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Assessing Forest Ecosystems across the Vertical Edge of the Mid-Latitude Ecotone Using the BioGeoChemistry Management Model (BGC-MAN)

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Abstract: The mid-latitude ecotone (MLE)—a transition zone between boreal and temperate forests, which includes the regions of Northeast Asia around 30°–60° N latitudes—delivers different ecosystem functions depending on different management activities. In this study, we assessed forest volume and net primary productivity changes in the MLE of Northeast Asia under different ecological characteristics, as well as various current management activities, using the BioGeoChemistry Management Model (BGC-MAN). We selected five pilot sites for pine (Scots pine and Korean red pine; *Pinus sylvestris* and *P. densiflora*), oak (*Quercus* spp.), and larch forests (Dahurian larch and Siberian larch; *Larix gmelinii and L. sibirica*), respectively, which covered the transition zone across the MLE from Lake Baikal, Russia to Kyushu, Japan, including Mongolia, Northeast China, and the Korean Peninsula. With site-specific information, soil characteristics, and management descriptions by forest species, we established their management characteristics as natural preserved forests, degraded forests, sandy and cold forest stands, and forests exposed to fires. We simulated forest volume (m^3) and net primary productivity (Mg C ha^{-1}) during 1960–2005 and compared the results with published literature. They were in the range of those specified in previous studies, with some site-levels under or over estimation, but unbiased estimates in their mean values for pine, oak, and larch forests. Annual rates of change in volume and net primary productivity differed by latitude, site conditions, and climatic characteristics. For larch forests, we identified a high mountain ecotype which warrants a separate model parameterization. We detected changes in forest ecosystems, explaining ecological transition in the Northeast Asian MLE. Under the transition, we need to resolve expected problems through appropriate forest management and social efforts.

Keywords: net primary productivity (NPP); growing stock volume (GSV); Mid-Latitude Ecotone (MLE); BioGeoChemistry Management Model (BGC-MAN); process-based ecosystem model

1. Introduction

Forest ecosystems have experienced changes owing to climate change and anthropogenic pressure [1,2], and these changes are particularly rapid in areas with a sensitive ecosystem structure and high population density. In addition, forest degradation, deforestation, and desertification are the main issues that threaten sustainable terrestrial ecosystems, therefore maintaining ecological productivity is important [3]. The northern mid-latitude region (MLR), which is located between 30°

and 60° N latitudes with various land covers and a lot of human activities, including the mid-latitude ecotone (MLE), is a transition zone between forests and drylands [4–6]. In Eurasia, dense vegetation is distributed along the MLE in regions such as Northeast Asia, Siberia, and Europe, however, drylands also exist in Mongolia, Central Asia, and the Mediterranean region [7,8].

Forests in the MLE consist of boreal and temperate forests, and form a belt connecting the Far East and Europe. This forest belt has important roles in maintaining ecological sustainability and preventing the expansion of drylands. The Northeast Asian MLE, including Korea, China, Japan, and Mongolia, has faced environmental changes during the past decades and will be affected by future climate change [9]. Through the forests of Mongolia and China, the boreal forests of Russia near Lake Baikal and Siberia are connected to the temperate forests in China and the Korean Peninsula [10]. Along this connection, each nation has different forest management issues and environmental conservation regimes.

Temperate forests in South Korea and Japan were restored during the 1960s to 1970s, and now both countries have successful restoration outcomes, with the aim of sustainable forest management [11]. As a case in point, the forest growing stock volume (GSV) in South Korean forests was 10.5 m^3/ha in 1952, and it reached 100.4 m^3/ha in 2007 [12]. However, forests in North Korea have suffered from deforestation and forest degradation due to logging for food and fuel production [13,14]. There are some differences in reports on the extent of deforestation in North Korea; the deforested areas there are estimated to have ranged between 1.2 million ha and 2.5 million ha during the late 1980s to 2000s [15]. These differences are also represented in the forests' net primary productivity (NPP) as a negative carbon budget in North Korea [16]. Temperate forests were changed to boreal forests in China, Northern Mongolia, and Russia near Lake Baikal. North China and Inner-Mongolia are widely known as regions facing ongoing deforestation and land degradation [17], but the Chinese and Mongolian governments strive to recover their forest ecosystems to secure ecological benefits [18–20], whereas, the forests near Lake Baikal and around the MLE have suffered natural or anthropogenic forest fire [21]. There is great uncertainty in measuring the effect of fire in boreal forests; one estimate revealed that 2.9% of Russian boreal forest loss was caused by forest fires [22].

Therefore, forest management regimes in the Northeast Asian MLE can be summarized as: (1) well-restored and managed areas in South Korea and Japan; (2) land degradation in North Korea; (3) semi-arid and new plantation in China and Mongolia; and (4) cold temperature with forest fire in Russia. The complexity of the management regimes of different countries leads to different forest statuses. NPP and GSV can represent the effects of these differences, and many modeling approaches were applied in the MLE of Northeast Asia using Flux data, Moderate Resolution Imaging Spectroradiometer-Leaf Area Index (MODIS-LAI), Boreal Ecosystem Productivity Simulator (BEPS), Vegetation Integrative Simulator for Trace gases (VISIT), MAPSS-CENTURY1 (MC1), and Biome-BioGeoChemistry (Biome-BGC) [15,16,23–27]. Forest fluxes were calculated from data obtained from field surveys, but such data were procured at different times and locations [10,24]. Therefore, the use of forest fluxes to understand different management regimes has limitations. Applying models can be the alternative to overcome the spatio–temporal limits of the fluxes. Both satellite-based and process-based ecosystem models were applied to simulate productivities in the Northeast Asian MLE [15,16,28–30]. However, these modeling approaches had limitations in reflecting management details because of different parametrizations and representations of ecological processes and spatio–temporal data limitations.

Our synthetic study elucidates the process of applying the BioGeoChemistry Management Model (BGC-MAN) in the MLE of Northeast Asia. The BGC-MAN, a modified mechanistic biogeochemical model, extends simulations into forest management options in certain forest stands. The model was tested in European forests but has not yet been tested in the MLE of Northeast Asia [31–34]. We assessed past changes in NPP and GSV in the MLE under different environmental characteristics, as well as under various current management activities, using the BGC-MAN. We selected representative forest stands in the MLE of Northeast Asia from literature and assessed changes to the ecosystem and model uncertainties from the simulated results.

