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A Simulation Study to Investigate Climatic Controls on Net Primary Production (NPP) of a Rugged Forested Landscape in the Mid-Western Korean Peninsula

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기복이 심한 한반도 중서부 산림경관에서 기후가 순일차생산(NPP)에 미치는 영향에 대한 모사연구

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ABSTRACT

We have investigated microclimatic controls on the spatiotemporal variations of net primary production (NPP) of a rugged forested watershed using the process-based biogeochemical model (BIOME-BGC). To validate the model simulation of water and carbon cycles at the plot scale, we have conducted field survey over deciduous broadleaf forest (DBF) and evergreen needleleaf forest (ENF) since 2000. The modeled values of soil temperature, soil moisture and soil respiration showed high correlation with those from the field measurements. The modeled seasonal changes of NPP showed high correlation with air temperature but no significant correlation with water related parameters. The precipitation frequency turned out to be the best climatic factor to explain the annual variation of NPP. Furthermore, NPP of ENF was more sensitive to precipitation frequency than that of DBF. With changes in vegetation cover and topography, the spatial distribution of NPP was of great heterogeneity, which was negatively correlated with the magnitude of NPP. Despite the annual precipitation of 1,400mm, NPP at the study site was constrained by the amount of water available for the vegetation. Such a modeling result should be verified by the field measurements.

Key words : **Forest watershed, NPP, Climate, Biogeochemical ecosystem model**

I. INTRODUCTION

In East Asia, where large populations impose a high demand for agricultural land, remaining forests are largely in topographically complex mountainous areas (Schimel *et al.*, 2002). Complex topography results in an increase of water outflow from the forest ecosystem, spatially heterogeneous meteorology and evapotranspiration, and redistribution of soil water (Running *et al.*, 1987; Band *et al.*, 1993; White *et al.*, 1998; Kang *et al.*, 2002), which characterizes the temporal and spatial variability of forest carbon flux.

Spatial variability of forest eco-hydrological processes is of special concern in scaling plot-level measurements up to landscape and regional scales (Pierce and Running, 1995; Cohen *et al.*, 2003; Kang *et al.*, 2004a, Kim *et al.*, 2005). Nonlinear relationships between biophysical variables and forest productivity

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imply discrepancies in forest productivities estimated at different spatial scales, because biophysical variables estimated at different scales are sometimes considerably different from each other (Kang *et al.*, 2002, 2004a). Although recent field studies including eddy-covariance flux tower measurements provide information related with ecosystem response to local topography (Schimel *et al.*, 2002), they never achieve a sufficient spatial sampling density to cover a complex topographic area and also never fill every key ecosystem process to explain entire terrestrial carbon cycles (Running *et al.*, 2000). A process-oriented ecosystem model is a useful alternative tool to simulate water and carbon dynamics of a forest ecosystem and to investigate ecosystem response to spatial and temporal climatic variability, especially for such a complex topographic area. Drawbacks of the modeling approach, however, become critical when reliability of model input data is uncertain and/or when the model structure is too abstract to explain the phenomena concerned. In addition, explicit consideration of disturbance history is another important issue in ecosystem modeling (Thornton *et al.*, 2002), in particular, for spatially explicit ecosystem modeling, because of lack of information about spatially explicit historical disturbance (Kang *et al.*, 2004b). Rigorous stand-level parameterization for the study area concerned should be addressed prior to spatially explicit model application.

Factors controlling carbon sequestration must be better understood in order to predict growth rates of atmospheric CO_2 and to develop strategies to restrain future increases (Barford *et al.*, 2001). Recently, a series of evidence was reported that spatial and inter-annual variations of forest carbon processes in Korean mixed-hardwood forests are closely related with precipitation or soil-water availability, in spite of relatively high precipitation over 1,400mm yr^{-1} (Kang *et al.*, 2003a, 2004c), whereas Kang *et al.* (2003b) showed that air temperature can be applied successfully to predict initiation of the growing season, and hence the length of growing seasons, which is positively related with net primary production (Kimball *et al.*, 1997; Keyser *et al.*, 2000). This evidence seems apparently to contradict the modeling analyses suggested by Churkina *et al.* (1998), who proposed incident solar radiation as the constraining factor for terrestrial primary productivity in Far East Asia, including Korea. More rigorous study is, therefore, necessary to understand the key climate or abiotic factors controlling terrestrial carbon sequestration in rugged mountainous areas (Schimel *et al.*, 2002), which provide prior knowledge of how to organize spatial data essential for spatial estimation of terrestrial carbon processes in rugged forested landscapes.

In this study, we examined the effect of climate on vegetation productivity in a rugged temperate forested landscape, using 3-yr field data and a process-based biogeochemical model. Our modeling approach is to use a process-oriented biogeochemical model (BIOME-BGC; Running and Coughlan, 1988; Thornton *et al.*, 2002). Field monitoring was implemented and utilized to validate the predicted stand-level hydrologic and carbon process at two different forest cover stands dominated by deciduous broadleaf trees (DBF) and evergreen needleleaf trees (ENF), respectively. Our specified purposes are: (1) to parameterize BIOME-BGC using field-measured data for the DBF and ENF biome types, respectively; (2) to use stand-level simulation to examine the effect of temporal climatic variability on the stand-level NPP; and finally, (3) to apply a framework for spatially explicit BIOME-BGC simulation incorporated with satellite remote sensing data in a rugged forested landscape.

