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Precision monitoring of radial growth of trees and micro-climate at a Korean Fir (*Abies koreana* Wilson) forest at 10 minutes interval in 2016 on Mt. Hallasan National Park, Jeju Island, Korea

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Abstract

To understand the dynamics of radial growth of trees and micro-climate at a site of Korean fir (*Abies koreana* Wilson) forest on high-altitude area of Mt. Hallasan National Park, Jeju Island, Korea, high precision dendrometers were installed on the stems of Korean fir trees, and the sensors for measuring micro-climate of the forest at 10 minutes interval were also installed at the forest. Data from the sensors were sent to nodes, collected to a gateway wireless, and transmitted to a data server using mobile phone communication system. By analyzing the radial growth data for the trees during the growing season in 2016, we can estimate that the radial growth of Korean fir trees initiated in late April to early May and ceased in late August to early September, which indicates that period for the radial growth was about 4 months in 2016. It is interesting to observe that the daily ambient temperature and the daily soil temperature at the depth of 20 cm coincided with the values of about 10 °C when the radial growth of the trees initiated in 2016. When the radial growth ceased, the values of the ambient temperature went down below about 15 °C and 16 °C, respectively. While the ambient temperature and the soil temperature are evaluated to be the good indicators for the initiation and the cessation of radial growth, it becomes clear that radii of tree stems showed diurnal growth patterns affected by diurnal change of ambient temperature. In addition, the wetting and drying of the surface of the tree stems affected by precipitation became the additional factors that affect the expansion and shrinkage of the tree stems at the forest site. While it is interesting to note that the interrelationships among the micro-climatic factors at the forest site were well explained through this study, it should be recognized that the precision monitoring made possible with the application of high resolution sensors in the measurement of the radial increment combined with the observation of 10 minutes interval with aids of information and communication technology in the ecosystem observation.

Keywords: *Abies koreana*, Ecological platform, Environmental factors, Korean fir trees, Micro-climate, Precision dendrometer, Radial growth, Real-time monitoring

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Background

It becomes clear that global warming affects various aspects of ecosystems as well as the society in this era of the Anthropocene (MEA 2005; Zalasiewicz et al. 2010, Steffen et al. 2011, Future Earth 2013, 2019, IPCC 2014, 2018). Ecologists are carrying out various studies to know the long-term consequences of the changing climate to the ecosystems around the globe (ILTER 2006; Kim 2006; U.S. LTER 2007; Müller et al. 2010; Kim et al. 2018; NEON 2019).

As tree growth is one of the most important natural phenomena that support various aspects of daily life of mankind, it has been a continuing subject for research. Tree growth is the end result of division, expansion, differentiation, and morphogenesis of cells. This sequential development, which requires a balanced supply of carbohydrates, water, minerals, and hormonal growth regulators in meristemic regions, is subject to complex interactions among various environmental factors. Many factors influence the quantity and quality of the radial growth of trees in forests, which include precipitation, soil moisture content, evapotranspiration, physical characteristics of soil, ambient temperature, light, wind, soil temperature, drought, rainfall interception, photoperiod, defoliation, pruning, thinning, topography, micro-site and micro-climate, altitude, fire, and frost (Agerter and Glock 1965). Kramer and Kozlowski (1979) categorized the factors into two groups, i.e., internal factors and environmental factors. Radial growth is the secondary growth of trees that is being affected by the micro-climatic factors, which are changing continuously at forests. In Korea, as it was not much studied on the dynamics of the radial growth of trees, it is needed for the scientists to understand better the dynamics as well as the affecting nature of the micro-climate to the growth of trees.

Korean fir (*Abies koreana* Wilson), a sub-alpine coniferous tree species, is growing on the upper part of the Mt. Hallasan National Park, Jeju, Korea, which is designated as the Biosphere Reserve of UNESCO. Korean fir is an endemic tree species nominated by Wilson (1920) and is categorized as an endangered species by IUCN (2011). In addition, Korean fir is designated as the Climate-sensitive Biological Indicator Species (CBIS) in Korea (Lee et al. 2010). There are studies on the habitat, distribution, and population dynamics of the tree species (Kong and Watts 1993; Kim 1996; Koh et al. 1996; Kim and Choo 2000; Kim et al. 2007, 2016, 2017; Song 2011; Song et al. 2014); the radial growth of the tree species using tree rings being affected by ambient temperature and precipitation of the sites (Kim 1994; Koo et al. 2001; Kang et al. 2013; Zhang et al. 2018); and potential effects of climate to tree growth including droughts (Kim and Kim 2000, Kim et al. 2015a). Currently, the growth dynamics of Korean fir trees as well as the interactions among the micro-climatic factors are not well known at the forest site of the mountain, however.

