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Measurements and simulation of forest leaf area index and net primary productivity in Northern China

P. Wang[a,b,c], R. Sun[a,b,*], J. Hu[a,b], Q. Zhu[a,b], Y. Zhou[e], L. Li[d], J.M. Chen[f]

[a]*State Key Laboratory of Remote Sensing Science, Jointly Sponsored by Beijing Normal University and the Institute of Remote Sensing Applications of Chinese Academy of Sciences, Beijing, China*

[b]*Beijing Key Laboratory of Enviromental Remote Sensing and City Digitalization, School of Geography, Beijing Normal University, Beijing, China*

[c]*Chinese Academy of Meteorological Sciences, Beijing 100081, China*

[d]*Institute of Remote Sensing Applications, Chinese Academy of Sciences, Beijing 100101, China*

[e]*Department of Natural Resources Science, University of Rhode Island, USA*

[f]*Department of Geography and Program in Panning, University of Toronto, 100 St. George Street, Room 5047,Toronto, Ont., Canada M5S 3G3*

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Abstract

Large scale process-based modeling is a useful approach to estimate distributions of global net primary productivity (NPP). In this paper, in order to validate an existing NPP model with observed data at site level, field experiments were conducted at three sites in northern China. One site is located in Qilian Mountain in Gansu Province, and the other two sites are in Changbaishan Natural Reserve and Dunhua County in Jilin Province. Detailed field experiments are discussed and field data are used to validate the simulated NPP. Remotely sensed images including Landsat Enhanced Thematic Mapper plus (ETM+, 30 m spatial resolution in visible and near infrared bands) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER, 15 m spatial resolution in visible and near infrared bands) are used to derive maps of land cover, leaf area index, and biomass. Based on these maps, field measured data, soil texture and daily meteorological data, NPP of these sites are simulated for year 2001 with the boreal ecosystem productivity simulator (BEPS). The NPP in these sites ranges from 80 to 800 $g\,C\,m^{-2}\,a^{-1}$. The observed NPP agrees well with the modeled NPP. This study suggests that BEPS can be used to estimate NPP in northern China if remotely sensed images of high spatial resolution are available.

Keywords: LAI; NPP; Forest; BEPS; Carbon cycle

1. Introduction

It is well known that the concentration of greenhouse gases has increased remarkably since the industrial revolution, especially in the last century. The concentration of carbon dioxide has risen from 280 before the industrial revolution to 376 ppm in the year 2003. Carbon dioxide, as a key greenhouse gas, causes gradual warming of the Earth's temperature (Qin and Zhou, 2003).

In terrestrial ecosystems, vegetation is one of the most important assimilators of carbon dioxide. Plants assimilate carbon dioxide in the atmosphere and incorporate it into the biomass through photosynthesis, and part of the assimilated carbon is emitted into the atmosphere through plant respiration (autotrophic respiration). The difference between photosynthesis and autotrophic respiration is defined as net primary productivity (NPP), which is a key parameter to describe life energy (Chen et al., 2002a). At the same time, it is also a major index of carbon-assimilation capacity (Peng et al., 2000). According to previous research findings, an increase of 2% in plant NPP will assimilate 1 Gt (10^{15} t) carbon on the assumption that respiration is invariable in the ecosystem (Roujean and Breon, 1995). Hence, the accurate estimation of the NPP of

*Corresponding author. State Key Laboratory of Remote Sensing Science, Jointly Sponsored by Beijing Normal University and the Institute of Remote Sensing Applications of Chinese Academy of Sciences, Beijing, China.

E-mail address: sunrui@bnu.edu.cn (R. Sun).

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terrestrial ecosystems is helpful in understanding the global carbon cycle.

Forests, as a major component of terrestrial ecosystems, play an important role in the energy, matter, and momentum exchange between the land surface and the atmosphere (Sun et al., 2004). The carbon storage of forest ecosystems accounts for up to 75% in terrestrial ecosystems (Geng et al., 2000). For this reason, measuring and modeling net primary productivity of forest ecosystems has received much attention (Qin and Zhou, 2003; Yu, 2003; Wen et al., 2004).

