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**Keywords:** mountain forests, lowland forests, net primary productivity, increment core, national forest inventory, MODIS, stand-level annual increment

**Abstract**

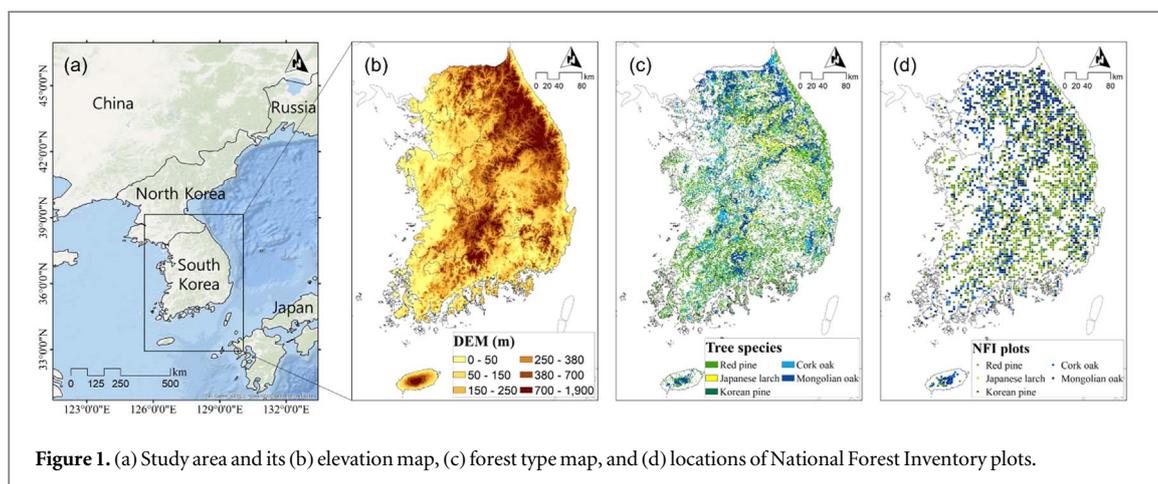
The velocity and impact of climate change on forest appear to be site, environment, and tree species-specific. The primary objective of this research is to assess the changes in productivity of five major temperate tree species (*Pinus densiflora*, PD; *Larix kaempferi*, LK; *Pinus koraiensis*, PK; *Quercus variabilis*, QV; and *Quercus mongolica*, QM) 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 MODerate resolution Imaging Spectroradiometer (MODIS) net primary productivity 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 in primary productivity by tree species over the past four decades. Based on our result from NFI plots and increment core data sets, the productivity of PD, QV, and QM in LLF was relatively higher than those in HMF, while LK and PK in HMF were more productive than lowland ones. Our analysis of the increment core data revealed a contrasting pattern of long-term productivity changes between coniferous and oak tree species. While the productivity of oak tree species tended to increase after the 1990s, the productivity in coniferous forests tended to decrease. These differences across forest types and their altitudinal classes are also noticeable from the MODIS product. The results of our study can be used to develop climate-smart forest management strategies to ensure that the forests continue to be resilient and continue to provide a wide range of ecosystem services in the Eastern Asian region.

**1. Introduction**

Forests play an important role in the preservation of a sustainable society, ecosystems, and the environment; this is especially the case considering the risk posed to the environment by global warming (Rudel *et al* 2005, Lindner *et al* 2010, Kim *et al* 2019). More specifically, forests provide a number of ecosystem services

including timber production, carbon sequestration, recreation, preservation of biodiversity, water management, and non-wood forest products. These services are closely related to forest productivity (Isbell *et al* 2009, Liang *et al* 2016).

Productivity estimates are important measures to characterize the mass budget of a forest ecosystem. Understanding changes in spatial patterns of



productivity and assessing its sensitivity to changes in the regional and global environment are important first steps in diagnosing or projecting terrestrial ecosystem feedbacks to such changes. Forest productivities have been measured not only using terrestrial data from long-term inventory and experimental plots but also using remotely sensed data (Dong *et al* 2003, Masek and Collatz 2006, Hilmer *et al* 2019). Net primary productivity (NPP) is widely used as an indicator of vegetation function and productivity in carbon cycle (Nemani *et al* 2003, Running *et al* 2004; Holm *et al* 2017). In principle, large scale NPP measures are currently provided by remotely sensed methods, such as the MODerate resolution Imaging Spectroradiometer (MODIS) NPP algorithm.