Conventionally, band dendrometers have been used to detect the changes of diameter growth (Reukema 1965; Tardif et al. 2001; Sheil 2003). Considering the dendrometer bands for having the potentials of being influenced by the thermal expansion, band elasticity, and the friction with the bark of tree stems (Sheil 2003), the data derived from band dendrometers have some issues in precision. In addressing the gaps for developing a more precise device for measuring radial increment, a precision dendrometer is available in detecting minute changes in radius with the precision of 0.005 mm (Phyto-Sensor Group 2010). The DE-1 M dendrometer uses a highly precise incremental LVDT (linear variable displacement transducer)-based sensor for monitoring micro-variations of the radii of tree stems in micron range which measures the output signal with variations of distance between the surface of tree stems and the end of the rod, which is anchored inside the tree stem. As the indices coming from the DE-1 M dendrometer allow investigators to detect the effects of irrigation rate and other environmental factors on water balance and growth of plants, it was initially applied to the study of agricultural fields (Selles et al. 2005; Silva-Contreras et al. 2008, 2012). Similarly, there are some studies using automatic point dendrometers in the continuous measurement of changes in plant diameter including growth dynamic and diurnal diameter changes, which can also provide signals documenting the response of trees to their environment in high temporal resolution (Biondi and Hartsough 2010; Wang et al. 2016).

Nowadays, the availability of the technologies in detecting the changes instantly, transmitting the data wirelessly to a computer server, archiving the data safely in the database system, and making the data available meeting the needs from the users with different time scales makes it possible to establish an ecological platform to monitor ecosystem changes from a remote site without continuous supply of electricity with power lines. The authors established an ecosystem research platform to monitor radial growth of Korean fir trees and micro-climatic factors at the forest site (Kim et al. 2013, 2015b).

Using this ecological platform, we observed the radial growth of Korean fir trees and the micro-climatic factors at the forest site including such parameters as ambient temperature, relative ambient humidity, and solar radiation. We also monitored soil temperature and soil moisture content at the depths of 20 cm, 30 cm, and 50 cm belowground.

Through this paper, we are going to present the radial growth patterns of Korean fir trees during the growing season in 2016; analyze the relationships between the radial growth and the environmental factors including precipitation, ambient temperature, relative ambient humidity, solar radiation, and soil moisture content and soil temperature; and address some issues related to radial growth of Korean fir trees at the forest site as follows:

- The time when the radial growth initiated for the season;
- The time when the radial growth ceased for the season;
- The length of days for the radial growth for the season;
- The factors that are related to the initiation of radial increment for the season;
- The factors that are related to the fluctuation of radial increment for the season; and
- The factors that are related to the cessation of radial increment for the season.

The information from this study during the growing season in 2016 will contribute to the advancement of current understanding of ecosystem changes affected by the changing climate at the forest site and the provision of the basis for further studies in more mechanized ways for networking and converging studies in different disciplines under changing climates at local, regional, and global scales.

Methods

Study site

The site for this ecological platform study is located at the eastern slope near the Jindallaebat Shelter of Mt. Hallasan National Park, Jeju Island, Korea (Fig. 1), where the vegetation is represented by the sub-alpine forest dominated by Korean fir tree species. Mt. Hallasan National Park belongs to the Jeju Island Biosphere Reserves of UNESCO, which is located at the center of the island. We established the study site within a 5-ha (100 m × 500 m) permanent vegetation study plot (Kim et al. 2016, 2017).

Tree species for investigation

Three trees of the Korean fir were selected at the study site for the measurement of radial increment. The three trees were identified with the numbers of the nodes, i.e., trees with nodes 17, 18, and 19.

High-precision measurement of radial change of the trees

Three sets of high-precision dendrometer (DE-1 M) were installed at breast height on the stems of the Korean fir trees. This dendrometer has the range of measurement in 0–10 mm, and it can detect the change of radial changes in 0.005 mm. Figure 2 shows the photo of the dendrometer installed at the study site.

Sensors for monitoring weather and environment at the study site

For monitoring the micro-climate at the forest site, sensors for monitoring ambient temperature, relative ambient humidity, solar radiation, and soil moisture content and soil temperature were installed at the site using rechargeable batteries powered by solar panels. To check the correct monitoring of the weather factors, we also installed the automatic weather station (AWS) at the site and checked with the correctness of the weather data from the sensors at the site. Figure 3 shows the photos of the study site where sensors were installed at the Korean fir forest on Mt. Hallasan.

