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The change in forest productivity and stand-dynamics under climate change in East Asian temperate forests: a case study from South Korean forests

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Abstract

The velocity and impact of climate change on forest appear to be site, environment, and tree species-specific. The primary objective of this research is to assess the changes in productivity of major temperate tree species in South Korea using terrestrial inventory and satellite remote sensing data. The area covered by each tree species was further categorized into either lowland forest (LLF) or high mountain forest (HMF) and investigated. We used the repeated Korean national forest inventory (NFI) data to calculate a stand-level annual increment (SAI). We then compared the SAI, a ground-based productivity measure, to MODIS net primary productivity (NPP) as a measure of productivity based on satellite imagery. In addition, the growth index of each increment core, which eliminated the effect of tree age on radial growth, was derived as an indicator of the variation of productivity by tree species over the past four decades. Based on these steps, we understand the species- and elevation-dependent dynamics. The secondary objective is to predict the forest dynamics under climate change using the Perfect Plasticity Approximation with Simple Biogeochemistry (PPA-SiBGC) model. The PPA-SiBGC is an analytically tractable model of forest dynamics, defined in terms of parameters for individual trees, including allometry, growth, and mortality. We estimated these parameters for the major species by using NFI and increment core data. We predicted forest dynamics using the following time-series metrics: Net ecosystem exchange, aboveground biomass, belowground biomass, C, soil respiration, and relative abundance. We then focus on comparing the impact of climate change on LLF and HMF. The results of our study can be used to develop climate-smart forest management strategies to ensure that both LLF and HMF continue to be resilient and continue to provide a wide range of ecosystem services in the Eastern Asian region.

Keywords: mountain forests, lowland forests, increment core, national forest inventory, MODIS NPP

Introduction, scope and main objectives

In the assessment of forest productivity, the distinctiveness of mountain areas should be considered. Mountains represent unique areas for the study of climatic change and the assessment of climate-related impacts. One reason for this is that the climate changes rapidly with elevation over relatively short horizontal distances; there are also rapid changes in vegetation and hydrology (Whiteman, 2000). Besides, mountain ecosystems have many endemic species due to their isolation compared to lowland vegetation communities that can occupy climatic niches spread over wider latitudinal belts. These forest systems are particularly susceptible to climate change (Dale et al., 2001) and may become more vulnerable in the future because of

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extensive drought and higher temperatures as a consequence of global change (Khabarov et al., 2016). However, as little is known about the long-term dynamics of productivity and adaptation and the mitigation potential of these forest systems in the Eastern Asian region, reliable information on productivity is required for sustainable forest management.

Large-scale studies on temperate mountain forests and their productivity are rare and regionally limited (Pretzsch et al., 2015), but necessary to support management decisions that take into account dynamic environmental conditions. The primary objective of this research is to assess the changes in productivity of major tree species at elevations between 1,800 m above sea level in South Korea using terrestrial inventory and MODIS derived NPP data. These tree species also widely distributed in East Asia regions such as Japan, North Korea, northeastern China and southeast of Russia (Suzuki et al., 2015). In addition, we compared the estimated productivity of major forest forming species in the high mountain areas with forests in the lowland.

Methodology/approach

1-1. Study area and tree species distribution

As a result of its geographical location (Fig. 1a), South Korea is affected by the Asian monsoon regime: in winter, cold air masses from the Asian continent prevail, while in summer, the country receives warm moist air masses of tropical origin. More than 60% of the country is mountainous, and the altitude of the terrain is high in the east and low in the west. Forests cover 63.6% (6,383,441 ha) of the total land area of South Korea. The Korean forest cover map (scale 1:5,000) was produced from visual interpretation of aerial photographs and National Forest Inventory (NFI) data, and it provides information on forest stands classified by tree species, diameter at breast height (dbh), age class, and canopy closure (Korea Forest Service, 2009). In this study, the area for each tree species was categorized as lowland forest (LLF) or high mountain forest (HMF). HMFs were classified as forests at elevations above 700 m based on the definition of Cool forest (Kim et al., 2019). When this definition is applied, the total HMF in South Korea is an estimated 821,634 ha based on high spatial resolution (10 m × 10 m) digital elevation model data and the forest map data (Table 1).