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, Pearson and Dawson 2003, Kim *et al* 2019) and may become more vulnerable in the future because of extensive drought and higher temperatures as a consequence of global change (van Mantgem *et al* 2009, Anderegg *et al* 2012, Seidl *et al* 2014, McIntyre *et al* 2015, 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.

Forest area covers about 63.7% (6369 000 ha) of the total land area of South Korea, and 60% of the terrain consists of mountains and uplands separated by deep, narrow valleys, with complex terrain. Currently,

many irregular phenomena have occurred in South Korean forests due to climate change (Kim *et al* 2017a, 2017b, Lim *et al* 2018). Based on previous research and monitoring data, a decreased growth rate and increased mortality among most of the major coniferous tree species in South Korea has been observed (Kim *et al* 2017a, 2017b). In addition, shifting tree species suitability and increased damage from insects have been observed in Korean forests (Kim *et al* 2017b). The velocity and impact of climate change appears to be site, environment, and tree species-specific (Kim *et al* 2019). Therefore, it is important to continue to monitor changes in forests in response to climate change (Kraxner *et al* 2017, Reyer *et al* 2017).

Large-scale studies on temperate mountain forests and their productivity are rare and regionally limited (Peters *et al* 2013, 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 (red pine (*Pinus densiflora*) Japanese larch (*Larix kaempferi*), Korean pine (*Pinus koraiensis*), cork oak (*Quercus variabilis*), and Mongolian oak (*Quercus mongolica*; hereinafter referred to as PD, LK, PK, QV, and QM, respectively)) at elevations between 1800 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, north-eastern China and southeast of Russia (Shao *et al* 1994, Ishikawa *et al* 1999, 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.

## 2. Materials and methods

### 2.1. Spatial data for South Korean forests

#### 2.1.1. Study area and tree species distribution

As a result of its geographical location (figure 1(a)), South Korea is affected by the Asian monsoon regime: in winter, cold air masses from the Asian continent

**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)	1985 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)	1179 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)

prevail, while in summer, the country receives warm moist air masses of tropical origin (Min *et al* 2015). 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% (6383 441 ha) of the total land area of South Korea.

The Korean forest cover map (scale 1:5000) 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).

### 2.1.2. NFI—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 (figure 1(a)). 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 4200 clusters and the Korean NFI system has collected samples representing 20% of Korea's forests every year (National Institute of Forest Science; NIFoS 2011). Forest stand characteristics (tree species, age, height, dbh, site index, and number of trees) and topographical factors (coordinates, elevation, slope, and aspect) were measured at all sites (NIFoS 2011). The stand volume of each plot is calculated based on the sum of stem volume for every tree with a diameter greater than 6 cm in each plot.

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) by the NIFoS (2011). In dendrochronological crossdating, variations in ring widths are first examined and then synchronized with all available samples from a given region (table 2).

## 2.2. Assessment of short-term forest productivity

### 2.2.1. Inventory plot-based forest productivity

Forest growing stock is well known as one of the major indicators of forest productivity (Hasenauer *et al* 2012). Generally, forest growth data provide volume increments in  $\text{m}^3 \text{ha}^{-1}$  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.

$$\text{SAI}_i = \left( \frac{V_2 - V_1 - V_{\text{removed}}}{t_2 - t_1} \right), \quad (1)$$

where  $i$  is the identification number of permanent plots in the NFI system;  $V_1$  and  $V_2$  are stand volume ( $\text{m}^3 \text{ha}^{-1}$ ) that is calculated from every observed tree with a dbh greater than 6 cm in each plot for the 5th and 6th NFI;  $V_{\text{removed}}$  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  $\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$ . In what follows, the differences in productivities of each tree species between LLF and HMF were assessed using Dunnett's two-tailed test. In this analysis, SAIs in LLF are considered as a control group. In addition, we estimated the current annual increment (CAI) and mean annual increment (MAI) during 1980–2017 based on the national forest statistics (Korea Forest Service 2018) and compared between these values and estimated SAIs. CAI is the increment of a stand volume during each year, while MAI informs on the growth over the whole period from origin to a specific age.