NPP models can be classified into three types: statistical, parameter models and process-based models. Statistical models, such as the Miami model and Thornthwaite Memorial model (Lieth and Whittaker, 1975), estimate NPP by establishing the statistical relationship between NPP and climate data. Parameter models calculate NPP through the energy conversion efficiency and the solar radiation absorbed by vegetation. Remote sensing vegetation indices can be directly used to estimate the fraction of absorbed photosynthetically active radiation (FPAR, Potter et al., 1993; Sun and Zhu, 2001b). Process-based models are based on physiological and ecological processes. Photosynthesis, evapotranspiration, autotrophic respiration, and dry matter partition are used to estimate NPP (Baldocchi and Harley, 1995; Amthor, 1994; Kim and Verma, 1991; Harley and Baldocchi, 1995; Leuning et al., 1995, 1998; Sellers et al., 1992, 1996a, b; Spitters, 1986; Wang and Leuning, 1998; Wang, 2000; Dai et al., 2004). These models can be run in small time steps, usually 1 day or less than 1 day, such as FOREST-BGC (Running and Coughlan, 1988), TEM (Raich et al., 1991; McGuire et al., 1992; Melillo et al., 1993), BIOME-BGC (Foley, 1994) and BEPS model (Liu et al., 1997). Process-based models have been widely used in estimating the distribution of NPP and researching the carbon cycle at the regional or global scale because of their well-established theoretical foundations.

In China, many researchers have conducted excellent work on NPP models and their applications. Relationships between NPP and meteorological data have been established to estimate regional NPP (Zhou and Zhang, 1996; Xiao et al., 1996; Zheng and Zhou, 2000). In the past several years, process-based models and remote sensing data have also been used widely to study the spatial pattern of terrestrial ecosystems NPP in China (Chen et al., 2001; Piao et al., 2001; Sun and Zhu, 2001a, b; Zhang et al., 2003a–d). However, due to lack of sufficient ground truth data to validate the models, NPP results of different models vary greatly. Measured data with flux towers represents net ecosystem productivity (NEP), which is the sum of carbon fluxes emitted from vegetation and soil, but differs from NPP. To obtain reliable ground NPP data, it is necessary to carry out field experiments at the pixel scale at different sites and then expand them to larger scales.

The objectives of this paper are the following: (1) describe field experiments in three sites in northern China, (2) analyze the relationships among leaf area index (LAI), vegetation indices (VIs) and biomass based on the field experiments of forest vegetation, and (3) simulate the spatial pattern of NPP using the boreal ecosystem productivity simulator (BEPS) in the three different sites.

2. Field experiments

2.1. Experiment sites

In order to simulate NPP in different forests and validate the BEPS, natural, regenerative and planted forests in three sites were selected. One is located in Qilian Mountain which is in Gansu province in northwestern China (the center coordinate being about 38.7°N and 99.55°E). The other two sites are, respectively, in the Changbaishan Natural Reserve (center coordinate: about 41.9°N and 127.9°E) and Dunhua County (center coordinate: about 43.2°N, 128.2°E). Both are in Jilin province in northeast China (Fig. 1). Field experiments at Changbaishan, Qilian Mountain, and Dunhua County were carried out during late August and early September in 2002, 2003, and 2004, respectively. LAI, biomass, longitude, latitude, slope, and aspect were measured at each experimental site.

Changbaishan Natural Reserve is one of the most valuable reserves in China for its rich gene pool of various species. The forest age is over 200 years and the elevation varies from 720 to 2691 m. It is humid and the precipitation is about 700 mm at lower elevations and increases to 1400 mm at the summit of the Changbaishan Mountain. The mean annual temperature varies from +4.9 °C at the foot of the mountain to −7.3 °C on the top. Due to climate and terrain conditions, different vegetation types are found, which include Korean pine and broadleaf mixed forest at elevations from 1100 to 1800 m, *Betula ermanii* forest in subalpine tundra at elevations from 1800 to 2100 m, and alpine tundra at elevations above 2100 m.

Qilian Mountain is covered by a regenerative forest aged approximately 100 years. The elevation here varies from 2200 to 4800 m. It is cold and dry in winter being affected

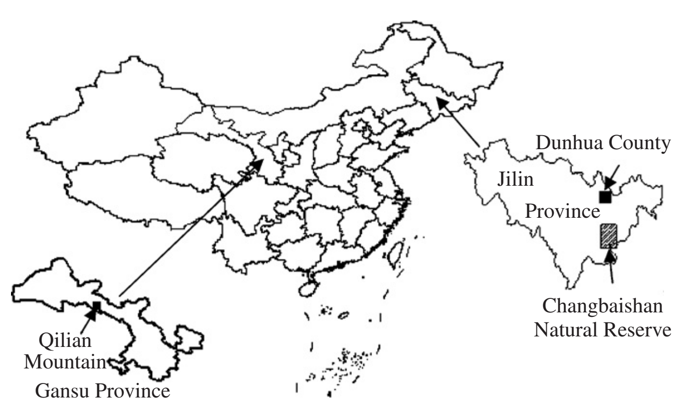

Fig. 1. Locations of the field experiment sites.

by the Mongolian anticyclone, while in summer, the temperature is high in the daytime but low at night with a large diurnal variation controlled by continental cyclones. Influenced by the climate and terrain, the area is dominated by different vegetation types, including *Picea crassifolia, Scbina przewalski* and grassland.