2. Materials and Methods

2.1. Applying BGC-MAN

BGC-MAN is a process-based ecosystem model, and the model also has the modules to apply forest management activities, so different forest ecosystem and management activities were analysed by BGC-MAN [31–34]. This process-based model requires more than 50 inputs, with daily weather data, bio-physical information, species characteristics of the forest stand, and site information. The model calculates different combinations by the climatic variables (e.g., daily weather data, solar radiation, vapor pressure, precipitation), bio-physical status (e.g., aspects, elevation, and soil and nitrogen characteristics), and species characteristics (e.g., leaf area index (LAI), stomatal conductance, carbon nitrogen ratio). From photosynthesis, the self-initialized model generates gross primary productivity (GPP), NPP, and the carbon allocation of the vegetation's carbon pools, including respirations.

The working steps for applying BGC-MAN in the MLE of Northeast Asia start from selecting study sites. Under the limited carbon flux sites and temporal availability, the study sites were selected based on the literature review. From the literature, we can figure out dominant tree species as well as the bio-physical status and management history of forest stands. To run the model, missing data and parameters were collected and adjusted by geo-spatial analysis and previous BGC-MAN studies in Europe. In addition, we adopted daily weather data from 1951 to 2005 to find current changes of the forest ecosystem. After that, we simulated forest volume (m^3) and NPP (Mg C ha^{-1}). We checked the results with different literature and general trends among the study regions.

2.2. Study Sites

To cover the MLE in Northeast Asia, we selected five pilot sites from each of the southern parts of the selected sites, including oak (*Quercus* spp.), pine (*Pinus sylvestris* and *Pinus Densiflora*), and larch (*Larix Mongolica and Larix Sibirica*) stands [35–38] (Figure 1). The study sites were distributed along latitudinal (vertical) transects. They were also located near the borders of forests with other land covers and different forest densities [7,39]. In addition, various human effects due to different management of forest activities were found from literature [6,40]. Therefore, this region has ecological and socio-economic transitions that vary according to each tree species and nation.

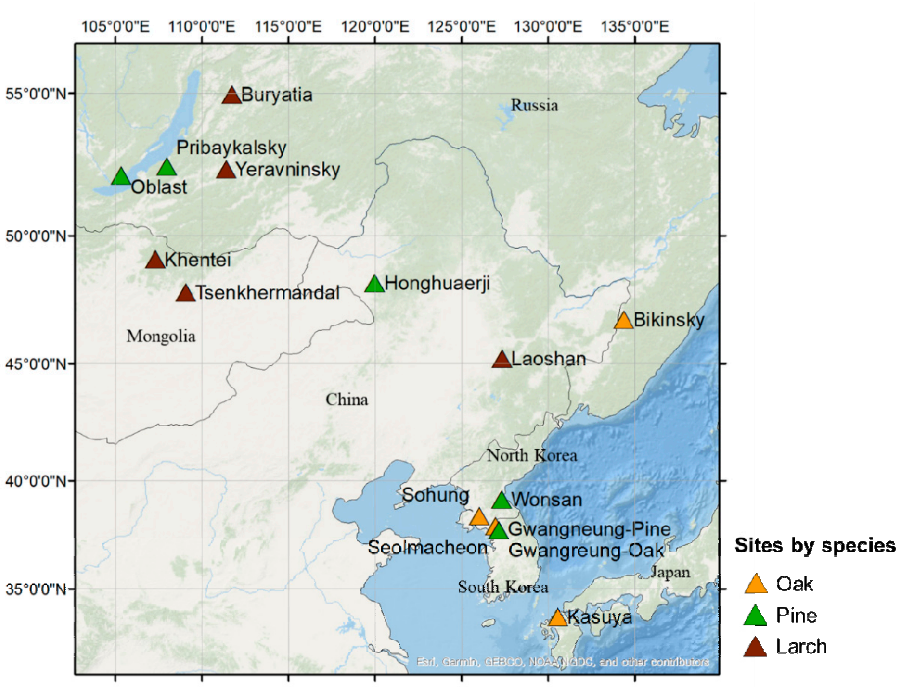

Figure 1. Study sites (oak, pine, and larch stands) along the mid-latitude ecotone (MLE) of Northeast Asia.

Oak forests are distributed in the Korean Peninsula, Japan, and Far East Russia. The Kasuya stand, located in Kyushu, Japan, is one of 34 long-term monitoring forest sites of JaLTER (Japan Long Term Ecological Research Network), so forest disturbance has been very limited here in comparison with the other forests [35,41]. Based on the literature review, its forest age is around 140 years. The Gwangneung stand in South Korea has been well-preserved as it is a national arboretum, therefore it has a very old forest stand age, around 80–200 years [16,36,42]. In addition, many field studies by the National Institute of Forest Science (NIFoS), as well as individual previous studies, have monitored forest changes. The Seolmacheon stand in South Korea was also recently added to the AsiaFlux network [43,44]. This forest stand is young, aged around 20–40 years, and some forest hydrology experiments have been conducted here. Detailed forest characteristics of the Sohung stand in North Korea, one of the degraded and partially restored areas, were assumed based on a previous case study for Reducing Emission from Deforestation and land Degradation (REDD+) [45]. Bikinsky is located in Far East Russia, near the border of China, and forest fires are common in the surrounding forests [46].

Pine forests are widespread around the Korean Peninsula, Northeast China, and near Lake Baikal. Gwangneung also has old protected pine forests for royal timber production, and presently has well-preserved natural forests [38,47,48]. Its forest age is more than 80 years. Wonsan, which is located on the east coast of North Korea, is one of the focus areas for restoring deforested North Korean forests [11,49]. Honghuaerji forest is located in a sandy area with a relatively young forest stand age. This site was established by Chinese government projects to restore the sandy lands and reduce soil desertification [50,51]. One of the Russian forest stands, named Oblast, is located on the western side of Lake Baikal near Irkutsk, and the other, named Pribaykalsky, is located on its eastern side. Both forest stands experience forest fires and they are some of the coldest among the pine tree sites [46].