**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)	1670	34.7 (8.4)	22.8 (7.7)	17.6 (4.7)	356.2 (157.1)
	Korean pine (PK)	1448	27.6 (8.9)	17.4 (8.0)	10.7 (3.9)	311.3 (148.8)
	Cork oak (QV)	6170	35.4 (11.4)	17.5 (6.4)	12.0 (3.9)	329.5 (148.2)
	Mongolian oak (QM)	6578	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)	2909	42.7 (18.9)	18.7 (7.7)	11.3 (3.1)	900.6 (157.6)

### 2.2.2. Tree-ring based forest productivity

The standardized index based on dendrochronological methods is widely used as a proxy of forest productivity (Fritts and Swetnam 1989, 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 (Szeicz and MacDonald 1994, 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). Of the standardization methods based on the biological age of tree rings, the C-method has the advantage of calculating an expected growth curve for each measurement series, whereas the regional curve standardization applies the same growth curve to all samples. The median index is calculated by the C-method, and is defined as the ratio of the measured ring width to expected ring width at a certain age given the environmental conditions at the tree's location. A detailed description of the analysis processes is given in 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.

### 2.2.3. Satellite based forest productivity—MODIS NPP

We used the Collection 5 MODIS MOD17A3 product that provides annual NPP estimate at  $1 \text{ km} \times 1 \text{ km}$  (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:

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

The MODIS GPP algorithm is based on the radiation use efficiency concept and it is defined as follow:

$$\text{GPP} = LUE_{\max} \times 0.45 \times SW_{\text{rad}} \times \text{FPAR} \times f_{\text{VPD}} \times f_{T_{\min}}, \quad (3)$$

where  $LUE_{\max}$  is the maximum light use efficiency,  $SW_{\text{rad}}$  is the short-wave solar radiation load at the surface of which 45% is photosynthetically active, FPAR is the fraction of absorbed PAR (photosynthetic active radiation) from the MOD15 LAI/FPAR product.  $f_{\text{VPD}}$  and  $f_{T_{\min}}$  are multipliers between 0 and 1 addressing water stress due to vapor pressure deficit (VPD) and low temperature limits ( $T_{\min}$ , daily minimum temperature). Note that we used two dominant forest biome types (i.e. ENF and DBF) for MODIS NPP analysis rather than applying tree species scheme used in individual or stand level data analysis.