Dunhua County is a 20–50-year-old planted forest. Elevations vary from 350 to 1183 m. Controlled by continental cyclones, characteristics of the climate include cold, wet, long winters, but hot, dry and short summers, together with a short vegetation growth period. Similar to Changbai Mountain, the mean annual rainfall is 628.4 mm, falling mainly in July and August. The mean annual temperature is 2.6 °C. The warmest month is July with an average temperature of 25.2 °C and the coldest is January with −24 °C. Korean pine and larch are the main planted forests on the mountain.

The difference global positioning system (DGPS, 6400LS, Trimble Company) was used to survey the geographical position of the experimental sites, with a sampling precision of 1 meter. In each forest plot, longitude, latitude and elevation of the four corners and center points were acquired. In addition, the positions of some obvious features such as crossroads and bridges were also recorded with DGPS to georeference the remotely sensed images.

2.2. *LAI measurement and computation*

LAI directly determines the energy balance, NPP and evapotranspiration (Tian et al., 2002). In our experiments, LAI was measured by tracing radiation and architecture of canopies (TRAC), which was developed at the Canada Center for Remote Sensing (Chen and Cihlar, 1995) and commercialized by Third-Wave Engineering, Ottawa, Canada. TRAC measures the transmitted direct photosynthetically active radiation (PAR) along transects beneath a plant canopy using a high-spatial-frequency (32 Hz) sampling technique. The element-clumping index can be achieved by using this device, which is an important factor in the calculation of LAI of coniferous forest (Chen et al., 2002b; Sun et al., 2004). Taking into account the vegetation representation, vertical zones, and road access conditions, 34 plots in Changbaishan Natural Reserve, 16 plots in Qilian Mountain and 24 plots in Dunhua County were selected to carry out the LAI measurement (Fig. 2).

LAI data were collected in an area of 30 m × 30 m, which equals the grid size of the Landsat ETM+ or four grid sizes of ASTER image. The canopy gap fraction and gap size distribution of four 30 m long lines were measured. In each plot, 12 data sets were observed and each data set was measured in a 10-m-long line. During the process of measurement, the operator walks along east-west oriented