Data sensing and transmission

Considering the fact that the environment for installing the wireless sensor network system is harsh at the forest site, the band frequency of 433 MHz was used for data transmission to collect data and deliver the information reliably at the site. Data from sensors were sent to data nodes, collected to a gateway wirelessly, and transmitted to a data server using CDMA (Code Division Multiple Access) communication method.

The period for the use of data for this study

For this study, we selected the year of 2016 because this is the first year that we had the complete data sets on the radial increment during the growing season of the year. For the statistical analyses, we used the daily data for 139 days observed during the period from 16 April to 1 September in 2016.

Calculation of the differences in the day-to-day radial increment of the Korean fir trees

In order to find the changing patterns of radial increment on daily basis, the differences in the day-to-day radial increment for each of the three trees of Korean fir were calculated by subtracting the radial increment of the previous days from that of current days using the equation:

$$\mathrm{DRI}_n = \mathrm{RI}_n - \mathrm{RI}_{n-1}$$

where DRI_n is the difference in the day-to-day radial increment on the nth day and RI_n is the radial increment on the nth day.

Calculation of moving averages for the highly fluctuating radial increment of the Korean fir trees

As the radial increment showed very fluctuating patterns depending on daily conditions of weather, such as precipitation and temperature changes, it is difficult to determine when the radii of trees began to increase and stop during a growing season. In order to smooth out

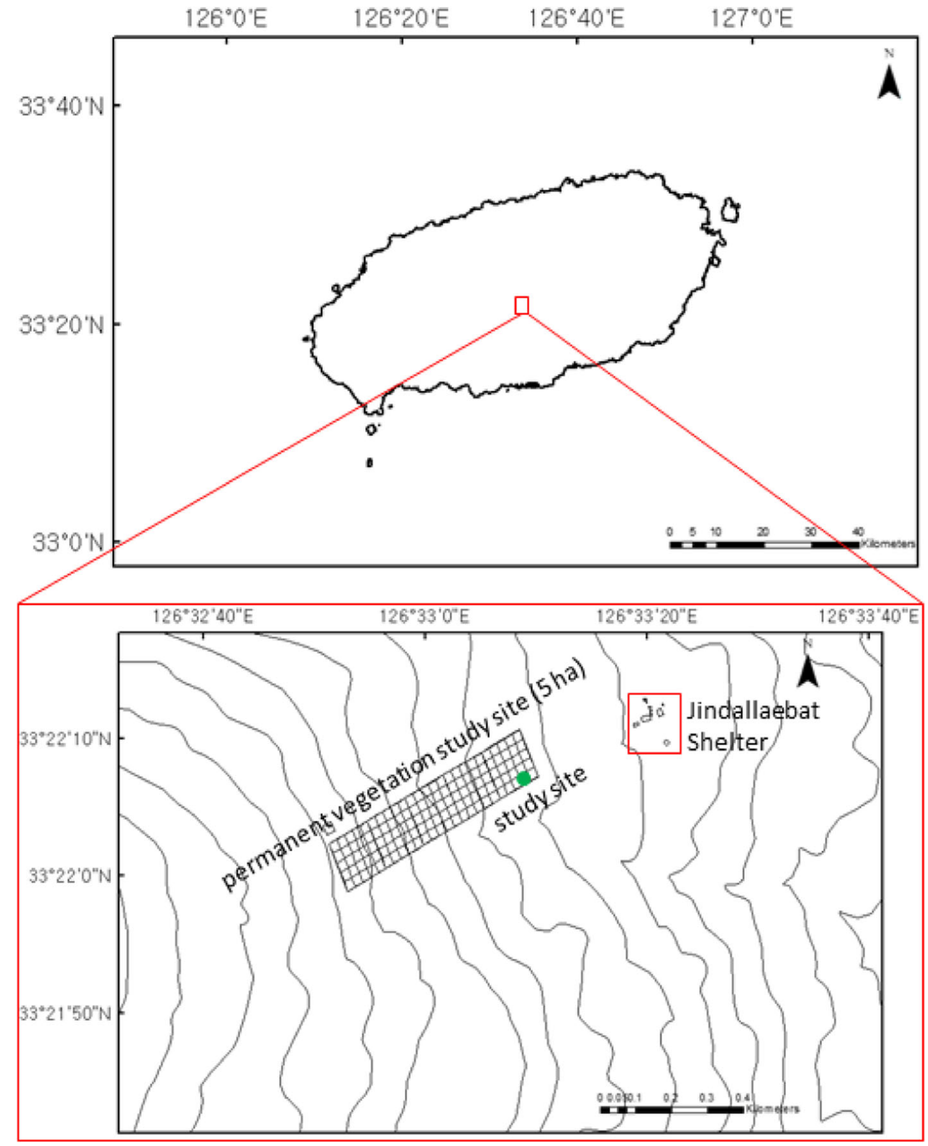

Fig. 1 Maps showing the location of study site near the Jindallaebat Shelter on Mt. Hallasan, Jeju Island, Korea