II. MATERIALS AND METHODS

2.1. Site description and field experiments

The Gwangneung Experiment Forest (GEF) is located at the west-central part of the Korean Peninsula and belongs to a typical cool-temperate broadleaved forest zone (Kang *et al.*, 2003b). It covers 21.7 km^2 in area, and elevation ranges from 51 to 655 meters (Fig. 1a). The GEF is composed of numerous vegetation patches of deciduous broadleaf forest (DBF) and evergreen needleleaf forest (ENF) characterized by different stand age and disturbance history (Fig. 1b). In general, DBF stands are dominated by *Quercus acutissima*, *Acer palmatum* Thunberg, and Fraxinus rhynchophylla Hance. Vegetation age ranges from 80 to 200 year-olds, and overstory canopy height is 18-20m. The DBF stands are natural forest without thinning but with unknown fire history, whereas the ENF stands are dominated by *Pinus koraiensis* with a mean canopy height of 16m. The stands were planted 70-80 years ago and have not experienced thinning, with unknown history of fire.

Field experiments were implemented at two stands:

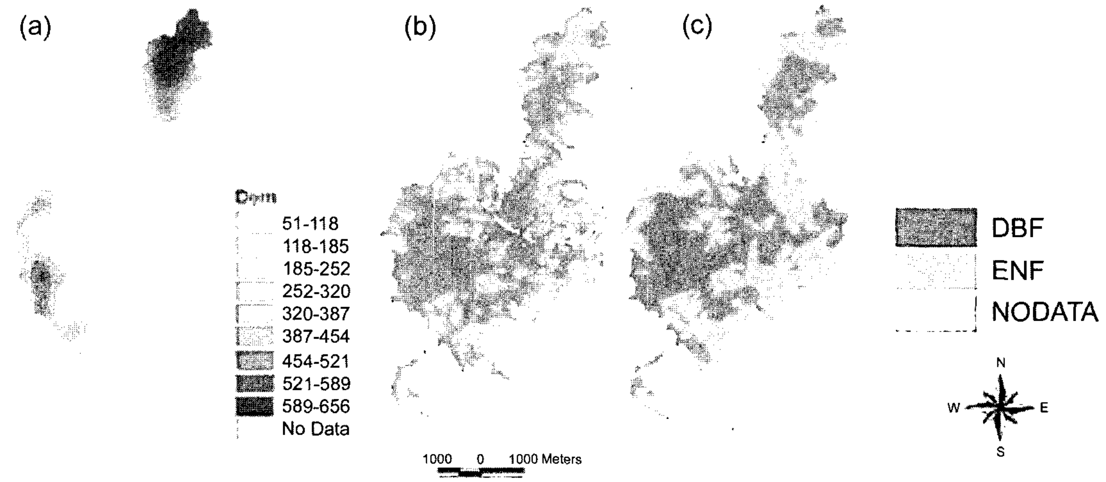

Fig. 1. Maps of (a) elevation (meters) and forest covers derived from (b) remote sensing and (c) reference GIS vegetation map. In the map legends, DBF and ENF mean deciduous broadleaf forest and evergreen needleleaf forest, respectively. Pixel resolution of the maps is 30m × 30m and total area is 21.7km^2.

an east-facing DBF and a north-facing ENF stand, respectively. Elevations are approximately 330m and 340m; surface slopes are about 15% and 50% for the DBF and ENF stands, respectively. Soil respiration was measured by using an closed-chamber infrared gas analyzer (IRGA) (EGM2 Soil Respiration Meter, PP Systems Inc.). Bulk mineral soil and root respiration rates were measured by removing surface litter, inserting the gas chamber to 1-cm soil depth, and recording CO_2 evolution (g CO_2 m^{-2} h^{-1}) for 2 minutes. Surface litter was removed to minimize errors associated with alteration of chamber air volume (Kang *et al.*, 2003a). Soil temperature at 10-cm soil depth was simultaneously measured by digital thermometer (SUMMIT, SDT 20, Korea). Five replicates of soil samples were collected at each site by homogenizing 10-cm soil covered with a soil respiration chamber and transported to the laboratory within 24 h for the following analyses. Subsamples of the collected soils were used to determine the gravimetric soil-water content (g H_2O g soil^{-1}) and soil organic matter content (g OM g soil^{-1}) in the laboratory, based on the loss of weight after drying the subsamples at 105°C for 24 hours and ignition at 550°C for 4 hours, respectively. Sampling locations were determined by the GPS system GeoExplorer (Trimble Inc.). Leaf area index (LAI) was measured by using a LI-COR 2000 Plant Canopy Analyzer (LI-COR Inc.).