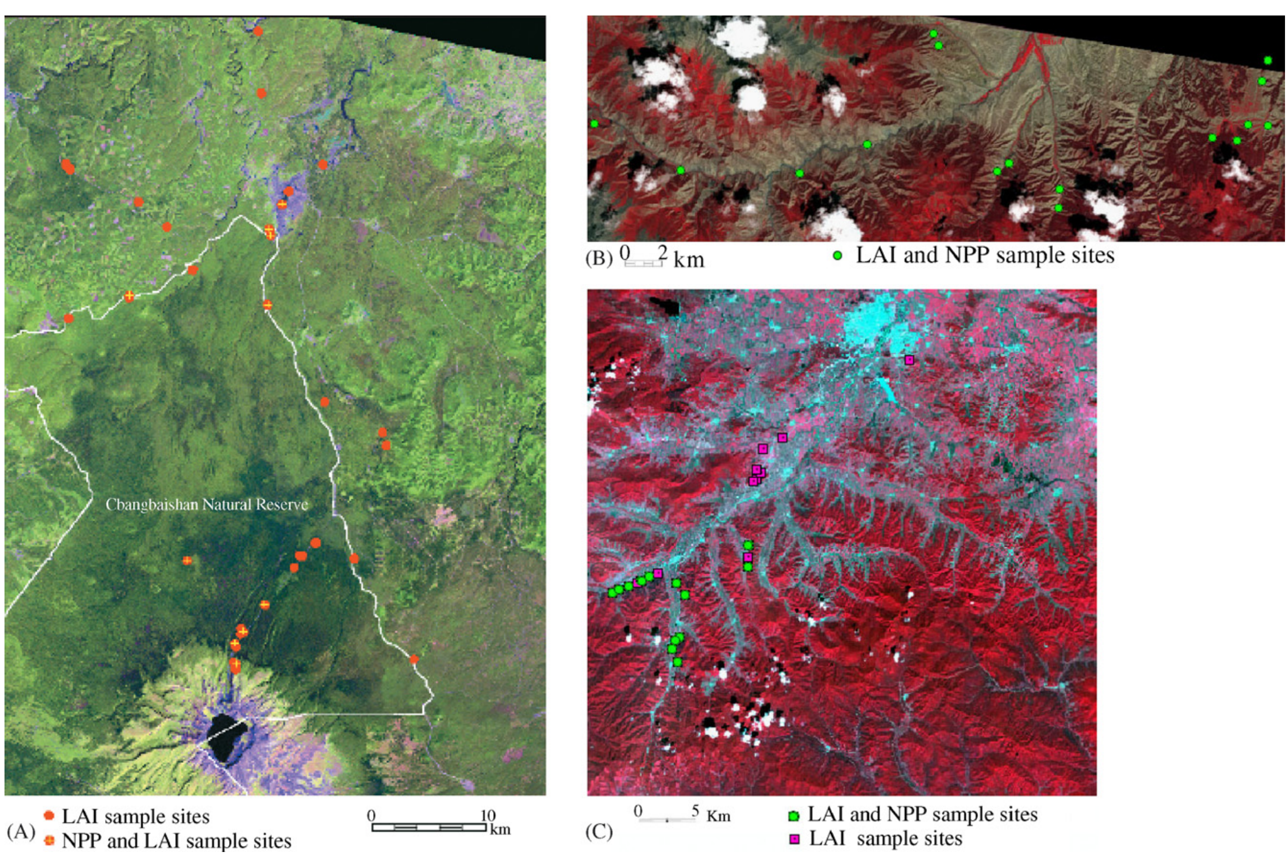

Fig. 2. LAI and NPP sample sites. (A) Changbaishan Natural Reserve, which is TM RGB composition image with 5, 4, 3 band. (B) Qilian Mountain, which is ASTER RGB composition image with 3, 2, 1 band (C) Dunhua County, which is ASTER RGB composition image with 3, 2, 1 band.

lines in order to remain at right angles to the direction of sunlight (see Fig. 3). The measurements were conducted as follows: from A to B, C to D, E to F, and then G to H.

Based on the element-clumping index derived from the gap size distribution, observed LAI data were calculated using "TRACWIN" software. Field observed files and some ancillary parameters including longitude, latitude, sun zenith angle and field experiment time were put into TRACWIN as input parameters to calculate field LAI. The LAI of each forest plot were calculated as the mean LAI of 12 data sets.

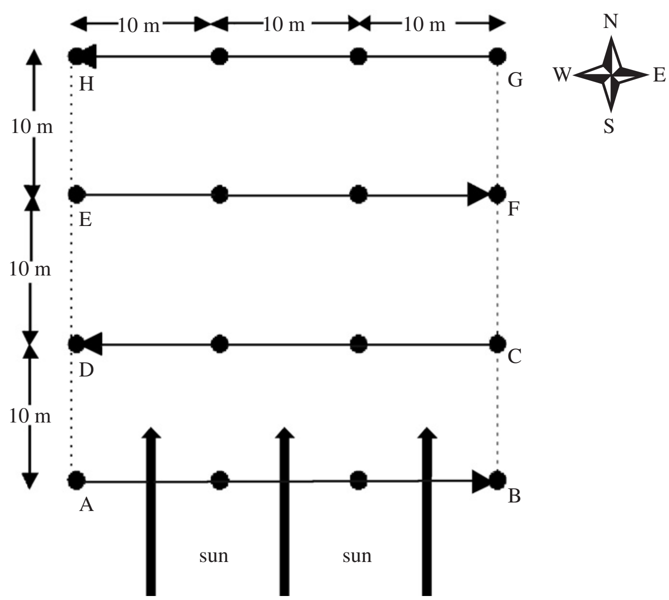

Fig. 3. Sketch map of LAI measurement.

2.3. Biomass and NPP measurement

The relative growth method was employed to estimate the biomass (Feng et al., 1999). The biomass is calculated using the empirical relationship between biomass, tree height and diameter at breast height (DBH) for different trees. The general formula of the relative growth method is as follows:

$$W = a(D^2H)^b \quad \text{or} \quad W = a(D)^b \tag{1}$$

in which, W is biomass, D is DBH, H is tree height, a and b are parameters.

10, 14 and 10 plots were selected, respectively, to measure the biomass in Changbaishan Natural Reserve, Qilian Mountain and Dunhua County (Fig. 2), with the same sampling areas as used for the LAI measurements. In each plot, about 10 trees and two tree cores for each tree were measured. Structural parameters including DBH, height of each tree, and the number of trees in each sampling area were also collected. The biomass of each plot was first calculated based on the species-specific relative growth formulas (Chen and Zhu, 1989). NPP per plot was obtained based on the difference of biomass in two successive years. In three sites, calculated NPP ranges from 80 to 800 $g\,C\,m^{-2}\,a^{-1}$ for 2001, which can be used to validate the NPP model. NPP and its species are listed in Table 1.