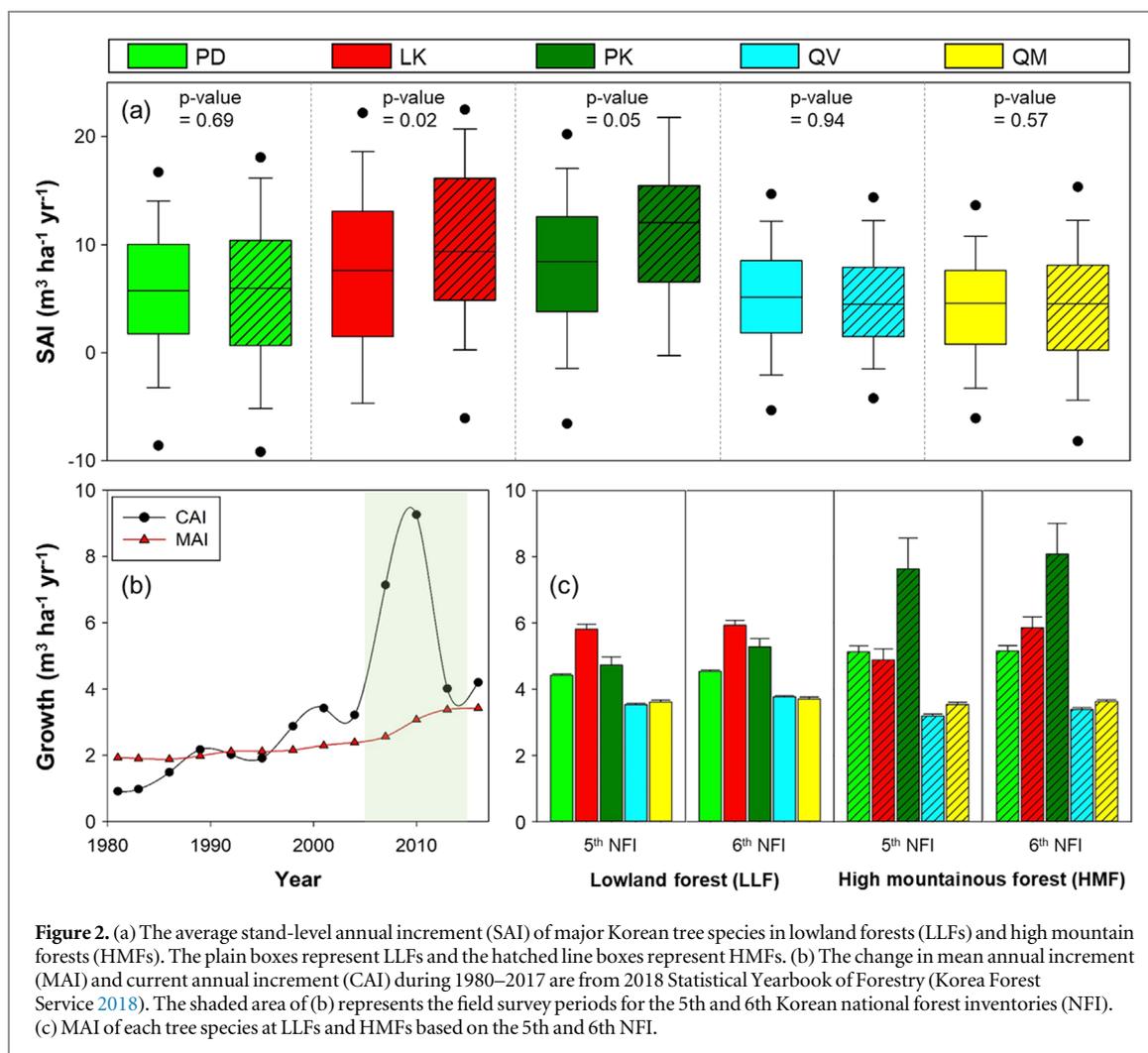
## 3. Results

### 3.1. Productivity changes from recursive NFIs

We calculated the SAI for each tree species by comparing the 5th and 6th NFIs (figure 2(a)). The mean SAIs for PD, LK, PK, QA, and QM in LLFs were estimated as 5.20, 6.56, 7.98, 4.74, and  $4.02 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ , 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 mean SAIs of all tree species in LLFs and HMFs were  $4.89$  and  $5.09 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ , respectively, and the standard deviation of SAIs in HMFs was larger than that of LLFs, implying more heterogeneous growth pattern of HMFs.

Figure 2(b) showed the change of mean CAI and MAI in South Korean forests from 1980 to 2017. The general pattern of tree growth is that the CAI remains slow in the 'stand initiation phase', becomes faster beyond that, and shoots up in 'stem-exclusion phase' to 'mature phase' until it reaches a peak, after which CAI declines (Oliver *et al* 1996). The MAI, on the other hand, increases at a steady rate in comparison to the CAI. Interestingly, CAIs were less than MAIs during the 1980s (figure 2(b)). The main reason for this is that more than 250 million ha of the forest had been reforested during the 1970s and 1980s (Bae *et al* 2014). Therefore, the forests were young and CAIs were low during that period.