2.2. Climate data collection

Data of daily maximum and minimum air temperature and precipitation were collected from an automatic weather station (AWS) in the GEF. Because the local meteorological data from the GEF AWS were available only from 1999 to 2001, we used national weather station data from Seoul, 20km south of the GEF, to extrapolate long-term local meteorological data of the GEF. We collected the Seoul meteorological data from the database of the Korean Meteorological Administration (KMA, http://www.kma.go.kr/). Linear regression models for daily maximum and minimum air temperature and precipitation were developed between the data (1999-2002) from Seoul and the GEF (r^2=0.98, 0.92, and 0.85 for daily maximum and minimum air temperature and precipitation, respectively; $p<0.01$ for all cases), which were applied to derive long-term meteorological data of the GEF from 1961 to 2002 by using the data from Seoul AWS. These long-term data were utilized for initializing BIOME-BGC as explained in a following section.

Site water balance (WB) was also prepared based on the local meteorological data, because WB is proposed as a potential limiting factor in forest productivity, together with local meteorology (Churkina *et al.*, 1998; Kang *et al.*, 2004c). The WB is calculated as the difference between precipitation and potential evapotranspiration (PET). The Priestly-Taylor PET given by Federer *et al.* (1996) was utilized in this study:

$$PET(mmday^{-1}) = 1.26 \times \frac{\Delta R_n}{L_v \rho_w (\Delta + \gamma)} \quad (1)$$

where R_n is the daily net radiation above the surface (W m^{-2}), L_v is the latent heat of vaporization (2448.0 MJ Mg^{-1}), Δ is the rate of change in vapor pressure with temperature (kPa K^{-1}), ρ_w is the density of water (1.0 Mg m^{-3}), and γ is the psychrometer constant (0.067 kPa K^{-1}).

2.3. BIOME-BGC and stand-level modeling

BIOME-BGC is a general ecosystem process model designed to simulate flux and storage of water, carbon and nitrogen for terrestrial biomes ranging from single plot to global scales. Details of the model are presented elsewhere, which include applications for multiple biome types and spatial scales (*e.g.*, Thornton *et al.* 2002; White *et al.*, 2000). The model is designed to realistically simulate soil-plant carbon (C) and nitrogen (N) cycling, but with simplifying assumptions to facilitate application at regional scales using a limited number (34) of biome specific physiological constants. All plant, litter, and soil carbon, nitrogen, and water pools and fluxes are entirely prognostic. The plant/ecosystem surface is represented by single, homogenous canopy, snow (when present) and soil layers, where understory vegetation is not distinguished from the aggregate canopy layer. The model also uses a daily time-step with daily maximum and minimum air temperature and precipitation as the primary inputs from which mean daily short-wave radiation, vapor pressure deficit, and day/night average temperatures are estimated. Biophysical processes represented by the model include: photosynthetic C fixation from atmospheric CO_2; N uptake from the atmosphere and soil; C/N allocation to growing plant parts; seasonal phenology, decomposition of fresh plant litter and soil organic matter; plant mortality, growth, litterfall, decomposition and disturbance (*i.e.*, fire and management); solar radiation interception and partitioning into sunlit and shaded leaf fractions; rainfall routing to leaves and soil; snow accumulation and melting; drainage and runoff of soil water; evaporation of water from soil and wet leaves; and evapotranspiration (ET) partitioning into transpiration, snow, soil and canopy evaporation components. The BIOME-BGC model has been successfully applied and validated over a range of diverse biomes, spatial scales and climate regimes (*e.g.*, White *et al.*, 2000), including individual boreal forest stands and sub-regions within the BOREAS study region (Kimball *et al.*, 1997, 2000; Kimball and Running, 1999; Amthor *et al.*, 2001; Kang *et al.*, 2004b).

For stand-level simulations, we prepared several sets of site-specific information for model parameterization. Site soil parameters were retrieved from both the field observation and Doh (2001). Plant eco-physiological parameters were obtained from White *et al.* (2000). Calibration of the parameters was based on the comparison of measured and modeled maximum LAI. The eco-physiological parameters were tuned within the range of values suggested by White *et al.* (2000) to fit the modeled annual maximum LAI in 2002 with the measured maximum LAI. Initial values for vegetation biomass and soil carbon and nitrogen pools were calculated by running BIOME-BGC for a long time to reach the ecosystem steady state in carbon fluxes. This initialization process (also termed spin-up simulation) loops through repeating meteorological data (1961-2002 for this study) several times until the total carbon levels stabilize.

Model validation was conducted by comparing the stand-level model predictions with field-measured soil temperature (°C), soil respiration ($gCm^{-2}d^{-1}$), and soil water content (SWC; %), which were gathered from the DBF and ENF stands, respectively. Mean absolute error (MAE) and bias were used together with coefficient of determination (r^2) and the Pearson correlation coefficients (r) for error analyses of the model predictions at the stand level.

2.4. Spatial modeling: Gridded-BIOME-BGC

The BIOME-BGC locally validated for DBF and ENF stands was applied to predict spatially explicit net primary production (NPP) in the GEF watersheds. The simplest mathematical representation of a landscape is accomplished by overlaying a grid of square pixels with equal dimensions, known as a raster format. In this study, the pixel size was designed to be 30m $\times$ 30m to fit with Landsat ETM+ (Enhanced Thematic Mapper plus) image resolution. For each pixel, BIOME-BGC was initialized by using a spin-up run and then utilized for predicting daily spatial NPP variations.