3. Model description

In this paper, the BEPS model was used to estimate NPP in three sites in Northern China. BEPS was developed by Liu et al. (1997) based on the forest biogeochemical cycles (FOREST-BGC) model (Running and Coughlan, 1988). It was initially used to simulate the forest ecosystem

Table 1
NPP and forest types in three sites in 2001

Site	NPP ($g\,C\,m^{-2}$)	Forest types	NPP ($g\,C\,m^{-2}$)	Forest types
CBS	563.2	Broad-leaved Korean pine	278.2	*Pinus sylvestris* var. mongolica
CBS	321.0	*Picea crassifolia*	473.5	*Picea crassifolia*
CBS	393.7	Betula ermanii	619.9	*Picea-Abies*
CBS	410.4	Korean pine and *picea-Abies* forests	335.7	Larch and fir forest
CBS	467.9	Fir and *betula ermanii* mixed forest	203.6	Broad-leaved Korean pine
QLS	549.3	*Picea crassifolia*	306.2	*Picea crassifolia*
QLS	373.0	*Picea crassifolia*	416.7	*Picea crassifolia*
QLS	261.5	*Picea crassifolia*	415.1	*Picea crassifolia*
QLS	522.8	*Picea crassifolia*	382.8	*Picea crassifolia*
QLS	485.8	*Picea crassifolia*	337.0	*Picea crassifolia*
QLS	469.5	*Picea crassifolia*	397.7	*Picea crassifolia*
QLS	472.4	*Picea crassifolia*	307.0	*Picea crassifolia*
DH	70.4	Korean pine	156.0	Korean pine
DH	142.9	Korean pine	85.1	Korean pine
DH	75.8	Korean pine	133.2	Korean pine
DH	78.5	Korean pine	134.5	Korean pine
DH	127.0	Korean pine	115.5	Korean pine

Note: CBS denotes Changbaishan, QLS denotes Qilian Mountain and DH is Dunhua County.

productivity in northern Canada, and later applied to other regions by some scholars (Matsushita and Tamura, 2002; Liu, 2001; Sun et al., 2004; Feng, 2004; Zhou, 2004). This model is a biogeochemical model and it simulates a new temporal and spatial scaling scheme of photosynthesis, respiration, distribution of carbon, and the balance of water and energy (Chen et al., 1999). The first advantage of this model is that it needs few input parameters; and the second is that the land surface parameters (LAI and land cover) derived from remotely sensed data solve the scaling problem from individual leaves to canopy by separating the canopy into sunlit and shaded leaf groups. Consequently, the model is effective and practical for large-area application (Liu et al., 1997; Chen et al., 1999, 2000).

Generally, input parameters of BEPS can be classified into three kinds: meteorological data, soil data and remotely sensed data. Meteorological data includes daily maximum and minimum air temperature, vapor pressure deficit, precipitation, and solar radiation. The soil available water capacity (AWC) map is produced from the soil texture map through the empirical relationship between soil water content and soil grain size distribution established by Saxton et al. (1986). Remotely sensed data include multi-temporal LAI data, land cover map, and biomass map. The preparations for these input parameters are discussed in detail by Sun et al. (2004).

The NPP was modeled in five steps with BEPS (Liu et al., 1997) and the outputs of the BEPS model include annual and daily NPP, respiration, gross primary productivity (GPP), transpiration and evaporation.

4. Results and discussion

One ETM+ image of Changbaishan Natural Reserve acquired on August 25, 2002 and two ASTER images of Qilian Mountain and Dunhua County on July 12, 2001 and August 19, 2003 were used, respectively. Geometric corrections were carried out based on ground-control points from 1:50,000 scale maps and some points collected by DGPS. Atmospheric corrections were performed using 6S software and the reflectance images were obtained to derive LAI and biomass above ground.