The differences among tree species and between LLF and HMF are also shown in the results of MAI values (figure 2(b)). The mean MAIs for PD, LK, PK, QA, and QM in LLFs changed from 4.42, 5.82, 4.72, 3.53, and  $3.61 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$  in the 5th NFI to 4.54, 5.93, 5.28, 3.77, and  $3.70 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ , in the 6th NFI, respectively. During the same period, in HMFs, they increased from 5.13, 4.89, 7.63, 3.19, and  $3.54 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$  to 5.16, 5.86, 8.08, 3.39, and  $3.62 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ , respectively. Our results show that the MAIs for every tree species in both LLFs and HMFs increased between the 5th and 6th NFIs. This result is well matched with the current trend in mean MAI in figure 2(c). The mean MAI of South Korean forests has been estimated to be gradually increasing since the 1980s. The MAI of forests should begin to decline when the forest reaches maturity or over maturity, and at this stage the change in growth rate would be negative. Therefore, the optimal rotation age is when the CAI and MAI are equal. The optimal rotation times for the major tree species in South Korea are in the range of 50–70 years (Korea Forest Service 2015). Based on the 6th NFI, the mean stand age was calculated as 39.03 years. Therefore, it is reasonable that MAIs for each tree species in the 6th



**Figure 2.** (a) The average stand-level annual increment (SAI) of major Korean tree species in lowland forests (LLFs) and high mountainous 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 2018). 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.

NFI are higher than they were in the 5th NFI. In our results, the SAI of each tree species was higher than the MAIs of each tree species. This result is also in concordance with figure 2. The definition and methods for SAI are similar to CAI. According to national statistics, the CAIs were estimated to be higher than the MAIs after the 1990s.

### 3.2. Productivity changes from tree-ring chronologies

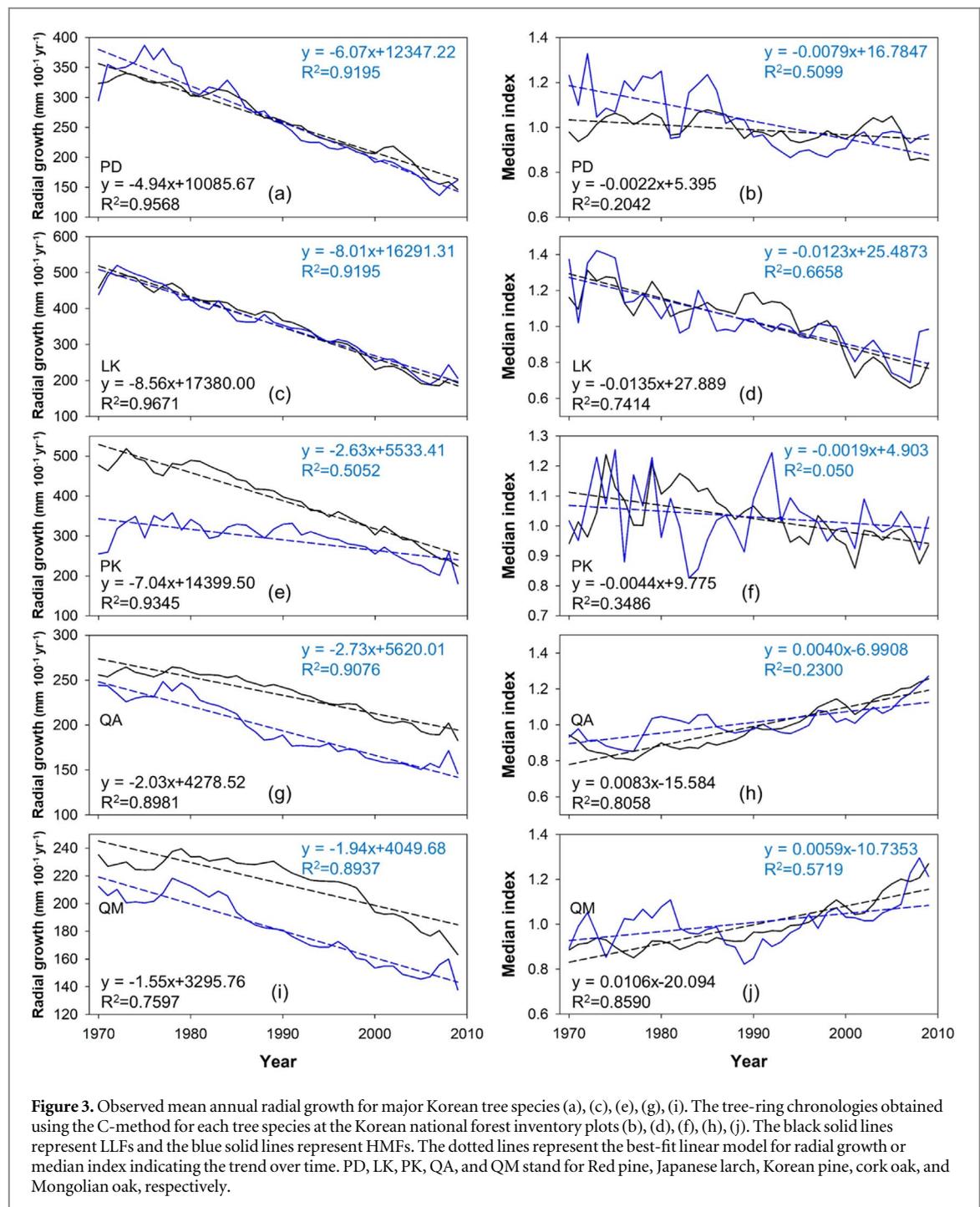
Results show that the observed annual radial growth of all tree species has gradually decreased from 1971 to 2010 (figures 3(a), (c), (e), (g), (i)). The results confirmed the general pattern of sigmoidal age-growth relation that is the width of tree rings decreases with age due to the increase in stem 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 (figures 3(a), (c)), while PK, QV, and QM have distinct growth discrepancies between the two elevation classes (figures 3(e), (g), (i)).