Meteorological data for each pixel were prepared by running a topoclimatic model, MT-CLIM (Running *et al.*, 1987; http://www.ntsg.umt.edu/). For the GEF watershed, a digital elevation model (DEM) with a grid resolution of 30m $\times$ 30m was constructed from a digital topographic map on GIS software (ArcGIS v8.0, ESRI) and utilized to derive topographic information including elevation, aspect, and slope for every pixel, which was incorporated with MT-CLIM to estimate pixel-wise local meteorology. However, we simply assumed a constant temperature lapse rate (6°C km^{-1}), following Kang *et al.* (2003b). A landcover map of the GEF was produced by using Landsat ETM+ images as illustrated in the following section. Since spatially explicit soil information (i.e. soil texture and effective soil depth) was not available for the study area, we made soil maps from the landcover map by assuming that soil texture and depth were spatially constant, specific to each landcover type (Kang *et al.*, 2004b).

2.5. Satellite-driven forest cover map

Optical satellite remote sensing data can be used to generate forest cover types (Franklin, 2001; Cohen *et al.*, 2003). In this study, each summer and winter Landsat ETM+ image was utilized for mapping the spatial distribution of DBF and ENF stands in the GEF. Although the winter image makes the distinction between DBF and ENF easier because of the deciduous characteristics of the DBF life-form, it runs into unexpected problems to use the winter image only, because bare soil makes a pretense of DBF in the winter image. A summer image was, therefore, utilized to screen out bare soils from the vegetation area, which is detected in the winter image only. After image-to-image rectification, NDVI (Normalized Difference Vegetation Index) was calculated for both images and then applied to classify forest covers by using unsupervised classification (ERDAS v. 8.4, ERDAS, Inc.) (Fig. 1b).

Accuracy of forest-cover classification was evaluated with another reference data set, an inventory-based vegetation map provided by the Korea Forest Research Institute (KFRI) with GIS polygon data (Fig. 1c). In this study, overall accuracy and Kappa accuracy were 71% and 42%, respectively. Although the Kappa value is generally superior to determine classification accuracy, it was not useful in this study, because the Kappa value is not suitable when forest cover is classified into just two categories (Lillesand and Kiefer, 2000).

2.6. Simulation analysis

Effects of climatic variation on stand-level carbon sequestration for the DBF and ENF stands were examined by using correlation analysis. In this study, net primary production (NPP) was used for the primary indices of the carbon sequestration, while air temperature, solar radiation, precipitation, water balance (Eq. 1), and annual precipitation frequency were used as surrogate environmental variables controlling NPP. Both daily and annual values of the above variables were used for the correlation analyses to investigate primary controlling factors in different temporal schemes. For the daily analysis, the daily environmental variables and daily NPP for the field experiment period (January 2000 to August 2002) were utilized, while the annual mean environmental variables and annual total NPP for the past 10 years (1992 to 2001) were used for the annual analysis, respectively.

III. RESULTS

3.1. Stand-level validation of BIOME-BGC

The model prediction indicated that the DBF site was significantly higher in soil water content (SWC) ($p<0.05$), soil organic matter (SOM) ($p<0.05$), and soil respiration ($p<0.05$) than the ENF site, and this trend was well coincident with the measured data from DBF and ENF sites (Fig. 2). Similarly, the model prediction indicated that the NPP of the DBF stand was greater than the NPP of the ENF stand ($p<0.05$).

The daily values of measured soil temperature (t_soil) were generally well predicted by the model for both seasonal variation and magnitude ($r^2=0.89$, slope of the regression=0.80, $p<0.01$ for DBF, and $r^2=0.85$, slope of the regression=0.90, $p<0.01$ for ENF; Fig. 2a). Soil respiration was predicted with some values being somewhat overestimated ($r^2=0.76$, slope of the regression=0.60, $p<0.01$ for DBF, and $r^2=0.30$, slope of the regression=0.41, $p<0.05$ for ENF; Fig. 2c), but the predicted seasonal variation generally fitted well with the measured data. The predicted SWC tended to be slightly underestimated but generally fitted well with the SWC measured from the DBF ($r^2=0.72$, $p<0.01$) and ENF stands ($r^2=0.73$, $p<0.01$; Fig. 2b).