The larch trees in Laoshan, China were planted in 1969 as an experimental forest, and various studies have been conducted in this site [26,37]. In Mongolia, the Tsenkhermandal and Khentei sites were selected for our simulation. Tsenkhermandal is located in the high mountains with a 110-year-old forest, and the Khentei site represents typical Mongolian larch forests near Ulaanbaatar. There have been different estimates of its forest age from previous studies, but it is estimated to be as old as 64–146, according to tree ring surveys [52–54]. Yeravninsky is a 100-year-old forest and is located on the eastern side of Lake Baikal across the mountains there. Buryatia is the northernmost site and comprises a 100-year-old high mountain forest. Both forest stands experience forest fires [46]. From these previous studies, a site information table, especially including information on species, forest age, and location with management history, was constructed (Table 1).

To add more details, site-specific management information and mortality rates were adopted from the previous studies. For the pine forests, a site-specific mortality rate of 1.4% was applied for the Gwangneung forest [38], but the average mortality rate was 3% in the other Korean young forests [55]. The average mortality of oak forests in Korea was 1.7–2.0%, however, it was as high as 4.2% in some oak stands [55]. We assumed that the mortality of old forest stands was lower than average but allowed a higher mortality rate for young forests. In the case of Russian forests, we applied an average mortality rate of 0.6% through calculations from data on growth and productivity [46]. Similarly, the mortality rate of larch forests from the Korean Peninsula was applied to the young forests in China. This value was 5.0–5.6% in *L. kaempferi*. For the other forests, a mortality rate of 0.2–0.3% was applied.

We set management characteristics as: (1) well-restored and managed areas in South Korea and Japan; (2) land degradation in North Korea; (3) semi-arid and new plantation in China and Mongolia; and (4) cold temperature with forest fires in Russia. Following these differences, the model adopted options of planting, clear-cutting, natural preservation, and logging. From the forest age, we initialized the planting and clear-cutting options for modeling to fit the respective management history. For example, many sites in South Korea and Japan were planted and naturally preserved if these were their historical management strategies, but we assumed clear-cutting in North Korea, following their history of deforestation.

Table 1. Site-specific information, including mortality rates, fire fractions, and applied management options.

Classes	Oak Forest Stands					Pine Forest Stands					Larch Forest Stands				
Species	*Quercus acuta*	*Quercus serrata*	*Quercus variabilis*	*Quercus mongolica*	*Quercus mongolica*	*Pinus densiflora*	*Pinus densiflora*	*Pinus sylvestris*	*Pinus sylvestris*	*Pinus sylvestris*	*Larix gmelinii*	*Larix sibirica*	*Larix sibirica*	*Larix gmelinii*	*Larix gmelinii*
Types	Evergreen	Deciduous	Deciduous	Deciduous	Deciduous	Evergreen	Evergreen	Evergreen	Evergreen	Evergreen	Deciduous	Deciduous	Deciduous	Deciduous	Deciduous
Location	Kasuya	Gwang–neung	Seolma-cheon	Sohung	Bikinsky	Gwang–neung	Wonsan	Hong–huaerji	Oblast	Pribay–kalsky	Laoshan	Tsenkher–mandal	Khentei	Yeravnin–sky	Buryatia
Nation [1]	JPN	ROK	ROK	DPRK	RUS	ROK	DPRK	CHN	RUS	RUS	CHN	MNG	MNG	RUS	RUS
Longitude (°)	130.550	127.149	126.955	126.032	134.373	127.162	127.320	119.993	105.334	107.985	127.340	109.068	107.316	111.411	111.728
Latitude (°)	33.650	37.750	37.939	38.391	46.770	37.748	39.149	48.200	52.185	52.504	45.200	47.835	49.100	52.397	54.960
Elevation (m)	355	340	293	169	160	425	481	836	730	620	370	1797	1021	922	1612
Aspect (%)	E	NW	NW	N	S	SW	N	SW	NE	SW	SW	N	NW	NW	N
Slope (%)	15	14	15	21	15	19	21	1	26	25	6	24	8	32	34
Sand (%)	42	50	52	42	15	50	42	89	65	55	37	31	45	34	38
Silt (%)	36	13	25	36	48	45	36	6	25	37	45	36	31	33	31
Clay (%)	22	37	23	22	37	5	22	5	10	8	18	33	24	23	21
Soil depth (m)	1.00	1.00	1.00	1.00	1.60	1.00	1.00	1.00	0.80	0.95	1.00	0.90	1.00	1.00	0.60
East horizon (°)	5	0	7	26	32	0	0	31	6	35	3	16	16	18	5
West horizon (°)	60	18	0	54	10	5	6	0	10	10	2	4	8	0	2
Forest age	140	80–200	20–40	-	80	80+	-	40–60	95	60	40–50	110	60–150	100	100
Mortality (%) [2]	1.7–2.0	1.7–2.0	2.0+	2.0+	1.7–2.0	1.4+	1.4–3.0	1.4–3.0	0.7	0.8–2.0	5.0–5.6	0.2	0.2–0.3	0.2–0.3	0.2–0.3
Fire fraction (%)	-	-	-	-	0.005	-	-	-	0.25	0.15	-	0.15	-	0.08	0.08
Options [3]	P, N	P, N	C, P, N	C, P, L	P, N	C, P, N	C, P, L	P, N	P, N	P, N	C, P, N	P, N	P, N	P, N	P, N

[1] Country code ROK, DPRK, JPN, CHN, MNG, and RUS represent South Korea, North Korea, Japan, China, Mongolia, and Russia, respectively. [2] Mainly based on Shvidenko et al. (2008) and Kim et al. (2017), but also followed site-specific information. [3] Options represent historic intervention in certain forest stands (P: Planting, C: Clear-cutting, N: Naturally preserved, L: Logging).