4.1. Leaf area index

Based on reflectance data, some vegetation indices (VIs), including simple ratio (SR), normalized difference vegetation index (NDVI) and reduced simple ratio (RSR) were acquired.

$$\mathrm{SR} = R_{\mathrm{red}}/R_{\mathrm{NIR}}, \tag{2}$$

$$\mathrm{NDVI} = (R_{\mathrm{NIR}} - R_{\mathrm{red}})/(R_{\mathrm{NIR}} + R_{\mathrm{red}}), \tag{3}$$

$$\mathrm{RSR} = \mathrm{SR} \times \big((R_{\mathrm{SWIR}} - R_{\mathrm{SWIR\ min}})/(R_{\mathrm{SWIR\ max}} - R_{\mathrm{SWIR\ min}})\big), \tag{4}$$

where R_{red} and R_{NIR} are the reflectance in red and near infrared bands, R_{SWIR}, $R_{\mathrm{SWIR\ max}}$, $R_{\mathrm{SWIR\ min}}$ are the reflectance, maximum and minimum reflectance in short wave infrared (SWIR) bands, respectively. $R_{\mathrm{SWIR\ max}}$ and $R_{\mathrm{SWIR\ min}}$ are defined as the 1% minimum and maximum cutoff points in the histograms of SWIR band reflectance. Because the spatial resolution of ASTER image is 30 m in SWIR bands and 15 m in visible and near infrared (VNIR) bands, RSR was calculated only for ETM+ imagery. The relationship between LAI and VIs are derived and the results are shown in Fig. 4.

From Fig. 4, we can see that RSR is closely related with LAI in Changbaishan Natural Reserve, which is consistent with the conclusion drawn by Leonard et al. (2000). However, SR and NDVI have poor relationships with LAI because of the diversity of forests, which prove that RSR could reduce the difference between vegetation types and suppress the background influence, so the accuracy of LAI retrieval for mixed forest can be improved. Meanwhile, SR has a better relationship with LAI than NDVI in the other two regions where vegetation is coniferous because NDVI will become saturated when LAI is high. So, SR was used to obtain the spatial distribution of LAI in Qilian Mountain and Dunhua County.

4.2. Biomass

The biomass map is produced by establishing the empirical relationship between observed biomass and LAI for the three experimental sites (Table 2).

4.3. Simulation

BEPS was originally used to simulate NPP in the boreal forest in Canada, where the climate is cold and the ratio between live stem and total stem is relatively small, so the maintenance respiration of live stems is smaller. In China, the climate is warmer, and there is more carbon consumed by the stem maintenance respiration. Considering this fact, we adjusted the live stem fraction of forest in the BEPS models. In the original model, the fraction of live stem ranges from 0.005 to 0.05. We adjusted the value to the range of 0.04–0.1.

The annual NPP results in 2001 were obtained through running the model in Changbaishan Natural Reserve, Dunhua County and Qilian Mountain (Fig. 5).

We can see that NPP values in Changbaishan Natural Reserve are higher than those in Dunhua County and Qilian Mountain, which is mainly caused by the type of forest and climate. Changbaishan Natural Reserve is a natural, undisturbed forest and the trees are shrubby and almost 200 years old. Meanwhile, the precipitation there is more plentiful than that in Qilian Mountain resulting in lower NPP in Qilian Mountain than in the Changbaishan Natural Reserve. The planted forests in Dunhua County are about 30 years old. The youthful