3.2. Factors controlling stand-level daily vegetation productivity

Factors controlling daily vegetation productivity were examined by using correlation analysis with daily meteorological variables at both the DBF and ENF sites (Table 1). For the DBF stand, daily NPP variations

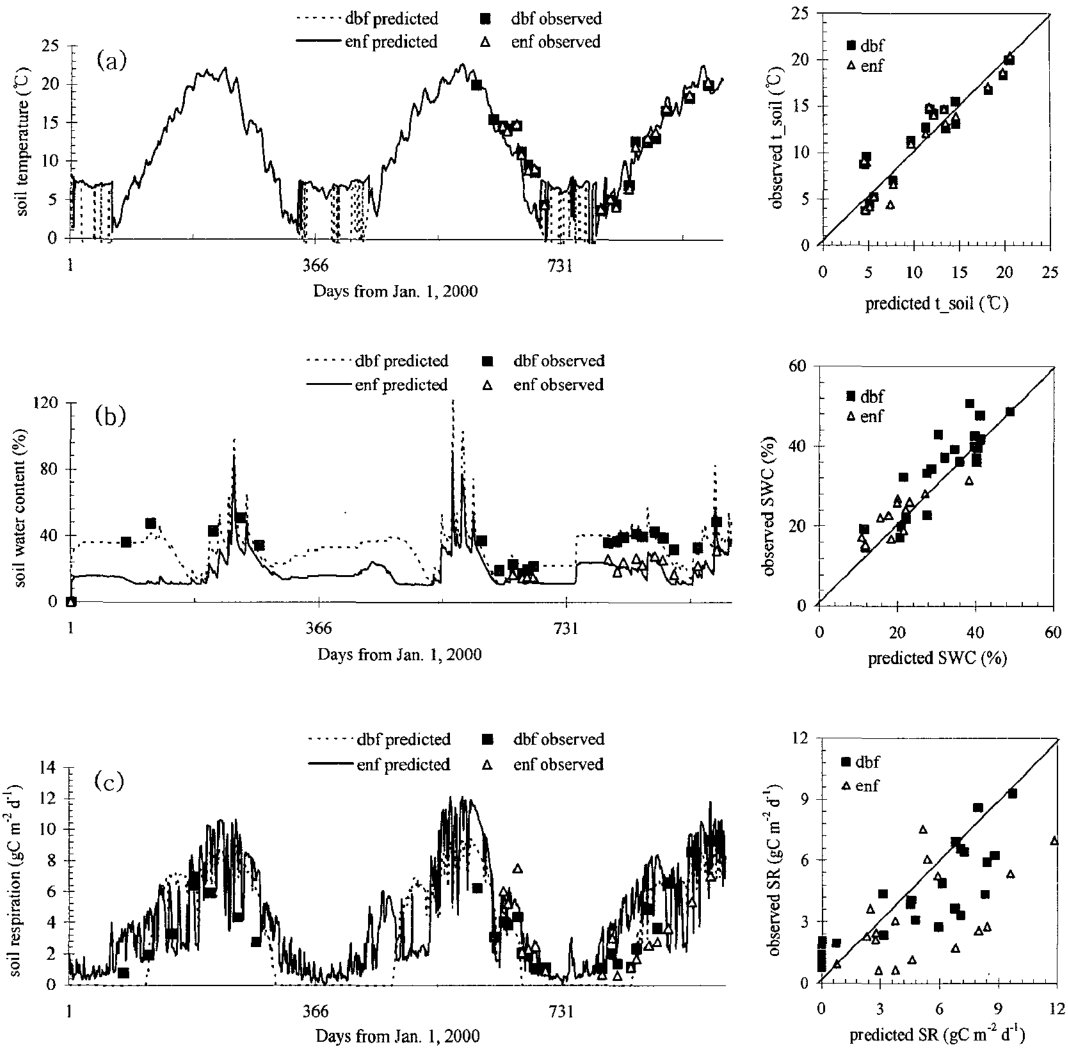

Fig. 2. Time series and scatter plots of the modeled and measured (a) soil temperature (°C), (b) gravimetric soil water content (%), and (c) soil respiration (gC m^{-2} d^{-1}) from both DBF and ENF sites. Solid lines and symbols in the time series graphs indicate daily model predictions and the field measurements, respectively. Solid lines in the scatter plots are 1 : 1 lines.

were well correlated with seasonal variation of air temperature (r=0.86, p<0.01) and incident shortwave solar radiation (r=0.31, p<0.01), while none of climatic factors, except air temperature (r=0.63, p<0.01), showed significant correlation with daily NPP for the ENF stand. Soil water status (i.e. WB) was insignificantly correlated with the daily NPP for both DBF and ENF.

3.3. Factors controlling stand-level annual vegetation productivity

Various climatic factors showed significant correlation with inter-annual NPP variations, which includes air temperature (r=0.72, p<0.05), solar radiation (r=-0.81, p<0.01), precipitation (r=0.67, p<0.05), and rainfall frequency (r=0.94, p<0.01) for the DBF stand but precipitation (r=0.54, p<0.01) and rainfall frequency (r=0.84, p<0.01) for the ENF stand (Table 1). Water-related climatic variables showed significant positive correlations with annual NPP for both DBF and ENF stands, whereas solar radiation showed significant negative correlations with the NPPs. A strong negative correlation of annual NPP with solar radiation found in the DBF stand contrasts with a

Table 1. Pearson correlation coefficients between daily environmental variables and daily NPP (g C m^{-2} d^{-1}) from January 2000 to August 2002 (n=972), and between annual environmental variables and annual total NPP (g C m^{-2} y^{-1}) from 1992 to 2001 (n=10). Here, WB is annual water balance (WB=Precipitation - PET).

