)	33,652 (33.95)
Very Low (0.0~0.2)	45,254 (45.66)	15,488 (15.63)	50,734 (51.19)
Total	99,115 (100.00)	99,115 (100.00)	99,115 (100.00)

*Area in km² (Ratio in %).

Fig.8 Vulnerability of forest ecosystem

*Vulnerability of vegetation distribution + Vulnerability of forest ecosystem function = Vulnerability of forest ecosystem.

Table 8 Vulnerability of forest ecosystem in area (km²) and ratio (%)

Vulnerability	Overall vulnerability of forest ecosystem
Very High (0.8~1.0)	603 (0.61)
High (0.6~0.8)	11,011 (11.11)
Moderate (0.4~0.6)	26,208 (26.44)
Low (0.2~0.4)	11,129 (11.23)
Very Low (0.0~0.2)	50,164 (50.61)
Total	99,115 (100.00)

*Area in km² (Ratio in %).

(11.72% of study area). In this high vulnerable area, both vegetation distribution and forest ecosystem function were sensitive to climate change and were exposed to less adaptation capacity. The reasons of high vulnerability could be 1) the increase of monthly mean temperature and minimum temperature, i.e. two of threshold for life-form interpreter of the MC1 model, 2) the soil condition influencing the vegetation production and soil carbon storages (BACHELET *et al.*, 2001), even though these reasons should be validated in future research.

The vulnerability of vegetation distribution was evaluated to be higher than that of forest ecosystem function in Korea. In the study of LEE *et al.* (2007a), the forest ecosystem was assessed with CEVSA model. They also resulted in relative high vulnerability of vegetation distribution, compared to the vulnerability of forest ecosystem function. However, the MC1 model, as one of the DGVMs, has limitation that it cannot perfectly explain the relatively heterogeneous topography and micro-climate of Korea. Also, the MC1 performance for Korean ecosystem could not be validated with the field observed NPP and SCS data at the plot-scale. The vegetation and carbon dynamics are significantly affected by natural disturbance, such as fires, in the MC1 run at the country scale, whereas carbon changes due to the fires are infrequent and difficult to quantify at the plot-scale (BACHELET *et al.*, 2008). So, it could be discrepant between the model results and field measurements. In addition, the MC1 model did not consider the direct anthropogenic effects on forest ecosystem. Therefore, the results of vulnerability assessment in this study needs to be supplemented by optimizing the previous models and developing Korea-specific vegetation model. To optimize and develop the Korea-specific model, it is required to apply the Warmth Index (YIM, 1977), mean minimum temperature of the coldest month (MTC), summer and winter precipitation (HORIKAWA *et al.*, 2007), and slope and direction of topography algorithms (LEE *et al.*, 2006). Recently, CHOI *et al.* (2009b) have conducted on a study to predict vegetation distribution by climate change using the WI and MTC, and in further research, they will develop regional scale model related to terrestrial carbon fluxes. It would be one of useful complementary source for forest ecosystem vulnerability assessment.

CONCLUSIONS

This study analyzed the overall vulnerability of Korean forest ecosystem by the integrated assessment of vulnerability of both vegetation distribution and forest ecosystem function using the MAPSS-CENTURY (MC1) model based on the past and future climatic data. Korean ecosystem was mostly occupied by the cool mixed forest, the warm mixed forest (Evergreen Needle-leaved dominant: EN), and the warm mixed forest (Deciduous and Evergreen Broad-leaved dominant: DEB). Their proportions were 96.06%, 3.28%, and 0.65%, respectively. Southern inland area and western and eastern coastal areas (11.72% of study area) were exposed to the very high or high vulnerability of forest ecosystem. Also, 61.84% of study areas have the "Very low" or "Low" vulnerability of forest ecosystem. Overall vulnerability of forest ecosystem in Korea was in the "Low" or "Moderate" level. However, Korean ecosystem would be exposed to the high vulnerability in southern west coastal area and southern east land area due to climate change. According to KONG (2005) and KIM and LEE (2006), in the high vulnerable area to climate change, the forest vegetations are easily exposed to the heat stress or drought and they are likely to die off due to the changes in forest climate region. Also, unsuitable environmental condition for forest growth and breeding would lead the reduction of forest production and the degradation of forest vegetation. Based on the spatial variation in vulnerability, we could suggest that the central and local governments need to prepare concentrated adaptation strategies for climate change based on the vulnerability assessment. However, these studies, using DGVMs, has limitation that it is difficult to consider the heterogeneous topography and micro-climate of Korea and the direct anthropogenic effects on forest ecosystem. Therefore, the results of vulnerability assessment in this study needs to be supplemented by optimizing the previous models and developing the Korea-specific vegetation model.

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