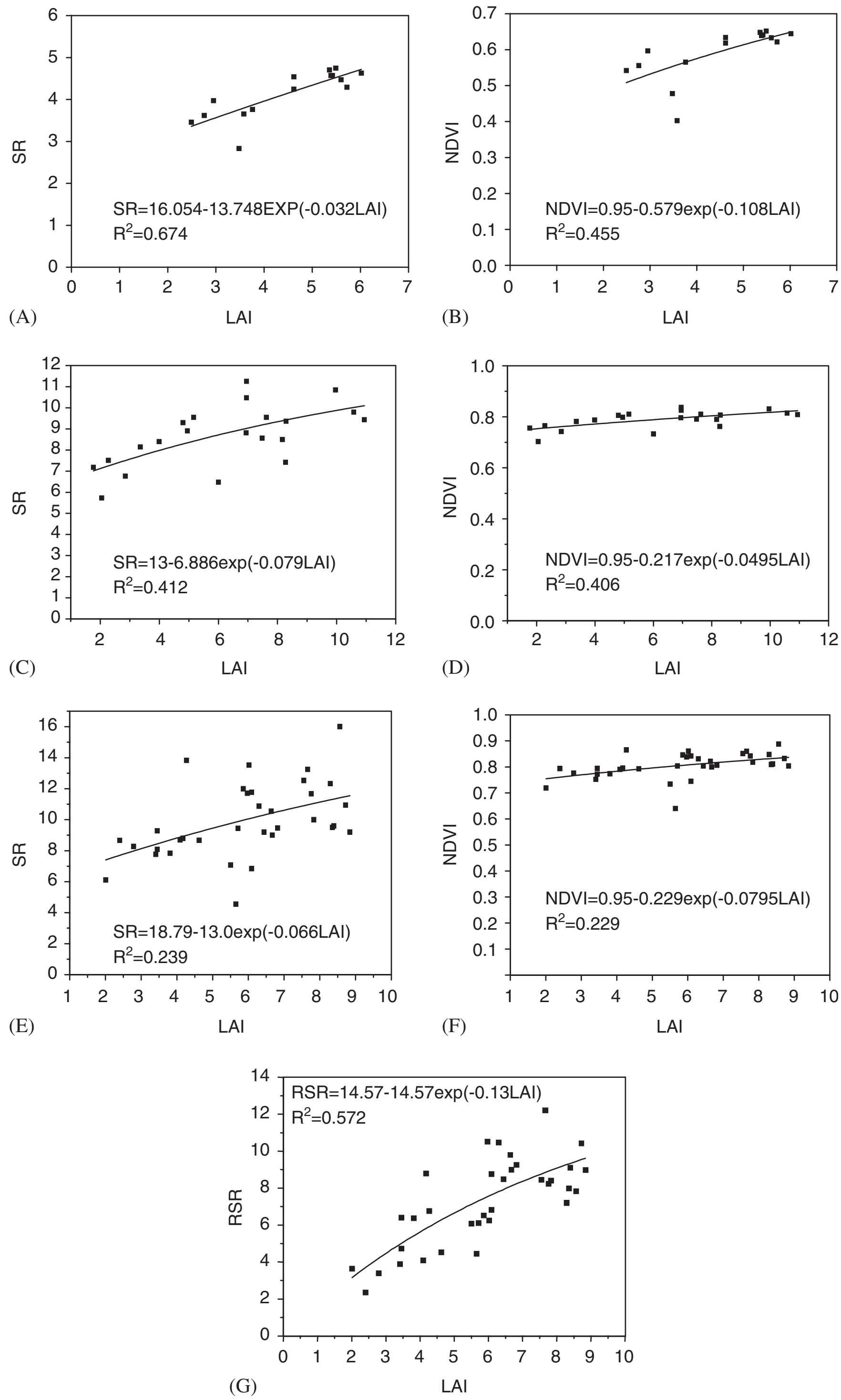

Fig. 4. Relationship between LAI and vegetation indices (SR, NDVI, RSR) A and B: Qilian Mountain; C and D: Dunhua County; E, F and G: Changbaishan Natural Reserve.

age and some interval cutting caused the NPP to be smaller than that in the other two places.

Based on the simulated NPP results, NPP of different vegetation types are calculated in the three sites. The results listed in Table 3 show that the mean NPP of coniferous forests is 451, 376 and $110\,g\,C\,m^{-2}\,a^{-1}$ in Changbaishan Natural Reserve, Qilian Mountain and Dunhua County, respectively. Compared with NPP for different forest types in Changbaishan Natural Reserve, we can see that the mean NPP for mixed forest is the highest, with a mean annual NPP of up to $500\,g\,C\,m^{-2}\,a^{-1}$; coniferous forests are next, and broadleaf forests have the lowest NPP (440 $g\,C\,m^{-2}\,a^{-1}$) among the forest types. The reason for the lowest mean NPP for broadleaf forests in Changbaishan Natural Reserve is that the *Betula ermanii* forest is also classified as a broadleaf forest type, which has a quite low NPP at elevations from 1800 to 2100 m.

4.4. Validation of NPP

The comparison of simulated NPP with ground truth data (Fig. 6) indicates that observed and modeled NPP are distributed evenly around the line 1:1 and the correlation coefficient is more than 0.9. The result demonstrates that simulated NPP has high accuracy for remote sensing application and that the BEPS model is suitable for northern China when using remotely sensed images with high spatial resolution.

Table 2
Equations between aboveground biomass and LAI

Site	Equation	R^2
Changbaishan Natural Reserve	$y=-0.9944x^2+42.481x$	0.7498
Qilian Mountain	$y=-0.7309x^2+32.011x$	0.5394
Dunhua County	$y=-0.0069x^2+0.3847x$	0.7558

y denotes aboveground biomass and x is LAI.