Table 1: Statistical summary of lowland forest (LLF) and high mountainous forest (HMF) in South Korea based on the Forest Cover Map (Korea Forest Service, 2009). Values in parentheses mean standard deviation.

Type	Tree species	Area (ha)	Ave. elevation (m)
Lowland forest (LLF)	Red pine (PD)	1,985,565	225.3 (169.7)
	Japanese larch (LK)	444,945	376.7 (180.2)
	Korean pine (PK)	228,034	316.5 (172.3)
	Cork oak (QV)	1,179,103	346.9 (152.4)
	Mongolian oak (QM)	366,523	437.0 (154.5)
High mountain forest (HMF)	Red pine (PD)	79,698	948.1 (185.0)
	Japanese larch (LK)	60,801	915.9 (96.8)
	Korean pine (PK)	17,055	926.4 (114.1)
	Cork oak (QV)	78,055	825.4 (88.9)
	Mongolian oak (QM)	359,876	923.4 (154.8)

1-2. National forest inventory – stand level and increment core data

The 5th (2006–2010) and 6th (2011–2015) NFI were conducted for the entirety of South Korean forests. The survey design consisted of systematic sampling at intervals of 4 km (longitude) × 4 km (latitude) across South

Korea (Fig. 1a). Four circular sample plots were located at the intersection of each grid line and each plot (16 m radius) covered 0.08 ha. The total inventory is around 4,200 clusters and the Korean NFI system has collected samples representing 20% of Korea's forests every year (NIFoS, 2013). The tree-ring dataset used in this study was taken from the 5th NFI. For each plot in the 5th NFI, increment cores were taken from six dominant or co-dominant trees. One core per tree was extracted from trees at breast height from a direction parallel to the slope. From each core, ring width was then measured precisely using a digital tree-ring system (up to 1/100 mm). In dendrochronological crossdating, variations in ring widths are first examined and then synchronized with all available samples from a given region (Table 2).

Table 2: Descriptive statistics of increment core samples from permanent plots of Korean National Forest Inventory (NFI) by tree species. Values in parentheses mean standard deviation.

Type	Dominant tree species	Number of increment cores	Age (year)	dbh (cm)	height (m)	Elevation (m)
Lowland forest (LLF)	Red pine (PD)	14,646	35.6 (9.8)	18.9 (7.3)	10.6 (3.2)	265.1 (142.0)
	Japanese larch (LK)	1,670	34.7 (8.4)	22.8 (7.7)	17.6 (4.7)	356.2 (157.1)
	Korean pine (PK)	1,448	27.6 (8.9)	17.4 (8.0)	10.7 (3.9)	311.3 (148.8)
	Cork oak (QV)	6,170	35.4 (11.4)	17.5 (6.4)	12.0 (3.9)	329.5 (148.2)
	Mongolian oak (QM)	6,578	31.5 (12.2)	15.5 (6.0)	10.7 (3.0)	401.5 (158.5)
High mountain forest (HMF)	Red pine (PD)	308	43.3 (16.2)	24.3 (9.2)	12.3 (3.4)	791.3 (122.2)
	Japanese larch (LK)	280	35.3 (8.8)	25.5 (8.3)	17.1 (4.9)	805.4 (112.2)
	Korean pine (PK)	184	36.1 (18.6)	20.0 (9.5)	11.4 (4.4)	840.1 (157.7)
	Cork oak (QV)	291	44.6 (15.7)	20.6 (7.7)	12.3 (3.2)	779.3 (80.2)
	Mongolian oak (QM)	2,909	42.7 (18.9)	18.7 (7.7)	11.3 (3.1)	900.6 (157.6)