		Air temperature (°C)	Radiation (MJ m^{-2} d^{-1})	WB (mm)	Precipitation (mm y^{-1})	Rainfall frequency
Daily NPP	DBF	0.86**	0.31**	0.037	---	---
	ENF	0.63**	0.15	0.041	---	---
Annual NPP	DBF	0.716*	-0.810**	0.225	0.667*	0.940**a
	ENF	0.087	-0.146	-0.234	0.543**	0.840**a

a, except for extraordinarily high precipitation over 2000mm
**, p<0.01; *, p<0.05

positive correlation between the variables suggested by Churkina *et al.* (2000) for Korean forested areas. We, however, supposed that the negative correlation is false correlation, which happened causally by a negative correlation (r=-0.81, p<0.01) of solar radiation with precipitation for the 1992-2001 periods.

Rainfall frequency was the best climatic variable to explain annual NPP variations for DBF (r^2=0.88, p< 0.01) and ENF (r^2=0.71, p<0.01) stands, when abnormally high precipitations of over 2,000mm (Table 1 and Fig. 3) were not considered. This indicates that vegetation growth in the GEF was strongly affected by drought stress following from low frequency of rainfall events in spite of relatively high annual precipitation of over 1,400mm. Generally, drought stress plays an important role in determining both structure and function of forest ecosystems, because of the close association between the carbon and hydrological cycles (Williams, 2001).

On the other hand, we found that the NPP of an ENF stand responded more sensitively to inter-annual variation of rainfall frequency (slope=6.8 gC m^{-2} y^{-1} mm-1; r^2=0.71, p<0.05) than the NPP of a DBF stand (slope=1.9 gC m^{-2} y^{-1} mm^{-1}; r^2=0.88, p<0.05) (Fig. 3).

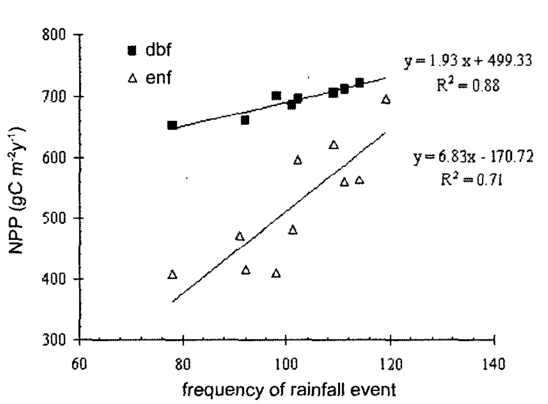

Fig. 3. A scatter plot between the predicted annual NPP (gC m^{-2} y^{-1}) and inter-annual variation of rainfall frequency. The solid lines are fitted regressions for DBF and ENF stands, and R^2 is the coefficient of determination. For DBF, data from years with higher precipitation than 2000mm y^{-1} were culled from this analysis.

3.4. Spatial and temporal variation of NPP

The predicted NPP was spatially and temporally heterogeneous, as shown in Fig. 4 (annual NPP variation) and Fig. 5 (monthly NPP variation). For the

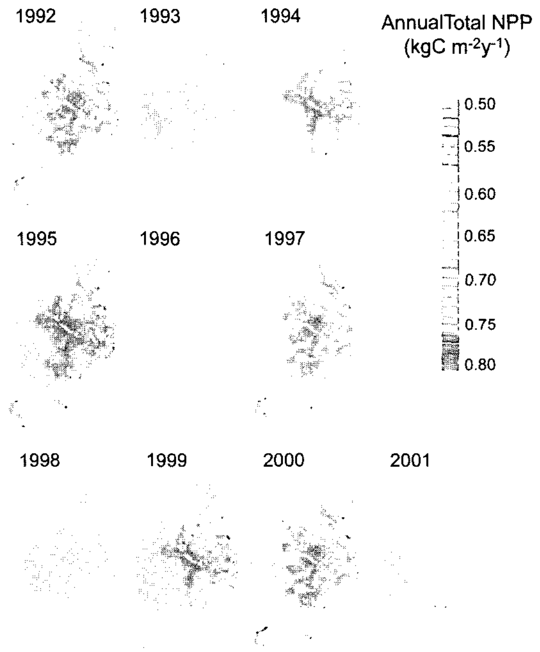

Fig. 4. Maps showing inter-annual and spatial variation of annual total NPP (kgC m^{-2} y^{-1}) from 1992 to 2001. Darker color indicates higher NPP in the maps.