Species- and elevation- dependent tree growth changes are more clearly observed when the age effect

is removed (figures 3(b), (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. The decreasing productivity pattern of LK and PK is more obvious in LLF than HMF. However, the productivity of oak tree species (QV and QM) has gradually increased since the 1980s. There was a more rapid increase of tree growth for both QV and QM in HMF than LLF during the 1971–2010 period. These results clearly suggest species- and elevation- dependent contrasting pattern of tree growth changes in South Korea. This conforms the results of the NFI plot data analysis described in section 3.1.

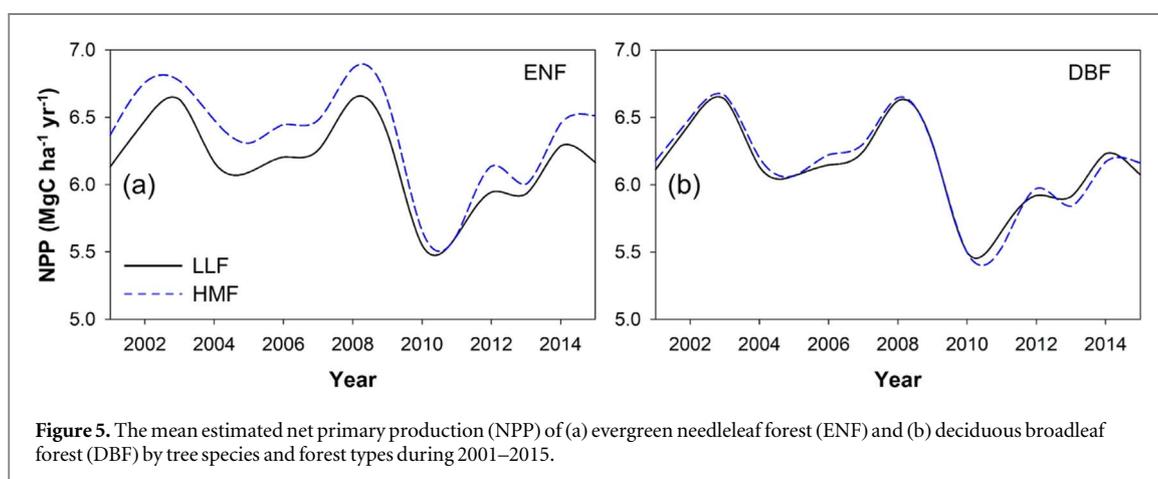
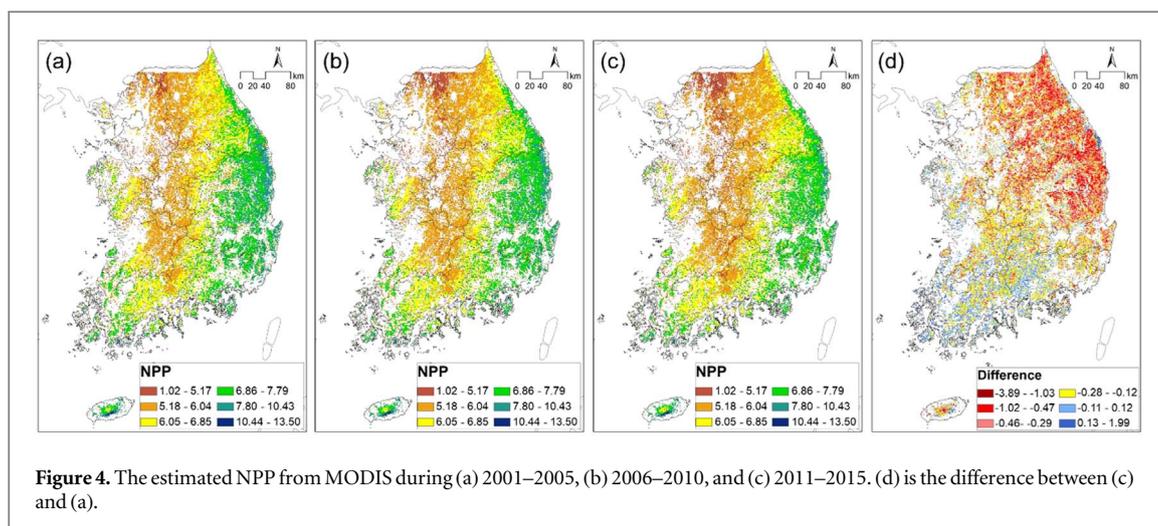
### 3.3. Productivity changes from satellite observed NPP