the short-term fluctuation and highlight the longer-term trend, moving averages were calculated using the time series of mean daily data of the radial increment for several days. For the calculation, the radial increment data for 9 days were used with the equation:

$$\mathrm{MA}_n = \frac{\mathrm{RI}_{n-4} + \mathrm{RI}_{n-3} + \cdots + \mathrm{RI}_n + \cdots \mathrm{RI}_{n+3} + \mathrm{RI}_{n+4}}{9}$$

where MA_n is the mean average of radial increment on the nth day and RI_n is the radial increment on the nth day.

By checking the 9-day moving averages of the radial increment, we can have better ideas on the initiation and cessation of the radial growth during the growing season in 2016.

Statistical analysis and data interpretation

In order to interpret the relationships of the data, SAS software was used in the correlation and regression analyses to the data sets monitored at the study site.

Results and discussion

Synchronous radial growth patterns of the Korean fir trees at the study site in 2016

The changing patterns of the radial increment of three trees of Korean fir monitored at 10 minutes interval during the period from mid-March to late September in 2016 are shown in Fig. 4. It is interesting to note from the observation of data sensed from the precision dendrometer that the radii of tree stems of the Korean fir began to increase from early spring due to the physical

Fig. 2 Photo of the dendrometer installed on the stem of a Korean fir tree at the study site

expansion of the tree stems caused by the increase of temperature since then. In response to diurnal change of temperature, the radii of the tree stems also showed diurnal fluctuation.

This study allows the authors to see the synchronous growth patterns in radial increment. It is interesting to note that the three trees showed very highly synchronous growth patterns among each other. The correlation coefficients among the trees in radial growth on daily basis were very high: between the trees with node 17 and node 18, $r = 0.975$ ($P < 0.0001$); between the trees with node 17 and node 19, $r = 0.974$ ($P < 0.0001$); and between the trees with node 18 and node 19, $r = 0.907$ ($P < 0.0001$). This also allows us to use the radial increment data for further interpretation related to the factors affecting the radial increment at the study site.

In order to find the changing patterns of radial increment on daily basis, the differences in the day-to-day radial increment for each of the three trees of Korean fir were calculated. Figure 5 shows the patterns of the day-to-day