Table 3
Mean NPP of different vegetation in three experimental sites

Sites	Vegetation	Mean NPP ($g\,C\,m^{-2}\,a^{-1}$)
Changbaishan	Mixed forest	500
Changbaishan	Coniferous forest	451
Changbaishan	Broadleaf forest	440
Changbaishan	Crop	232
Dunhua County	Coniferous forest	110
Qilian Mountain	Coniferous forest	376

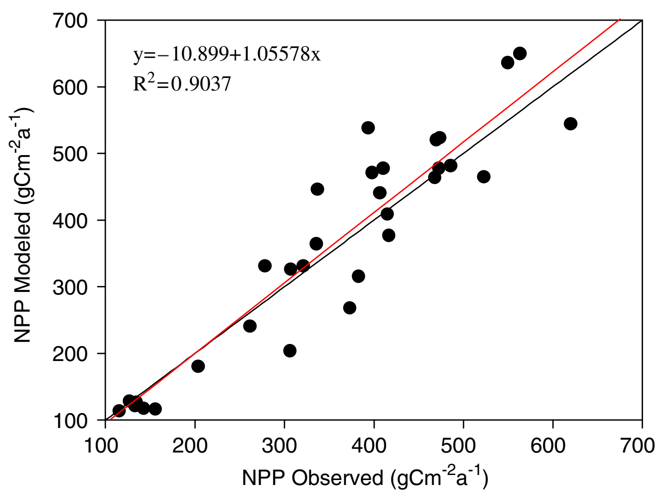

Fig. 6. Comparison between observed NPP and simulated NPP using BEPS model in the three experiment sites.

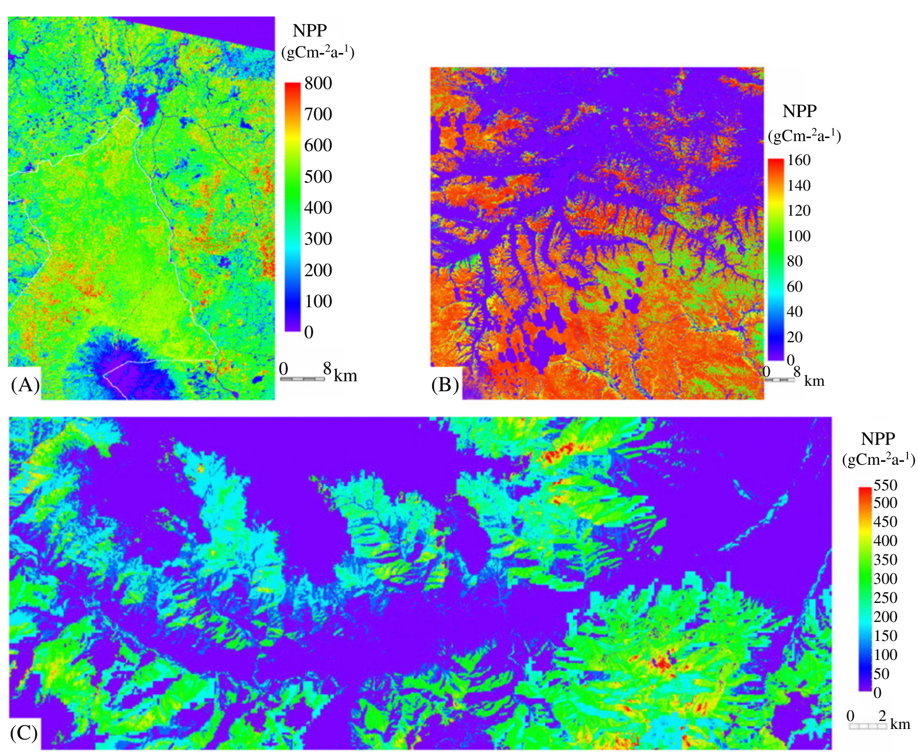

Fig. 5. Simulated annual NPP results in 2001 in three sites. (A) Changbaishan Natural Reserve, (B) Dunhua County, and (C) Qilian Mountain.

5. Conclusion

Three forest sites were selected in northern China to measure LAI, biomass and NPP. One is a natural forest in Changbaishan Natural Reserve, and the other two are regenerative forests and planted forests in Qilian Mountain and Dunhua County, respectively. The field observations were used not only to establish the relationship between LAI and biomass but also to validate the modeled NPP.

Based on high spatial resolution remote sensing data, the BEPS model was run to simulate the spatial pattern of NPP in 2001 at the three sites. The results show that for the coniferous forests, NPP in Changbaishan Natural Reserve is the largest with mean NPP of $451\,g\,C\,m^{-2}\,a^{-1}$, while NPP in Qilian Mountain is smaller with mean NPP of $376\,g\,C\,m^{-2}\,a^{-1}$; NPP of planted forest in Dunhua County is lowest ($110\,g\,C\,m^{-2}\,a^{-1}$) because of its young age. The modeled NPP is consistent with observed data, which demonstrates that BEPS can well estimate NPP in northern China with high spatial resolution remote sensing data. The field observed NPP and simulated NPP map can be further used to validate the results simulated by using coarse resolution remote sensing data.

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