Based on the MODIS NPP product, the NPP of the five forest types was calculated during study periods of 2001–2015. Figure 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 ( $\pm 1$  Std. dev; 1.056) Mg C ha<sup>-1</sup> yr<sup>-1</sup> for 2001–2005, 6.364 ( $\pm 1.064$ ) Mg C ha<sup>-1</sup> yr<sup>-1</sup> for 2006–2010, and 6.216 ( $\pm 1.036$ )



Mg C ha<sup>-1</sup> yr<sup>-1</sup> for 2011–2015. These values are consistent with previous research at global and national scales (Running *et al* 2004; Yoo *et al* 2013). Examining the spatial distribution of NPP in figure 4, the estimated NPP was higher in the southeast region of South Korea throughout the 2001–2015 period in comparison to other regions. However, a decreasing trend in NPP was also found in this region (figure 4(d)). 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 (figure 4(d)).

Figure 5 shows the estimated mean NPP for the ENF and DBF forest types in lowland and mountainous regions during 2001–2015. Synchronized inter-annual variation of NPP was found across forest types and elevation classes, indicating a large-scale climate driven annual NPP variation over the Korean peninsula. The most obvious pattern in the MODIS NPP for overall forests is a very significant drop from 2009 to 2010 that can be explained by drought. From autumn 2008 to spring 2010 except summer 2009, a historical drought occurred in South Korea (Korea Meteorological Administration; KMA 2010). The mean precipitation in autumn 2009 and spring 2010 were 143.1



and 231.3 mm, much less than the average mean autumn (258.1 mm) and spring precipitation (267.4 mm) for the past 30 years (1989–2018) (KMA 2018). Therefore, the entire region of South Korea experienced a severe drought that led to regional water shortages and influenced the use of water, including for agricultural and household activities (Kim *et al* 2014). In addition, natural ecosystems were damaged by the drought and vegetation indices on the national scale were low (Nam *et al* 2015).

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) (figure 5). This indicates that the HMF has responded more to the recent climate change in South Korea than the LLF.