2.3. Data Processing

To generate sufficient bio-physical data, which is required for running the BGC-MAN (Table 2), we supplemented the data with global scale GIS data, such as the Shuttle Radar Topography Mission (STRM) and Harmonized World Soil Database (HWSD). For the nitrogen deposition values and pre-industrialization and current values, we adopted global modeling results [56,57]. Parameters of nitrogen fixation were applied from several previous studies, which suggested different nitrogen fixation values of mature oak forests (12.1–14.0 N kg ha^{-1} year^{-1}), pine (0.3–3.2 N kg ha^{-1} year^{-1}), and mixed larch hardwood (0.6–4.9 N kg ha^{-1} year^{-1}) [58–60]. For the larch forest, we followed previous studies, with consideration of the nitrogen fixation value from a mixture of western white pine and western larch [60,61]. We adopted parameters for species characteristics from Europe (the west side of the MLE), but we also adjusted some of the carbon and nitrogen allocation, as well as night time freezing temperature values [10,33,62].

Table 2. Species characteristics for running BioGeoChemistry Management (BGC-MAN).

Parameters	Units	Oak	Pine	Larch
Annual leaf and fine root turnover fraction	year^{-1}	1.0	0.3	1.0
Annual live wood turnover fraction	year^{-1}	0.7	0.3	0.7
Annual whole-plant mortality fraction	year^{-1}	0.008	0.180	0.050
Annual fire mortality fraction	year^{-1}	0.017	0.700	0.056
New fine root C:new leaf C	ratio	1.0	0.523	0.8~1.2
New stem C:new total wood C	ratio	1.29	2.5	1.2~2.2
New live wood C:new total wood C	ratio	0.120	0.059	0.1
New coarse root C:new stem C	ratio	0.250	0.290	0.23
Current growth proportion	ratio	0.5	0.5	0.5
C:N of leaves	kgC/kgN	26.9	33.1	25.8~27
C:N of leaf letters	kgC/kgN	63.3	132.0	111.9
C:N of fine roots	kgC/kgN	73.5	38.0	42.0
C:N of live wood	kgC/kgN	63.5	50.0	42.0
C:N of dead wood	kgC/kgN	450.0	1400.0	442.0
Leaf litter labile proportion	DIM	0.200	0.257	0.390
Leaf litter cellulose proportion	DIM	0.560	0.493	0.440
Leaf litter lignin proportion	DIM	0.240	0.250	0.170
Fine root labile proportion	DIM	0.340	0.252	0.300
Fine root cellulose proportion	DIM	0.440	0.493	0.450
Fine root lignin proportion	DIM	0.220	0.253	0.250
Dead wood cellulose proportion	DIM	0.704	0.710	0.760
Dead wood lignin proportion	DIM	0.296	0.290	0.240
Canopy water interception coefficient	1/LAI/d	0.038	0.051	0.041
Canopy light extinction coefficient	DIM	0.540	0.510	0.500
All-sided to projected leaf area ratio	DIM	2.0	2.6	2.6
Canopy average specific leaf area	m^2/kgC	35.0	13.0	20.3
Ratio of shaded SLA	DIM	2.0	2.0	2.0
Fraction of leaf N in Rubisco	DIM	0.0880	0.0457	0.0750
Maximum stomatal conductance	m/s	0.0018	0.0010	0.0022
Cuticular conductance	m/s	0.00004	0.000014	0.00001
Boundary layer conductance	m/s	0.005	0.09	0.008
Leaf water potential	MPa	(−0.1)–(−3.5)	(−0.5)–(−2.2)	(−0.7)–(−2.6)
Vapor pressure deficit	MPa	200–2550	50–2500	800–3200
Night time freezing temperature	C	(−1)–(−8)	(−2)–(−8)	(−8)–(−20)

For the daily weather data, we used global climate data at a grid resolution of 0.5° from the Environmental Policy Integrated Model (EPIC) and modified them through reflecting temperature lapse and horizontal angle of solar radiations using the Mountain Microclimate Simulation Model (MTCLIM) [63–66]. Because the study sites were vertically distributed, climatic characteristics of this region can be described by comparing the northernmost site (Buryatia, Russia) and the southernmost site (Kasuya, Japan) (Figure 2). In Russia, the temperature dropped to −34.5 °C in the winter, and climbed to 21.04 °C in the summer, whereas the temperature varied from −11.31 °C to 27.38 °C in Japan. The climatic variability of the MLE also could be explained by the warmth index (WI) which was used to present the distribution and suitability of vegetation [67,68]. The distribution of the WI in Kasuya, Gwangneung, Seolmacheon, Sohung, Bikinsky, Wonsan, Oblast, Pribaykalsky, Laoshan, Tsenkhermandal, Khentei, Yeravninsky, and Buryatia were 97.04, 123.36, 102.09, 142.98, 70.90, 84.12, 68.06, 62.89, 57.90, 85.57, 46.84, 63.56, 55.43, and 23.26, respectively. In addition, the accumulated precipitation in the sites in Russia and Japan was 30.41 cm and 157.29 cm, respectively. These differences contributed to different ecological transitions along this the region [5,9].