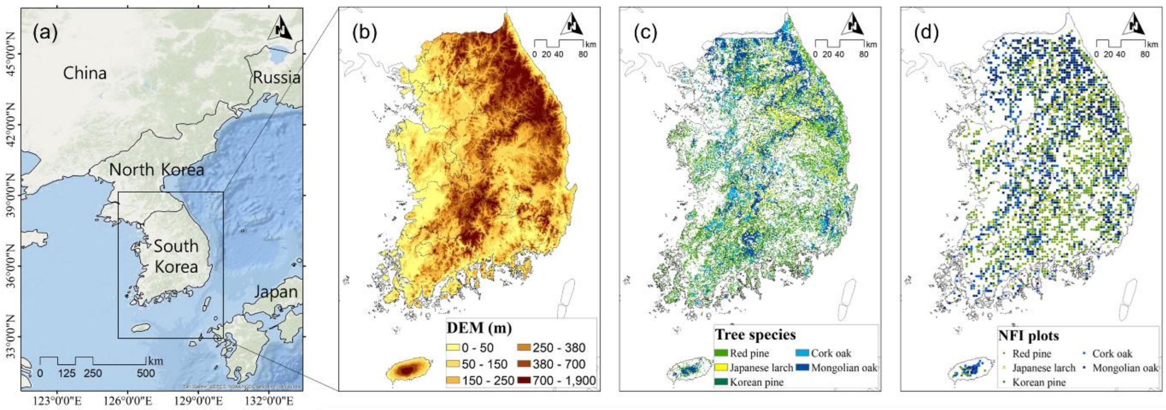

Figure 1. (a) Study area and its (b) elevation map, (c) forest type map, and (d) locations of National Forest Inventory plots.

2-1. Inventory plot-based forest productivity

Generally, forest growth data provide volume increments in m^3 ha^{-1} per growth period (Hasenauer, 2006). The growth period varies depending on the temporal measurement interval of sample plots. Our study focused on a stand-level annual increment (SAI). Between two observations for the 5th and 6th NFI, the SAI was calculated from the difference between stem volumes V_1 and V_2 of the remaining stand at both times minus the volume of trees which died (or were removed) between the observations.

$$SAI_i = \left(\frac{V_2 - V_1 - V_{removed}}{t_2 - t_1}\right) \quad (1)$$

where i is the identification number of permanent plots in the NFI system; V_1 and V_2 are stand volume (m^3 ha^{-1}) that is calculated from every observed tree with a dbh greater than 6 cm in each plot for the 5th and 6th NFI; $V_{removed}$ is stem volume of observed dead trees from t_1 to t_2; t_1 and t_2 are the specific year of field survey during the period of 5th and 6th NFI; and SAI is in m^3 ha^{-1} yr^{-1}.

2-2. Tree-ring based forest productivity

The standardized index based on dendrochronological methods is widely used as a proxy of forest productivity (Trotsiuk et al., 2016). In dendroclimatological studies of forests at various stand ages and climate-growth relationships can be biased because at any given time different trees respond differently to climate depending on their age (Besnard et al., 2018). To overcome these limitations, the C-method was adopted to remove age-related growth trends from the raw ring-width series (Biondi and Qeadan, 2008). In this study, we assessed the productivity changes for the selected major tree species during the period of 1971–2010 using the estimated tree growth based on the C-method.