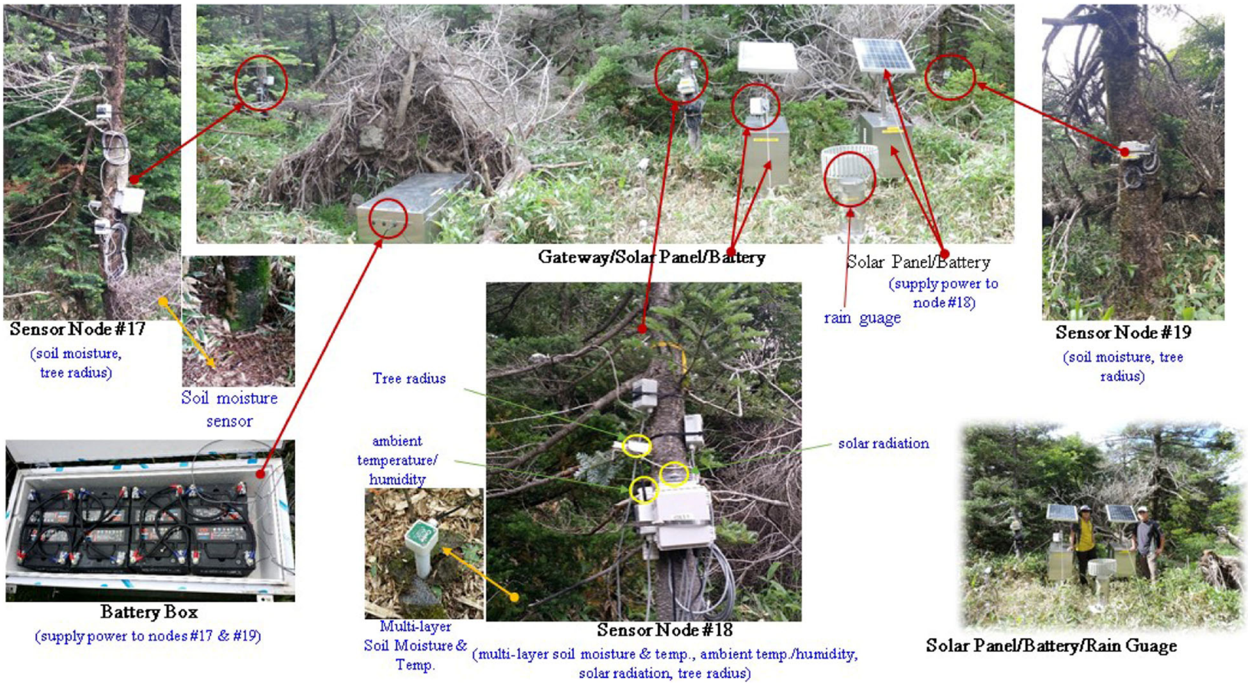

Fig. 3 Photos of the study site where sensors are installed at the Korean fir forest on Mt. Hallasan

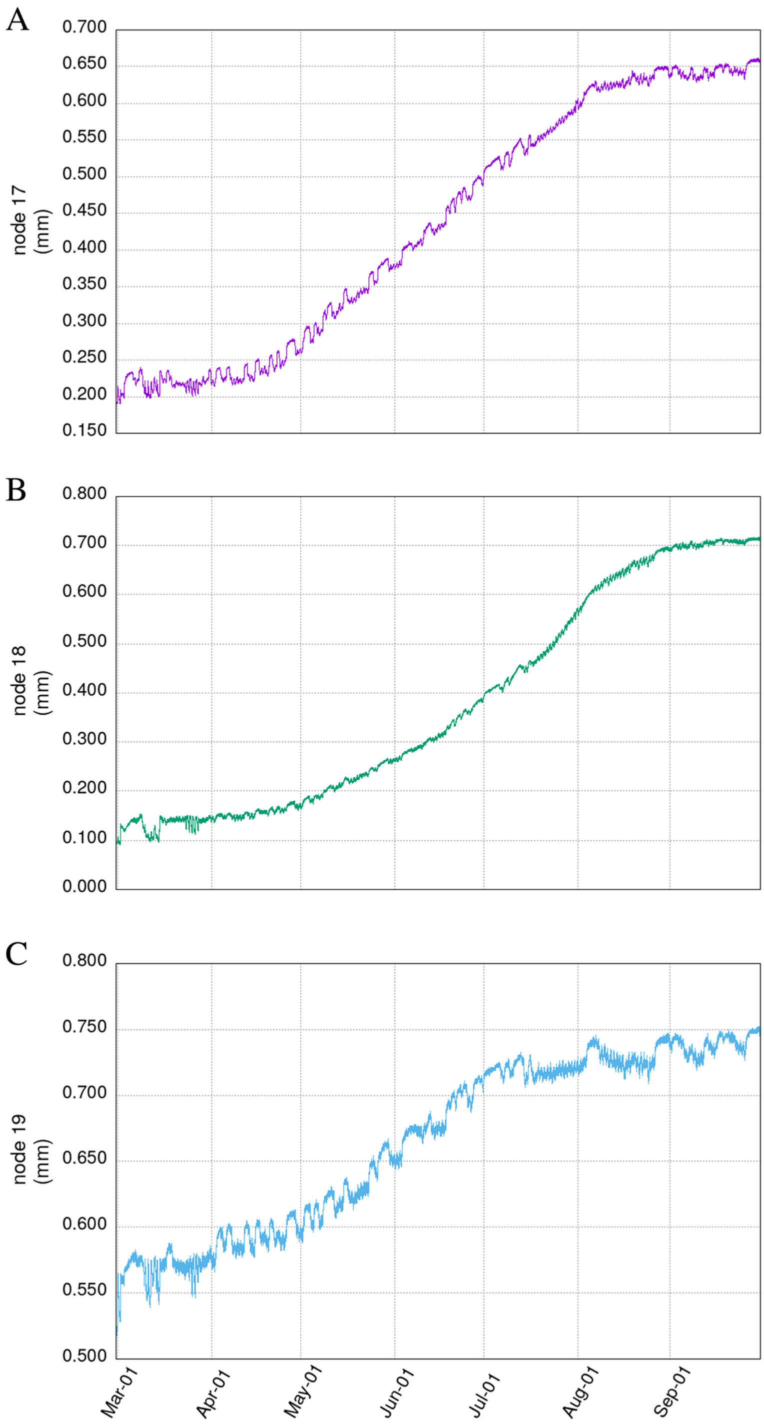

Fig. 4 The change of radial increment of trees at the study site during the period from March to September in 2016. **a** Node 17. **b** Node 18. **c** Node 19