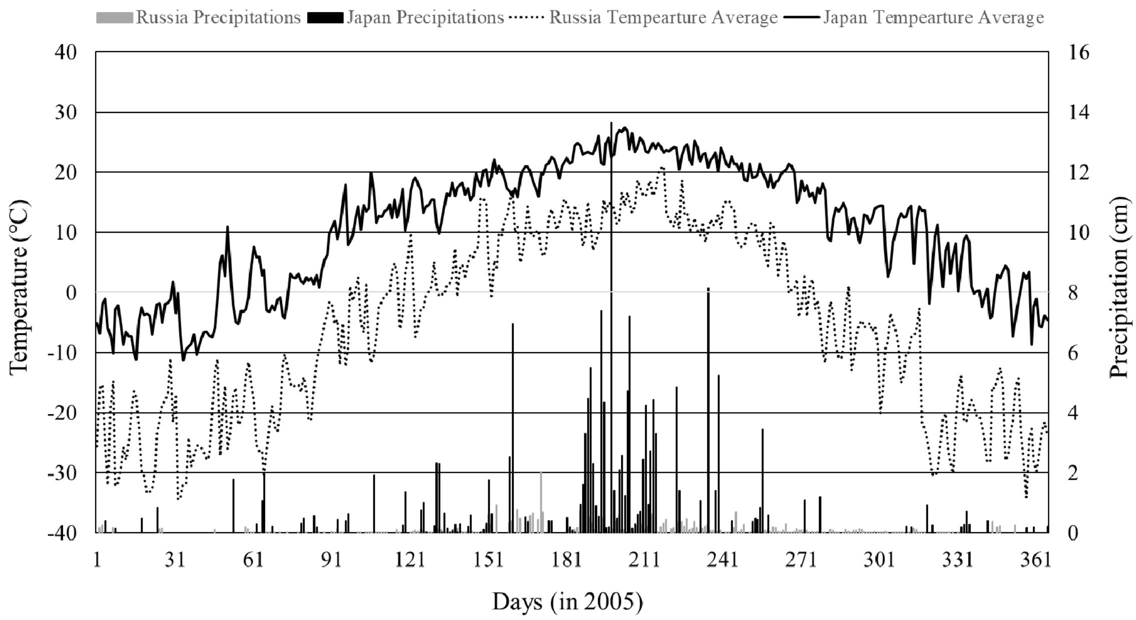

Figure 2. Climatic characteristics of the northernmost site (Buryatia, Russia) and the southernmost site (Kasuya, Japan) in 2005.

3. Results

3.1. GSV and NPP

From the BGC-MAN simulations, the estimated values of the GSVs of oak forests in Kasuya (Japan), Gwangneung (South Korea), Seolmacheon (South Korea), Sohung (North Korea), and Bikinsky (Russia) were 410, 511, 154, 65, and 153 m^3 ha^{-1}, respectively, in 2005. The GSVs of pine forests in Gwangneung (South Korea), Wonsan (North Korea), Honghuaerji (China), Oblast (Russia), and Pribaykalsky (Russia) were 392, 145, 147, 282, and 124 m^3 ha^{-1}, respectively, during the same period. The GSVs of larch forests in Laoshan (China), Tsenkhermandal (Mongolia), Khentei (Mongolia), Yeravninsky (Russia), and Buryatia (Russia) were 127, 156, 150, 227, and 116 m^3 ha^{-1}, respectively (Figure 3).

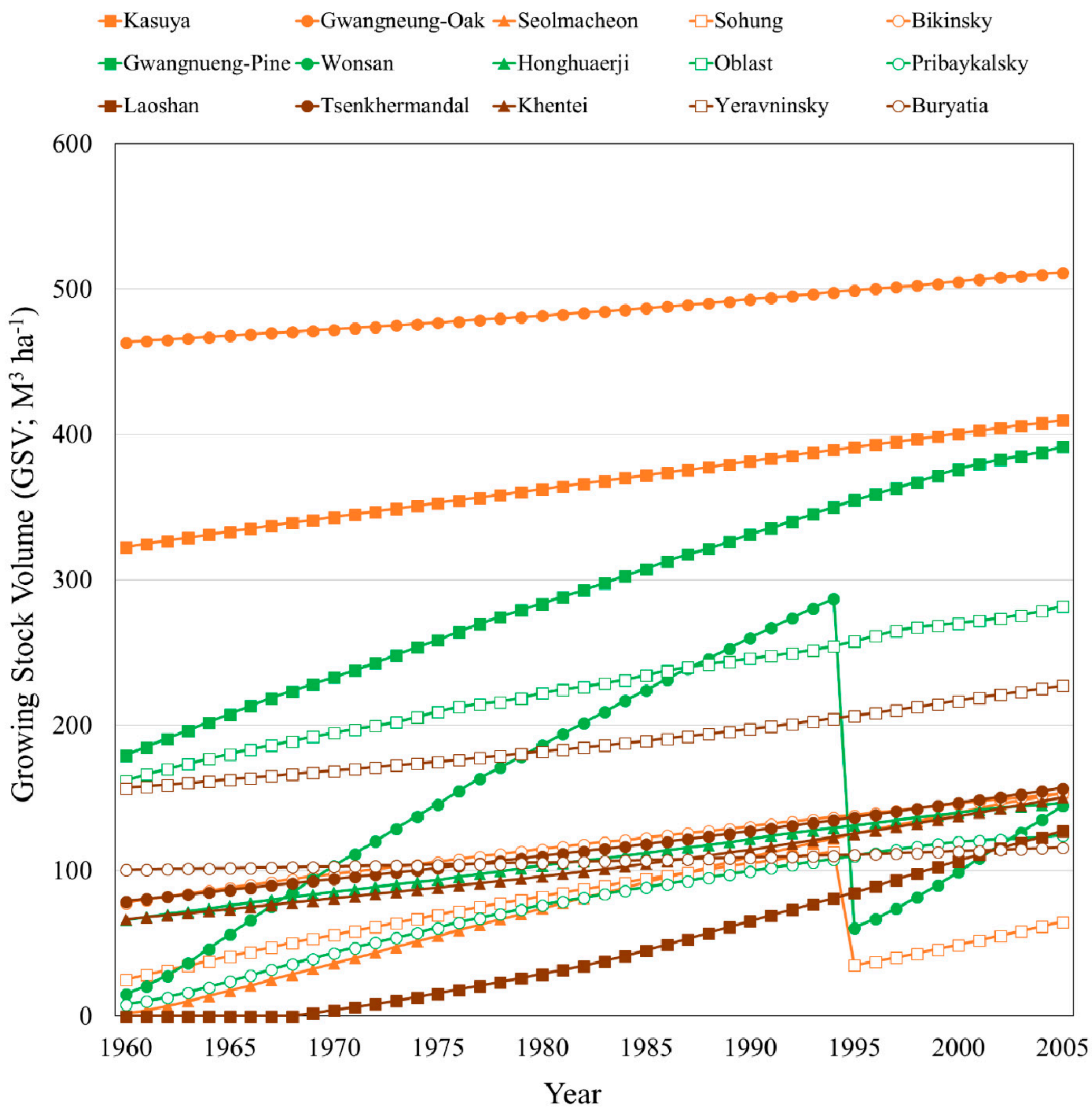

Figure 3. Growing stock volume (GSV) estimation through BGC-MAN simulations from 1960 to 2005.