2-3. Satellite based forest productivity – MODIS NPP

We used the Collection 5 MODIS MOD17A3 product that provides annual Net Primary Productivity (NPP) estimate at 1 km × 1 km (Running et al., 2004). The annual NPP is calculated from GPP by subtracting the two autotrophic respiration components – i.e., (i) maintenance respiration R_m and (ii) growth respiration R_g – and summing up over a year to get annual values:

$$\mathrm{NPP} = \sum_{i=1}^{365} GPP - R_m - R_g \quad (2)$$

Results

1. Productivity changes from recursive NFIs

We calculated the SAI for each tree species by comparing the 5th and 6th NFIs (Fig. 2a). The mean SAIs for PD, LK, PK, QA, and QM in LLFs were estimated as 5.20, 6.56, 7.98, 4.74, and 4.02 m^3 ha^{-1} yr^{-1}, respectively. During the same period, in HMFs, the mean SAIs for these species were estimated as 5.46, 9.89, 11.58, 4.57, and 3.94, respectively. For LK and PK, we found a relatively large difference in the SAI between LLFs and HMFs. These growth differences for LK and PK over the altitudinal gradient were illustrated significantly in the result of Dunnett's two-tailed test. The t-value for LK and PK were estimated -2.295 (p-value: 0.024) and -2.079 (p-value: 0.047), respectively. The differences among tree species and between LLF and HMF are also shown in the results of MAI values (Fig. 2b). The mean MAIs for PD, LK, PK, QA, and QM in LLFs changed from 4.42, 5.82, 4.72, 3.53, and 3.61 m^3 ha^{-1} yr^{-1} in the 5th NFI to 4.54, 5.93, 5.28, 3.77, and 3.70 m^3 ha^{-1} yr^{-1}, in the 6th NFI, respectively. During the same period, in HMFs, they increased from 5.13, 4.89, 7.63, 3.19, and 3.54 m^3 ha^{-1} yr^{-1} to 5.16, 5.86, 8.08, 3.39, and 3.62 m^3 ha^{-1} yr^{-1}, respectively. Our results show that the MAIs for every tree species in both LLFs and HMFs increased between the 5th and 6th NFIs.

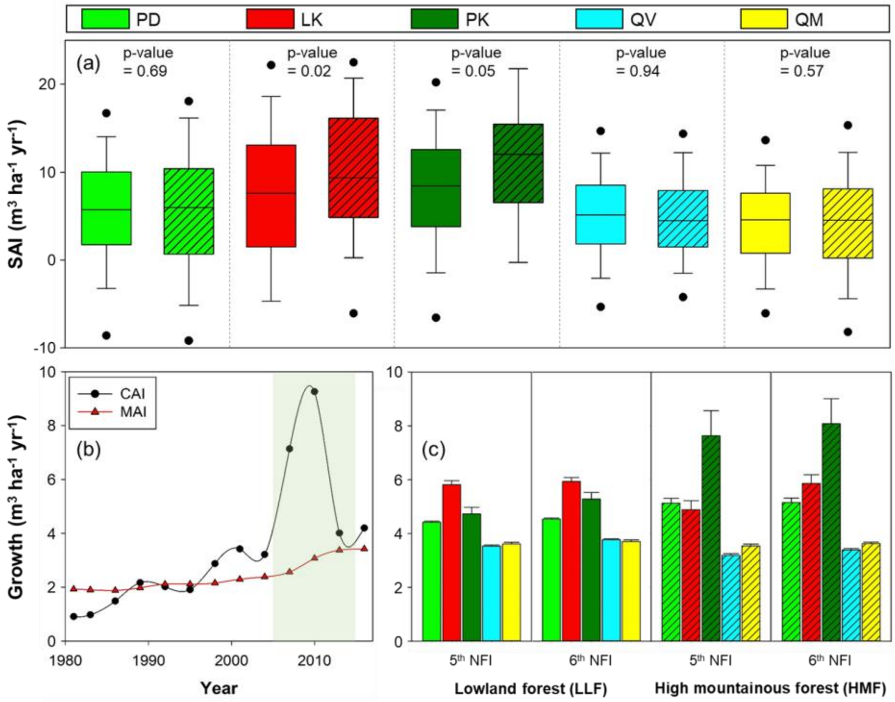

Fig. 2: (a) The average stand-level annual increment (SAI) of major Korean tree species in lowland forests (LLFs) and high mountain forests (HMFs). The plain boxes represent LLFs and the hatched line boxes represent HMFs. (b) the change in mean annual increment (MAI) and current annual increment (CAI) during 1980–2017 are from 2018 Statistical Yearbook of Forestry (Korea Forest Service, 2018a). The shaded area of (b) represents the field survey periods for the 5th and 6th Korean national forest inventories (NFI). (c) MAI of each tree species at LLFs and HMFs based on the 5th and 6th NFI.