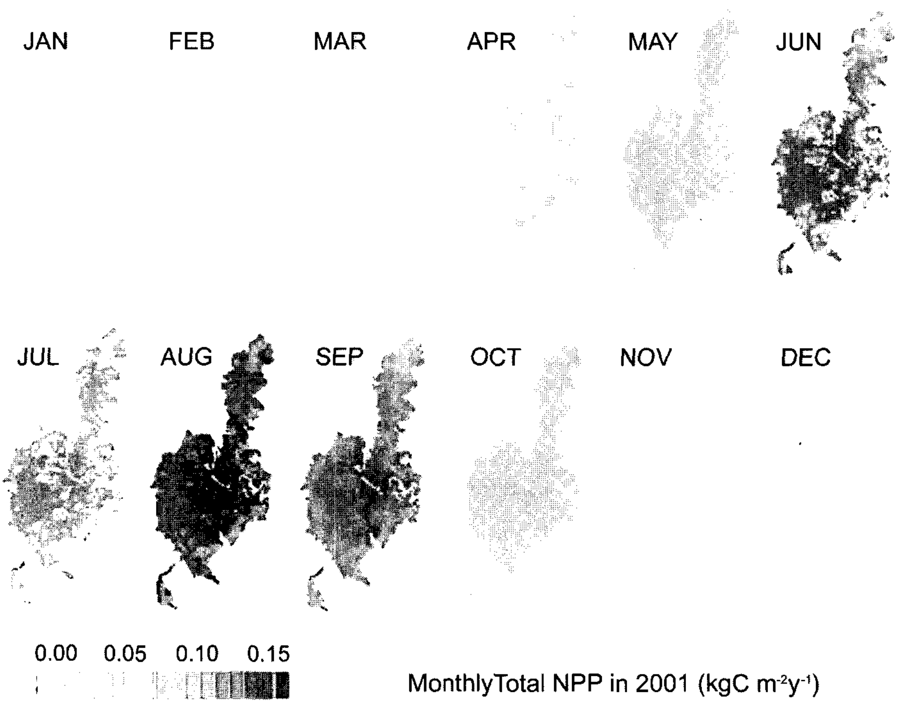

Fig. 5. Maps showing monthly spatial variation of monthly total NPP (kgC m^{-2} y^{-1}) from January to December in 2001. Darker color indicates higher NPP in the maps.

last 10 years (1992-2001), aerial mean NPP in the GEF varied considerably from 537 (±132) to 720 (±30) g C m^{-2} y^{-1} (Fig. 4). In monthly NPP variation (Fig. 5), ENF showed longer growing seasons than DBF from March to November, but NPP of DBF appeared higher than NPP of ENF during the active growing season from May to September, which consequently resulted in higher annual NPP for DBF (710±42 g C m^{-2} y^{-1}) than for ENF (523±100 g C m^{-2} y^{-1}). We found that there was a strong negative relationship between the aerial mean NPP and the magnitude of spatial variation surrogated as standard deviation in this study (Fig. 6). This result indicates that unfavorable growing conditions tend to increase spatial variability in a complex topographic forested landscape.

IV. Discussion and conclusions

4.1. Stand-level validation of BIOME-BGC simulations

In this study, a stand-level biogeochemical model, BIOME-BGC, was validated with various field measurements and then applied to simulate spatial variations of NPP in a topographically complex forested landscape incorporated with remote sensing and GIS data. The model predictions showed good agreement with diverse field measurements including soil temperature, SWC, and soil respiration.

Although soil temperature and soil respiration were

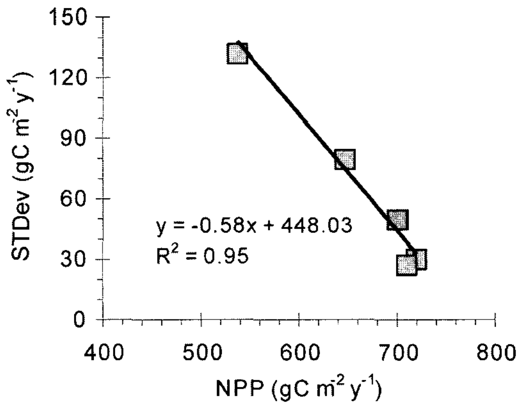

Fig. 6. A scatter plot showing a strong negative relation between standard deviations (gC m^{-2} y^{-1}) and aerial mean NPP (gC m^{-2} y^{-1}) for 1992-2001.

generally well predicted by the model, overestimations during winter seasons were detected because the model does not consider snow cover effect on soil temperature (Kang *et al.*, 2000), which probably resulted in underestimates of forest carbon sequestration ability in the study area. Snow cover affects the rate of soil respiration and nitrogen mineralization by decreasing the microbial substrate quality of SOM caused by anaerobic conditions under the snow cover during winter. Accordingly, the winter anomalies caused by heavy snowfall have an impact on the primary production in the next growing season (Barford *et al.*, 2001; Townsend *et al.*, 1995). At this moment, the latest public version of BIOME-BGC (v.4.11) does not include this process in the model algorithm, and hence is likely to overestimate soil heterotrophic respiration in areas with frequent and/or heavy winter snowfalls, like this study site (Kang *et al.*, 2004c).

4.2. Climatic factors controlling stand-level vegetation productivity

For the DBF stand, daily NPP variations were well correlated with seasonal variation of both air temperature and incident shortwave solar radiation, while none of climatic factors, except air temperature (r =0.63, p<0.01), showed significant correlation with daily NPP for the ENF stand. In contrast with strong dependency of daily NPP on air temperature, inter-annual NPP variations were correlated more significantly with rainfall frequency for both DBF (r= 0.94, p<0.01) and ENF (p=0.84, p<0.01) stands than other climatic variables. In addition, we found that the NPP of an ENF stand responded more sensitively to inter-annual variation of rainfall frequency than the NPP of a DBF stand, which indicates more sensitive response of ENF stand to drought condition.