fluctuation in radial increment of the trees during the growing season in 2016. It is very interesting to note that they showed highly fluctuating patterns, and more interestingly, they also showed very synchronous growth patterns, which indicates that the high-precision dendrometers are working effectively. In addition, this reassures the point stated above that the data for the observation of the radial increment are good to use in further interpretation related to the factors affecting the radial increment at the study site. The correlation coefficients among the trees in the difference in

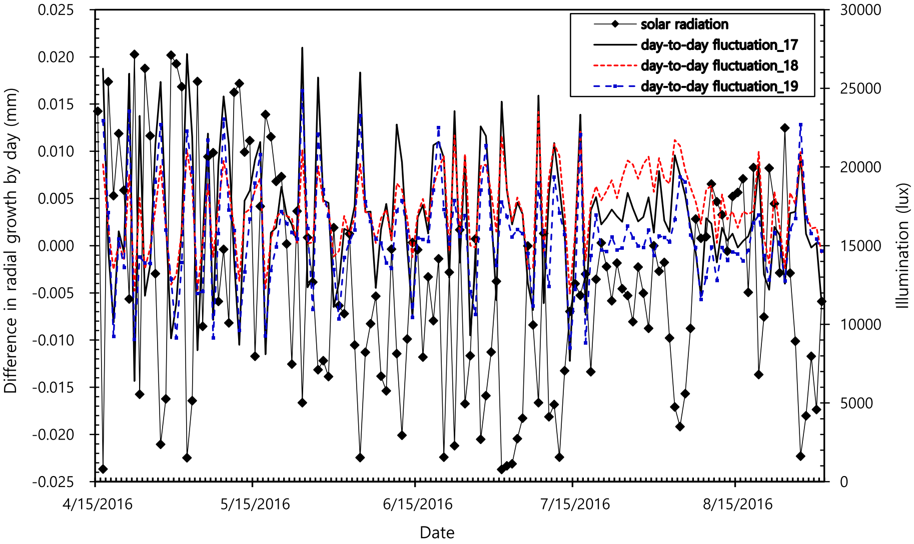

Fig. 5 The patterns of the day-to-day fluctuation in radial increment of Korean fir trees compared with the mean daily solar radiation during the growing season in 2016 at the study site

the day-to-day radial increment on daily basis were very high: between the trees with node 17 and node 18, $r = 0.866$ ($P < 0.0001$); between the trees with node 17 and node 19, $r = 0.867$ ($P < 0.0001$); and between the trees with node 18 and node 19, $r = 0.750$ ($P < 0.0001$).

When the relationship between the radial increment on daily basis and the difference in the day-to-day radial increment for each tree was tested using correlation analysis, the trees with nodes 17 and 19 did not show any significant relationships in correlation. Meanwhile, the tree with node 18 showed a high correlation between them ($r = 0.230$, $P = 0.006$).

Estimating the growing period for radial increment of Korean fir trees in 2016

It is interesting to note that this study allows the authors to address the question on when the Korean fir trees initiated the radial growth at the study site. As the radii continue to increase from March affected by the increase of daily temperature, it is difficult to understand when the trees were growing due to the real initiation of radial growth in 2016. When we checked the levels of the maximum radii of the tree stems at the end of the last growing season in 2015, the levels of radii for the tree stems with node 17, 18, and 19 indicated in the dendrometers were 0.22–0.23 cm, 0.15, and 0.59–0.60 cm, respectively. By comparing these values with the levels of radii of the tree stems in spring in 2016, we can find that the moving averages of the radial increment for 9 days for the trees with nodes 17, 18, and 19 had the same levels in late April to early May, indicating that the trees began to initiate the radial growth around this time.

This study also allows the authors to address the question on when the trees cease the radial growth at the study site. By checking the moving averages of the radial increment for 9 days, the growth of radii of the trees seemed to cease in late August to early September. Since then, the radii of the stems of the Korean fir trees still fluctuated and began to shrink due to the decrease in daily temperature and the initiation of the dry period after September through autumn and winter of the year.