2. Productivity changes from tree-ring chronologies

Results show that the observed annual radial growth of all tree species has gradually decreased from 1971 to 2010 (Fig. 3a, c, e, g, i). The results confirmed the general pattern of sigmoidal age-growth relation that is the width of tree rings decreases with age due to the increase in stem area as trees age (e.g., Kim et al., 2019), and yet, the rate of change varies across both tree species and forest types. We found negligible differences between the annual growth rates of PD and LK in LLFs and PD and LK in HMFs (Fig. 3a, c), while PK, QV, and QM have distinct growth discrepancies between the two elevation classes (Fig. 3e, g, i). Species- and elevation-dependent tree growth changes are more clearly observed when the age effect is removed (Fig. 3b, e, f, h, j). Our results suggest that the tree growth of the major coniferous tree species (i.e., PD, LK and PK) in the 1970s was higher than the growth rate in the 2000s.

3. Productivity changes from satellite observed NPP

Based on the MODIS NPP product, the NPP of the five forest types was calculated during study periods of 2001–2015. Fig. 4 showed the spatio-temporal changes of NPP over five-year periods for South Korean forests from 2001 to 2015. The mean NPP in the forest area was estimated as 6.458 (± 1 Std. dev; 1.056) Mg C ha^{-1} yr^{-1} for 2001–2005, 6.364 (± 1.064) Mg C ha^{-1} yr^{-1} for 2006–2010, and 6.216 (± 1.036) Mg C ha^{-1} yr^{-1} for 2011–2015. These values are consistent with previous research at global and national scales (Running et al., 2004; Yoo et al., 2013). The total NPP in South Korean forests had decreased by 3.74% between the periods 2001–2005 and 2011–2015. However, the NPP slightly increased in the southern part of South Korea during the same period (Fig. 4d).