Along the MLE in Northeast Asia, the GSV ranges were wide in the order of oak, pine, and larch forests. Protected forests showed much higher GSV, but GSVs in this region converged around 154 m^3 ha^{-1}. Following the same order of sites among all forest types as for the GSV results, NPP values in oak forests were also estimated to be 5.05, 5.39, 5.22, 4.18, and 3.70 Mg C ha^{-1}, respectively, in 2005. The NPP values of pine forest sites were 6.39, 6.75, 2.68, 3.49, and 2.50 Mg C ha^{-1}, and the NPPs of larch forests were 5.24, 1.12, 1.35, 1.27, and 0.49 Mg C ha^{-1}, respectively (Figure 4).

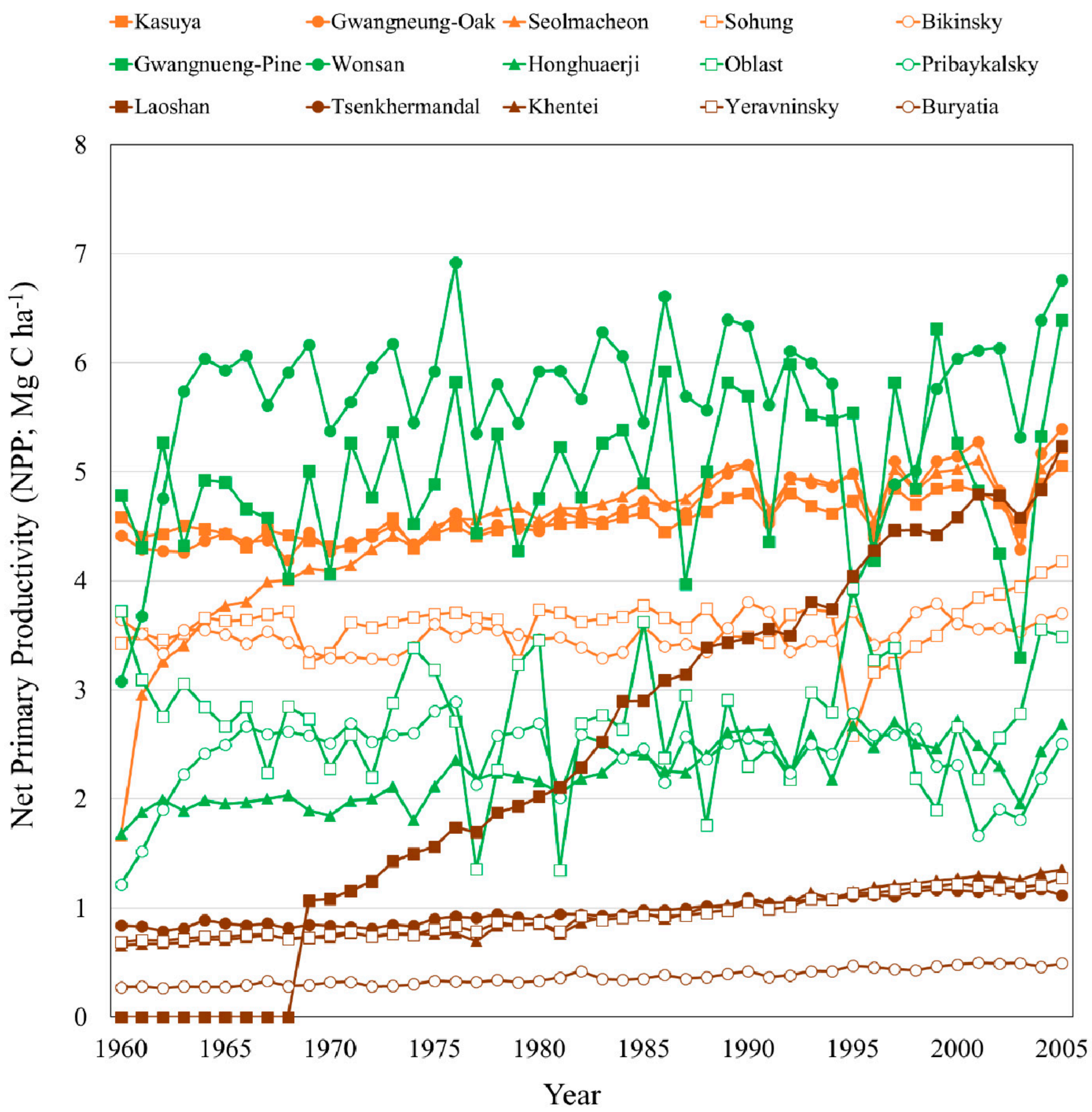

Figure 4. Net primary productivity (NPP) estimation through BGC-MAN from 1960 to 2005.

3.2. Comparing with the Literature

The estimated GSV and NPP values from the self-initialized model were compared with the previous literature. Many field studies, as well as modeling results for GSV and NPP, were available for some of our study sites, so we could compare our results with them directly. We obtained GSV and NPP values from previous reports if the data were available, however, we also assumed the values from diameter at breast height (DBH), gross primary productivity (GPP), and stand height in order to overcome the data limitation.

For the oak forests, the forest volume of Kasuya (Japan) was estimated at around 109–516 m^3 ha^{-1}, when considering some old forest stands. To estimate the value, we obtained the DBH and stand density from JaLTER and Inoue et al. (2008) [35,69], and applied the biomass expansion equation from the National Institute of Forest Science (NIFoS), Republic of Korea [70]. The tree volume of oak forests in Gwangneung (South Korea) was around 550 m^3 ha^{-1} [36], and estimated annual NPP was 4.30–6.70 Mg C ha^{-1} [42,71]. In Seolmacheon (South Korea), we could estimate the tree volume from the DBH on National Forest Inventory (NFI) data, which was around 78–159 m^3 ha^{-1} [43]. In addition, using the hydrology model named RHESSys (Regional Hydro-Ecological Simulation System), we calculated GPP as 11.93–13.96 Mg C ha^{-1} [72]. Sohung (North Korea) is one of the reforestation areas in North Korea, and a previous study assumed some forest characteristics, however, it estimated a forest volume of around 56–66 m^3 ha^{-1} during 1989–2013 [45]. Bikinsky (Russia) is located in Far East Russia near the Chinese border. The forest volume here was estimated at around 154 m^3 ha^{-1}, and annual NPP at 5.05 Mg C ha^{-1}.