Consequently, this study allows the authors to answer the question on how long trees grow in radius during the growing season. Considering the date for the initiation of radial increment in late April to early May and the date for the cessation in late August to early September, we can estimate that the trees grew in radius for about 4 months in 2016. Considering the fact that the dates for the initiation and the cessation of the radial growth can change affected by the weather factors including temperature and precipitation, we can also maintain that the long-term observation of the radial growth during the growing seasons can lead to better understanding of the dynamics of the radial growth of the trees as the basis for better understanding of the responses of ecosystems affected by the changing regimes of climate (Reukema 1965; Leštianska et al. 2015).

When we checked the levels of the maximum radii of the tree stems at the end of the growing season in 2016, the levels of radii for the tree stems measured by the dendrometers with node 17, 18, and 19 were 0.64 cm, 0.71 cm, and 0.73 cm, respectively. By subtracting the initial values in spring from the terminal values of the radii of the tree stems in 2016, we can calculate the amounts of radial increment for the stems of Korean fir

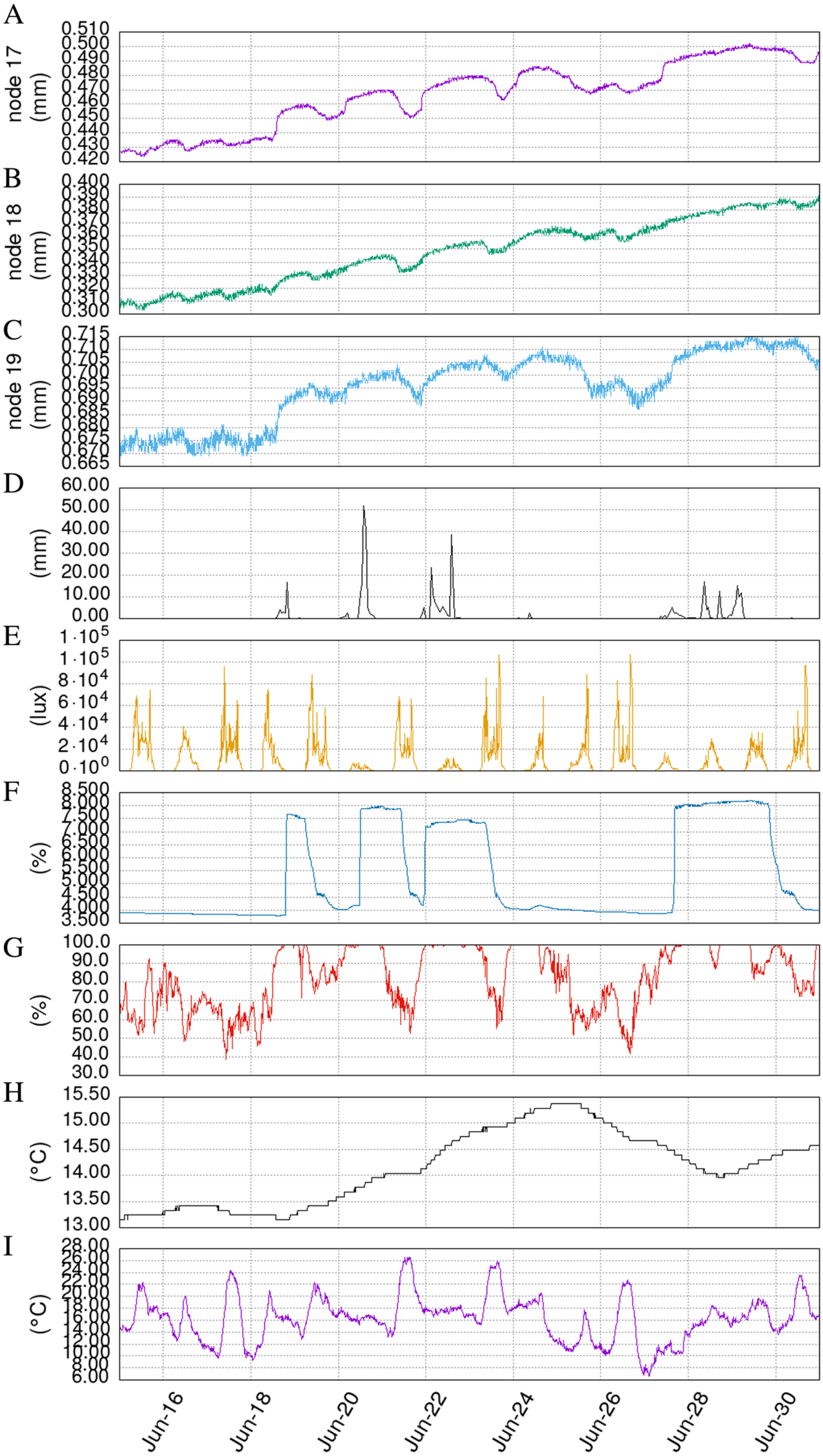

Fig. 6 (See legend on next page.)