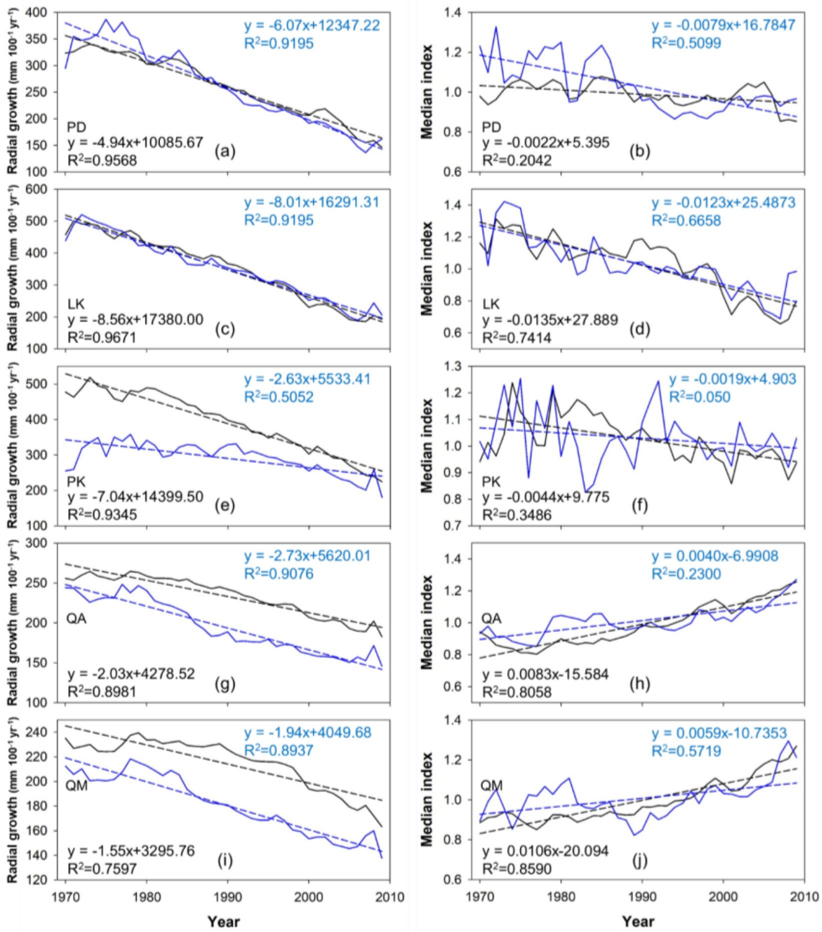

Fig. 3: Observed mean annual radial growth for major Korean tree species (a, c, e, g, i). The tree-ring chronologies obtained using the C-method for each tree species at the Korean national forest inventory plots (b, d, f, h, j). The black solid lines represent LLFs and the blue solid lines represent HMFs. The dotted lines represent the best-fit linear model for radial growth or median index indicating the trend over time. PD, LK, PK, QA, and QM stand for Red pine, Japanese larch, Korean pine, cork oak, and Mongolian oak, respectively.

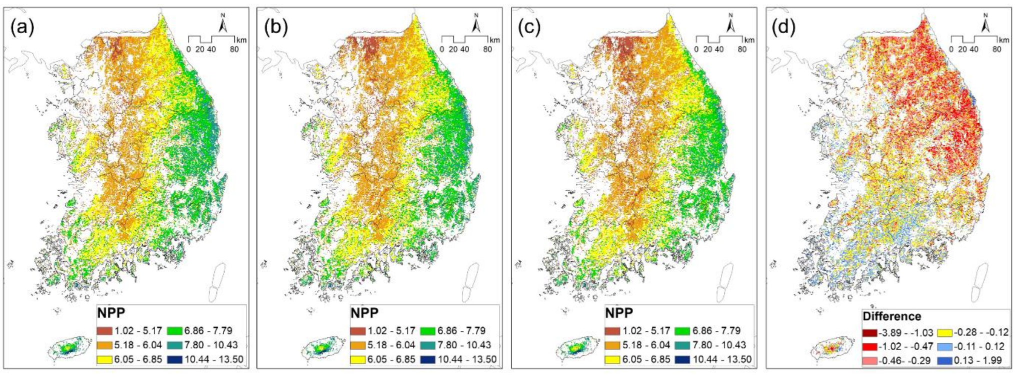

Fig. 4: The estimated NPP from MODIS during (a) 2001–2005, (b) 2006–2010, and (c) 2011–2015. (d) is the difference between (c) and (a).

For ENF, the mean NPP of HMF was higher than that of LLF, while the mean NPP of DBF in mountainous regions was lower than the mean NPP of DBF in lowland regions. These results suggest two important patterns: (1) the trend of forest productivity is affected by forest types, and (2) the change of forest productivity largely depends on the elevation. It is also noteworthy that the variation in NPP (Std. dev: 0.359 in ENF and 0.329 in DBF) in HMF was larger than that in LLF (Std. dev: 0.305 in ENF and 0.303 in DBF) (Fig. 5). This indicates that the HMF has responded more to the recent climate change in South Korea than the LLF.