#### 4. Discussion and conclusions

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 (table 3). 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. Wang *et al* 2004, 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, McDowell *et al* 2010, Adams *et al* 2017). Our previous efforts reported in Kim *et al* (2017a, 2017b) confirmed tree growth reduction and mortality increase of dominant

**Table 3.** Ratios of high mountain forest productivity to lowland forest productivity by three data sets.

Data	Research period	HMF-to-LLF				
		Red pine	Japanese larch	Korean pine	Cork oak	Mongolian oak
MODIS NPP	2001–2015		1.033 <sup>a</sup>			1.003 <sup>b</sup>
NFI plot	2006–2015	1.046	1.470	1.333	0.967	0.925
Increment core	2001–2009	1.003	1.118	1.058	0.963	0.980

Note. HMF: High mountain forest, LLF: Lowland forest

<sup>a</sup> The value for Evergreen Needleleaf Forest.

<sup>b</sup> The value for Deciduous Broadleaf Forest.

**Table 4.** Descriptive statistics of observed dominant tree species change in a permanent plot of the Korean National Forest Inventory (NFI).

Type	Dominant tree species	Number of plots				The rate of change (%)
				Changed to other species	Changed from other species	
		5th NFI	6th NFI			
Lowland forests (LLF)	Red pine	3028	2891	159	22	−4.52
	Japanese larch	287	270	23	6	−5.92
	Korean pine	197	182	20	5	−7.61
	Cork oak	570	572	8	10	0.35
	Mongolian oak	647	651	9	13	0.62
High mountain forests (HMF)	Red pine	134	125	11	2	−6.72
	Japanese larch	51	49	5	3	−3.92
	Korean pine	12	11	3	2	−8.33
	Cork oak	26	25	2	1	−3.85
	Mongolian oak	470	476	3	9	1.28

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, 2017b). 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.

The MODIS NPP and the median index from increment core data show the inter-annual variation of forest productivity during 2001–2015 and during 1971–2009. However, the variation patterns of the median index are not perfectly matched with MODIS NPP during an overlap-time period (2001–2009). For example, the median index of every tree species shows a tendency to increase from 2006 to 2008 (figure 3). This trend is also shown in the estimated NPP from MODIS (figure 5). In addition, MODIS NPP increased in 2003, decreased in 2006, and then increased again in

2008. This fluctuation pattern is similarly shown in the median index of coniferous tree species during the same period. However, different patterns of change in the annual median index of oak tree species are observed. There are two possible explanations for these results. Firstly, the area of each forest type in MODIS product may not perfectly match spatially the tree species of NFI data. In addition, while the MODIS product is remotely sensed data which represents a specific area, the increment core data is collected at tree-level. The other possible reason is the definitional differences between these results. MODIS NPP is theoretically total NPP while the core data is showing annual diameter growth of the stem. The stem growth may not fully represent total NPP due to various reasons (Ohtsuka *et al* 2005; Cleveland *et al* 2015).

Based on the results of productivity change, we additionally questioned how the composition of Korean forests has changed during the two NFI surveying periods. Interestingly, two repeated NFIs also suggests ongoing compositional change in South Korean temperate forests. Considering only changes to other species, the data shows that the dominant tree species in NFI permanent plots over LLFs and HMFs had changed by 4.63% and 3.46% respectively during the two consecutive surveying period (table 4). In addition, the rate of change in composition differs between the coniferous and oak tree species. The number of permanent plots identified in 5th and 6th NFIs changed

dramatically over LLFs. For instance, the number of coniferous dominant plots decreased by 4.5%–7.6%, while oak dominated plots increased by 0.3%–0.6%. For HMFs, the number of permanent plots dominated by coniferous species decreased by 3.9%–8.3%. The number of QM dominated plot increased by 1.3%. Across two altitudinal classes, we found that the composition change rate in HMFs is relatively faster in LLFs. The national statistics also reported that the area of coniferous and mixed forests decreased, and the area of broad-leaved forests has increased gradually since the 2000s (Korea Forest Service 2018). These changes have become faster in the 2010s. Our results parallel the national statistics for tree species. It is also noteworthy that there is a clear distinction between changes in forest productivity during two separate periods (1970–1989 and 1990–2009). We observed a more rapid change in the standardized growth index in the later period indicating that the changes have accelerated in recent years. The variations of standardized growth index for LK, PK, QV, and QM in HMF during the research period are larger than those in LLF.

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 (Schumacher and Bugmann 2006, 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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## Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## Declaration of interest

None.

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