The tree volume of the Gwangneung (South Korea) pine forest was estimated from a previous DBH survey at around 378–645 m^3 ha^{-1}, and a National forest inventory (NFI) plot located near the site indicated 270 m^3 ha^{-1} [38]. The predicted annual NPP was 5.37–7.20 Mg C ha^{-1} [48]. Wonsan (North Korea), which was deforested and subsequently reforested, has an annual NPP range of 4.30–6.03 Mg C ha^{-1} based on the VISIT model simulation [16]. The forest volume of Honghuaerji (China) was estimated as 117–173 m^3 ha^{-1} [50]. In the case of Oblast (Russia), the forest volume was estimated at around 282 m^3 ha^{-1}, and annual NPP was estimated at around 3.06 Mg C ha^{-1}. The GSV of forests in Pribaykalsky (Russia) was reported to be around 102 m^3 ha^{-1}, and this forest's NPP was predicted to be 2.72 Mg C ha^{-1}.

For the larch trees of Laoshan (China), which are part of an experimental forest, GSV was estimated at around 117.86 m^3 ha^{-1} in 2001, therefore a GSV value exceeding 133.36 m^3 ha^{-1} would be expected in 2005 [73]. Other model simulations estimated the 300-year cumulated NPP to be 215.4–236.6 kg m^{-2}, which can be converted to 7.18–7.89 Mg C ha^{-1} [26], but these estimations have big variations, as these were young forest stands. The GPP of the forest in Khentei (Mongolia) was reported to be around 5.62–6.10 Mg C ha^{-1} [24], and the GSV was estimated to be 64–146 m^3 ha^{-1} via tree ring survey [52,53]. The forest volume of Yeravninsky was reported to be 227 m^3 ha^{-1}, and annual GPP as 3.38 Mg C ha^{-1}. In Buryatia (Russia), the forest volume was estimated to be 117 m^3 ha^{-1}, and annual GPP as 2.81 Mg C ha^{-1} (Table 3).

Table 3. Comparing BGC-MAN simulations and previous literature.

Types	Simulation	Literature	Sources	Species	Locations
GSV (m^3 ha^{-1})	410	109–516	Estimation [35,69,70]	Oak	Kasuya
	511	550	Chae (2011) [36]	Oak	Gwangneung
	154	78–159	Kwon et al. (2009) [43]	Oak	Seolmacheon
	65	56–66	Piao et al. (2016) [45]	Oak	Sohung
	153	154	Shvidenko et al. (2008) [46]	Oak	Bikinsky
	391	378–645	Noh et al. (2013) [38]	Pine	Gwangneung
	146	117–173	Zhu et al. (2003) [50]	Pine	Honghuaerji
	282	282	Shvidenko et al. (2008) [46]	Pine	Oblast
	124	102	Shvidenko et al. (2008) [46]	Pine	Pribaykalsky
	127	118–133	Shi et al. (2001) [73]	Larch	Laoshan
	227	227	Shvidenko et al. (2008) [46]	Larch	Yeravninsky
	116	117	Shvidenko et al. (2008) [46]	Larch	Buryatia
NPP (Mg C ha^{-1})	4.28	4.30–6.05	Lim et al. (2003) [71]	Oak	Gwangneung
	5.39	4.00–6.55	Lim et al. (2010) [42]	Oak	Gwangneung
	3.70	5.05	Shvidenko et al. [46]	Oak	Bikinsky
	6.39	5.37–7.20	Eum et al. (2005) [48]	Pine	Gwangneung
	6.75	4.30–6.03	Cui et al. (2014) [16]	Pine	Wonsan
	3.49	3.06	Shvidenko et al. (2008) [46]	Pine	Oblast
	2.50	2.72	Shvidenko et al. (2008) [46]	Pine	Pribaykalsky
	5.23	7.18–7.89	Kondo et al. (2013) [26]	Larch	Laoshan
	1.28	3.38	Shvidenko et al. (2008) [46]	Larch	Yeravninsky
	0.49	2.81	Shvidenko et al. (2008) [46]	Larch	Buryatia
GPP (Mg C ha^{-1})	8.72	11.93–12.06	Shin et al. (2012) [72]	Oak	Seolmacheon
	2.85	5.62–6.10	Takagi et al. (2015) [24]	Larch	Khentei

Furthermore, the simulated NPPs were compared with the Moderate Resolution Imaging Spectroradiometer (MODIS)'s NPP (MOD17A3H) product from the National Aeronautics and Space Administration (NASA), the United States [74]. Since the MOIDIS NPP product data are available from 2000 and our study has the BGC-MAN results until 2005, the six years of overlapping NPP results were compared to find the relationship (Figure 5).