This study provides additional evidence that, as suggested by Kang *et al.* (2004c), annual productivity for both DBF and ENF vegetation is limited by soil-water availability, in spite of relatively high annual precipitation of over 1,400mm y^{-1}. In contrast to the previous study (Kang *et al.*, 2004c), however, this study identified rainfall frequency as a more appropriate indicator for soil droughts than annual precipitation.

4.2. Spatial pattern of vegetation productivity

In general, the spatial pattern of vegetation productivity depends on the variation of plant responses and adaptations to environmental driving variables (Wang *et al.*, 2003). Similarly, we found considerable spatial and temporal variation of vegetation productivity within the GEF watersheds, caused by heterogeneous forest cover, inter-annual and spatial climatic variability, and local topography. The spatial NPP heterogeneity decreased with vegetation productivity, which indicates that the NPP heterogeneity is intensified in unfavorable growing conditions in mountainous landscapes. Aerial means of annual NPP in GEF were in the range of 537~720 gC m^{-2} y^{-1}. In spite of longer growing seasons for ENF, annual NPP for ENF vegetation (523 ± 100 gC $m^{-2}y^{-1}$) was lower than NPP for DBF (710 ± 42 gC $m^{-2}y^{-1}$).

These results imply an important aspect for the pine-oriented reforestation history of Korea since the mid-1960s, driven by the Korean Government. Reforestation results in diverse age distributions of less than 30-40 years and high forest growth rates now (Choi *et al.*, 2002). Based on our results, we infer that the pine-oriented plantation decreases the potential forest growth rate, compared with original deciduous forests, makes Korean forests more susceptible to droughts, and also results in lower stream outflow, in Korean forested landscapes, because of greater rainfall interception and evapotranspiration of pine vegetations than deciduous vegetations (Kang *et al.*, 2004b). In addition, our results provide evidence of a strong relationship between inter-annual variations of vegetation productivity and water-drought events in the GEF watersheds in the mid-western Korean Peninsula. This study, therefore, indicates that the hydrologic process should be an important concern in terrestrial carbon-cycling studies in mid-latitude temperate forests.

4.3. Limitations and future studies

However, we recognize that our key correlation analyses were based on a model NPP prediction that was not directly validated by field measurements, which gives our analyses considerable uncertainty. Although two eddy-covariance fluxtower measurement systems at the DBF and ENF stands, respectively, have been operating from 2001, there are potential problems in interpreting the flux-measurement data for now, because of locally complex topographic effects as indicated by Schimel *et al.* (2002). With the improvement of footprint analysis theory in rugged watershed areas, direct validation of model-predicted NEE and GPP will be available in the near future.

In addition, because the spatial modeling approach used in this study did not consider lateral connectivity of water flow, our approach is likely to underestimate the amount of spatial soil water heterogeneity. Zheng *et al.* (1996) indicated that plant-available soil water was not evenly distributed across rugged slopes and was higher at the slope bottom than at the ridge. As evidenced by Band *et al.* (1993), since the topographic distribution of plant-available soil water could intensify spatial variations of vegetation productivity, more rigorous soil-water routing routine needs to be incorporated for further enhanced spatial estimation of vegetation productivity in future studies.

적 요

과정-중심적인 생지화학 모형인 BIOME-BGC을 이용해 기복이 심한 산림유역에서 미기후가 순일차생산성(NPP)의 시공간적 변화에 미치는 영향을 조사하였다. 임분규모에서의 물과 탄소순환과정에 대한 모형예측을 검증하기 위하여 2000년부터 각각 낙엽활엽수림(DBF)과 상록침엽수림(ENF)에서 현장 조사를 수행하였다. 모형예측은 지온, 토양수분, 토양호흡 등의 다양한 현장 측정치들과 높은 상관성을 보였다. 모형에서 예측한 NPP의 계절변화는 기온과 높은 상관성을 보였으나, 물 관련 인자들과는 통계적으로 유의한 상관성이 나타나지 않았다. 반면에 여러 인자 중에서, 강우빈도가 NPP의 연변화를 설명하는 가장 좋은 기후인자로 판명되었다. 또한 DBF 임분보다 ENF 임분의 NPP가 강우빈도에 보다 민감한 것으로 나타났다. 공간적인 NPP 분포는 조사 유역에서 식생피복 및 지형의 기복에 따라 매우 이질적으로 나타났는데, NPP 이질성의 정도는 NPP의 절대량과 음의 상관관계를 보였다. 이러한 결과는 생육환경이 부적절할 때에 산림경관에서의 NPP 이질성이 커짐을 보여준다. 본 연구결과에 의하면 본 조사유역의 NPP는 연간 1,400mm 이상의 많은 강우에도 불구하고 식생이 이용할 수 있는 물의 양에 의해 제한 받는다는 것을 알 수 있었으며, 이러한 모형연구결과는 향후 현장조사를 통하여 검증할 필요가 있다.

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