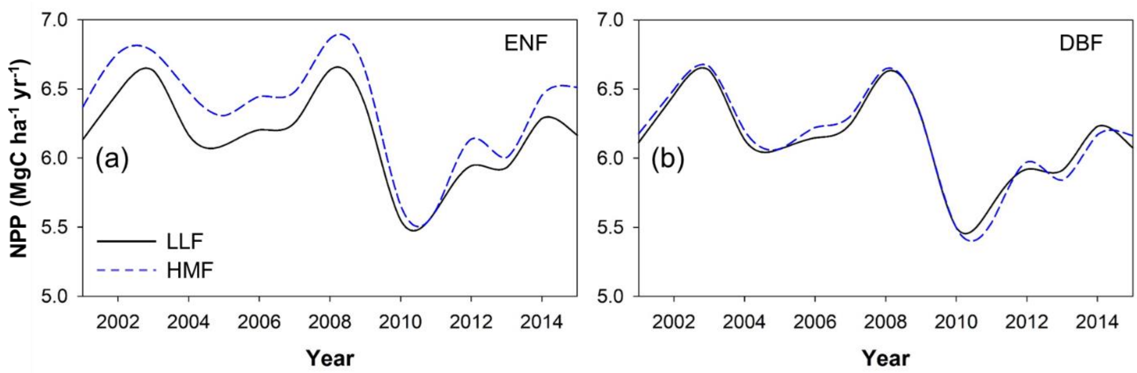

Fig. 5: The mean estimated net primary production (NPP) of (a) evergreen needleleaf forest (ENF) and (b) deciduous broadleaf forest (DBF) by tree species and forest types during 2001–2015.

Discussion

Our multi-data based results from tree increment core, NFI, and satellite data clearly showed species- and elevation-dependent patterns of Korean forest productivity. It is worth noting that we were able to discern the consistent patterns of productivity differences across tree species and elevation from ground and satellite data despite of the coarser spatial resolution and forest type classification in MODIS analysis. Our results suggest that tree increment core data are invaluable for investigating long-term forest productivity changes and its sensitivity to changing climate conditions (e.g., Babst et al., 2012). This tree core data in our analysis clearly showcased species- and elevation-dependent patterns of productivity changes. For example, the average productivity for the major coniferous tree species (PD, LK, and PK) in South Korea has decreased gradually over the past 40 years. This obvious pattern is likely explained by warming induced water stress which is one of the widely reported global phenomenon in temperate forests (Allen et al., 2010; Adams et al., 2017). Our previous efforts reported in Kim et al. (2017a,b) confirmed tree growth reduction and mortality increase of dominant coniferous tree species over South Korea since 2000. These studies further investigated and concluded that climate change, particularly intensified spring drought associated with increasing temperature, is a main driver underlying the species-specific growth and compositional changes (Kim et al., 2017a). This species-specific growth pattern is a general view in the context of vegetation-climate interaction implying that continuing warming is no longer stimulator of tree growth in South Korean coniferous forests due to already unfavorable climate conditions for those forests. Babst et al. (2013) used large-scale tree ring datasets and their findings supported site- and species-dependent climate constraints on tree growth – i.e., trees at high latitudes/altitudes are generally sensitive to temperature, while trees at low latitudes/altitudes with drier conditions are generally sensitive to precipitation.

Conclusions

Our results can be summarized as follows: (1) differences in the tendency of forest productivity change depend on tree species and elevation of forest areas such as LLF and HMF; (2) The MODIS NPP product is useful to assess the forest productivity of national scale. However, it is not enough to apply tree species level.

Therefore, the monitoring data from periodic field surveys is required to complement remote sensing data such as MODIS product. Besides, the development of the method for the target tree species or country will be useful to improve the assessment of forest productivity; (3) the forest productivity of studied tree species is different between LLF and HMF. The forest productivity for major coniferous tree species of South Korea was estimated to be higher in HMF than in LLF. The opposite would be found for oak tree species; (4) overall forests productivity of South Korean forest has decreased gradually since the 2000s, except oak forests of which productivity increased during the same period. These results together with the additional composition analysis suggest that species- and elevation-dependent tree growth and productivity changes under rapid environmental changes lead to compositional shift in Korean forests. The changes will affect the quality and quantity of plant and wildlife habitats (Lindner et al., 2010). Therefore, spatio-temporal forest management strategies specified by tree species and altitudinal zoning are needed for sustainable development and to cope with climate change in South Korea.

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