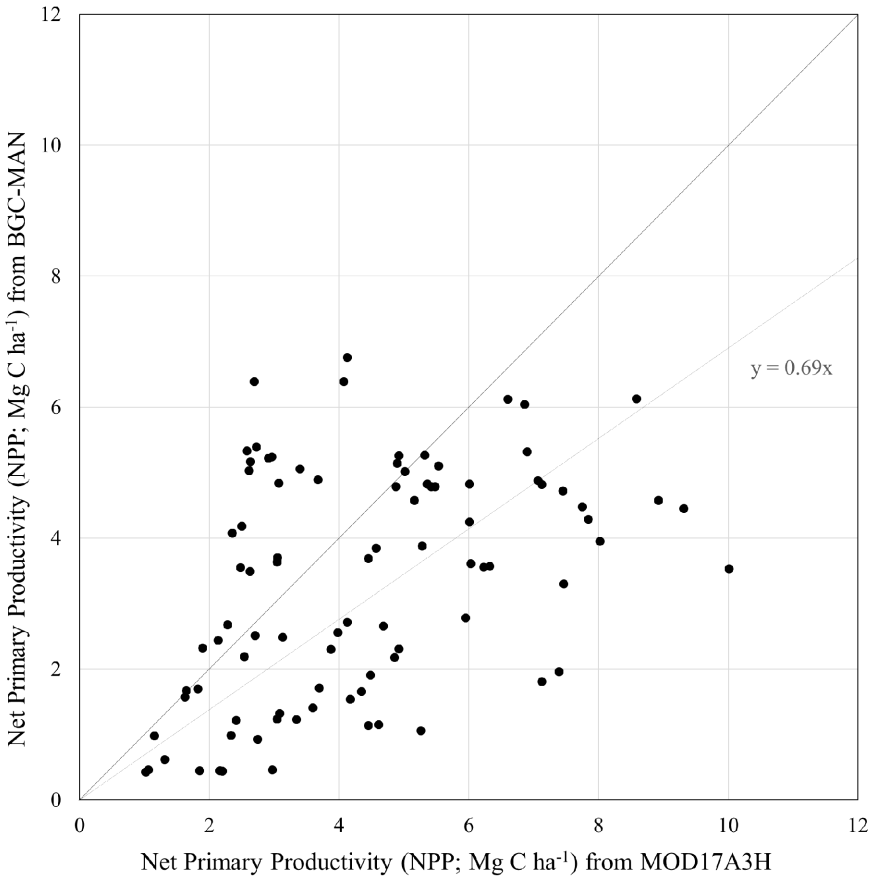

Figure 5. Relationship between the net primary productivities (NPPs) from MOD17A3H and BGC-MAN.

The NPP from the BGC-MAN simulation with climatic variations and the MODIS NPP from different characteristics of spectral reflectance may vary from time to time, but overall, they showed a positive correlation. The BGC-MAN results were underestimated compared to the NPPs from the MODIS NPP product, and the variations were shown in some larch forests because there was under estimation of the NPP from BGC-MAN.

4. Discussion

We identified changes to the forest ecosystems in the Northeast Asian MLE, and these results can explain some ecological transitions there. Under these transitions, we need to resolve expected problems through appropriate forest management and social efforts. The ecological transitions in the MLE of Northeast Asia are apparent from the annual rates of change of the forest volume and NPP. These values were estimated for a total of 15 sites under different environmental conditions and different forest management activities, and the simulation results were quite different according to latitude, site conditions, and climatic variations. At the species level, the overall BGC-MAN results from pine and oak forest sites were quite acceptable, even though we used parameterizations from European pine and oak forests to simulate *P. sylvestris*, *Q. robur*, and *Q. petraea agg.* characteristics here [31,33,34,62,75], however, there were some instances of under or over estimation. These BGC-MAN parameters were effective for *P. densiflora* and the other oak tree species in the MLE of the Northeast Asia. The GSVs of larch forests from Laoshan, Tsenkhermandal, Khentei, and Buryatia were quite similar to previous reports, but the estimated NPP was very low. This implies that, although our simulations were already based on modified biomass allocation parameters, the European parameters of *L. decidua* need to be adjusted further for the simulation of *L. Mongolica and L. Sibirica* [10,76]. This variation might be caused by some ecotypes and ecoregions on the high mountains [9,52,77]. With the heavy wind and cold temperature, larch forests in Mongolia and Russia were differentiated in stomatal conductance and the tree root system in comparison with European larch forests and larch forests in China and the Northern Korean Peninsula.

Another reason for these variations in larch forests could be the over estimation of forest fires in the self-initialized model. We assumed values for depicting forest fires, GSV, and NPP based on an inventory [46], and there might be differences in spatial resolution between the published reports and modeling stands. This means that the statistics aggregate the effect of forest disturbance and management, but the model was directly affected by the initialized parameters. When we use a process-based ecosystem model, the model usually simplifies environmental changes [10,78]. Furthermore, the model was self-initialized, so the generalization of established parameters would be limited in specific ecosystems [62]. Therefore, the model requires more adjustments in order to be suitable for application in specific ecosystems. However, the historical information of the sites was limited, and this gave rise to difficulties in the first initialization of the model. Therefore, more detailed management and human intervention data in a site-specific manner will be required in future research to apply the model to specific sites with greater accuracy.

For the study sites subjected to simulations in this study, the reported NPP values along the Northeast Asian MLE were 7.21 Mg C ha^{-1} for Mt. Jumbong, South Korea [79]; 5.16–8.04 Mg C ha^{-1} around the Korean Peninsula [16]; 2.04–6.20 Mg C ha^{-1} along the border of the Korean Peninsula and China [80]; 3.23 Mg C ha^{-1} for the boreal forests (*L. gmelinii*) of China [81]; 2.45 Mg C ha^{-1} for the larch forests of Eastern Siberia [82]; and 6.34 Mg C ha^{-1} among the East Asian regions, including our study area [23]. These estimated values also showed similar trends to our simulation results, which indicated a lower NPP at higher latitudes, although there were some limitations for larch forests. In particular, because the forest changed from temperate to boreal forest, these climatic influences are important for estimating ecosystem productivity [83,84]. In addition, there were many reports that MODIS NPPs were overestimated in Mid-Latitude region, so variations in NPP can be understood as general states [16]. In some forest stands without deforestation, such as in North Korea, the actual forest ecosystem's productivity will be more positive than our simulations, for which we assumed dramatic deforestation and forest degradation due to logging for energy and food production [13,15]. Therefore, we found that the BGC-MAN was effective in explaining not only ecological and social transitions of forests in the MLR of Northeast Asia but could also explain future estimations under various scenarios of afforestation, if the parameters and other site-specific information were available.

5. Conclusions

Through our synthetic study, we aimed to elucidate the process of applying the BGC-MAN in the MLE of Northeast Asia, and we applied the model to oak, pine, and larch forests. There were some limitations, but the parameterizations of oak and pine species from European species were acceptable in similar ecosystems in the Northeast Asian MLE when we compared the simulated results of forest NPP and GSV with literature values. However, the parameterizations for the larch species, which were distributed over the entire study region, need to be modified to be as specific as possible for the different forest sites. Overall, our simulations were representative of the differences in NPP and GSV by latitude, parameter, and climatic variations, although there were limitations due to the self-initialized model and insufficient data in this region. Under this complexity, the results explained the changes in ecosystem along the latitudinal (vertical) ecological transects as well as the effects of differences in forest management under the model uncertainties. Therefore, we can conclude that the BGC-MAN is suitable for application in this region, especially for oak and pine forests, and it also can represent the different management regimes among the different regions studied. Therefore, our results can contribute to future research attempting to apply the BGC-MAN and process-based ecological models in the MLE of Northeast Asia.

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