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Fig. 6 The change of radial increment of trees and environmental factors at the study site for sensing micro-climate under the canopy of the Korean fir from 15 to 30 June 2016. In the figure, **a** the changing patterns of the radial increment with dendrometer node 17, **b** radial increment with dendrometer node 18, **c** radial increment with dendrometer node 19, **d** daily precipitation, **e** solar radiation, **f** soil moisture content at the depth of 50 cm, **g** relative ambient humidity, **h** soil temperature at the depth of 50 cm, and **i** ambient temperature were illustrated

trees with nodes 17, 18, and 19 were 0.42 cm, 0.56 cm, and 0.14 cm, respectively. With these, we can calculate the amount of diameter growth of the trees as 0.82 cm, 1.12 cm, and 0.28 cm, respectively. By these, we can find that Korean fir trees with nodes 17 and 18 grew fast in diameter; meanwhile, the tree with node 19 grew very slowly compared to the other two trees and that the reason for this difference should be further clarified by examining the conditions of the individual trees at the study site.

Changes in micro-climate at the forest during the growing season in 2016

Figures 6 and 7 show the changing patterns of the radial increment of the Korean fir trees and environmental factors sensed at the study site at 10 minutes interval (except precipitation, with a daily interval) under the forest canopy of the Korean fir during mid-growing season, 16–30 June 2016, and the late growing season, 1–15 August 2016. These figures are useful in letting us understand the nature of the dynamics of the forest as well as in making comparisons of the patterns of the radial increment of the Korean fir trees with micro-climatic factors sensed at the forest site.

The period from 16 to 30 June 2016 is characterized by the early rainy season in Jeju, when there were four events of rainfall with more than 50 mm per day. The period from 1 to 15 August 2016 is characterized by the dry summer in Jeju, when there were six events of rainfall with an average of 8.7 mm per day and about 10 days without rain.

Precipitation

For this study, we used the precipitation data measured from the AWS located at the Jindallaebat Shelter nearby on Mt. Hallasan. Figure 8 shows the patterns of daily precipitation measured at the AWS during the growing season in 2016 compared with mean daily soil moisture content at the depths of 20 cm, 30 cm, and 50 cm belowground at the study site.

From Fig. 8, daily precipitation is the factor that affects daily soil moisture contents significantly, which will be explained later related to the relationships between daily precipitation and mean daily soil moisture contents.

Soil moisture content

Soil moisture content was continuously measured from the soil moisture sensors at the depths of 20 cm, 30 cm, and 50 cm belowground at 10 minutes interval. Figure 8 shows three important patterns of soil moisture content during the growing season in 2016. It is quite evident to note that soil moisture content increased with the increase of soil depth and that soil moisture content was very sensitive to the events of precipitation. In addition, it is very interesting to note that soil moisture content dropped abruptly soon after the precipitation stopped, which reflects the geology of the Mt. Hallasan where water can percolate into deep seepage to the underground through permeable layers developed on the lava flows (Woo et al. 2013, http://geopark.jeju.go.kr/english/?mid=0101).

As are shown in Figs. 6, 7, and 8 during mid- to late growing season of the year in 2016, soil moisture content did not show any diurnal or seasonal patterns at different depths of soil belowground.

Solar radiation

As are shown in Figs. 6 and 7 during mid- to late growing season of the year in 2016, solar radiation clearly showed diurnal patterns observed at 10 minutes interval. During daytime, the reduction in solar radiation was clearly shown synchronously with the events of precipitation.

Relative ambient humidity

As are shown in Figs. 6 and 7 from mid- to late growing season of the year in 2016, relative ambient humidity basically showed diurnal patterns during the days without precipitation and different patterns from those of the ambient temperature.

During nighttime, the relative ambient humidity became very high due to the decrease in the ambient temperature caused by no inputs in solar radiation. In reverse, during daytime, the relative ambient humidity became low due to the increase in the ambient temperature caused by increased solar radiation. With the events of precipitation, the relative ambient humidity became very high due to the saturation of moisture in the air with the precipitation.

It is interesting to note that the radial increment for the three Korean fir trees showed very synchronous patterns with the changes of relative ambient humidity indicating that the expansion and shrinkage of the radii of the trees are sensitive to the wetting and drying of tree stems affected by the frequency, magnitude, and duration of precipitation at the forest site (Fig. 9).

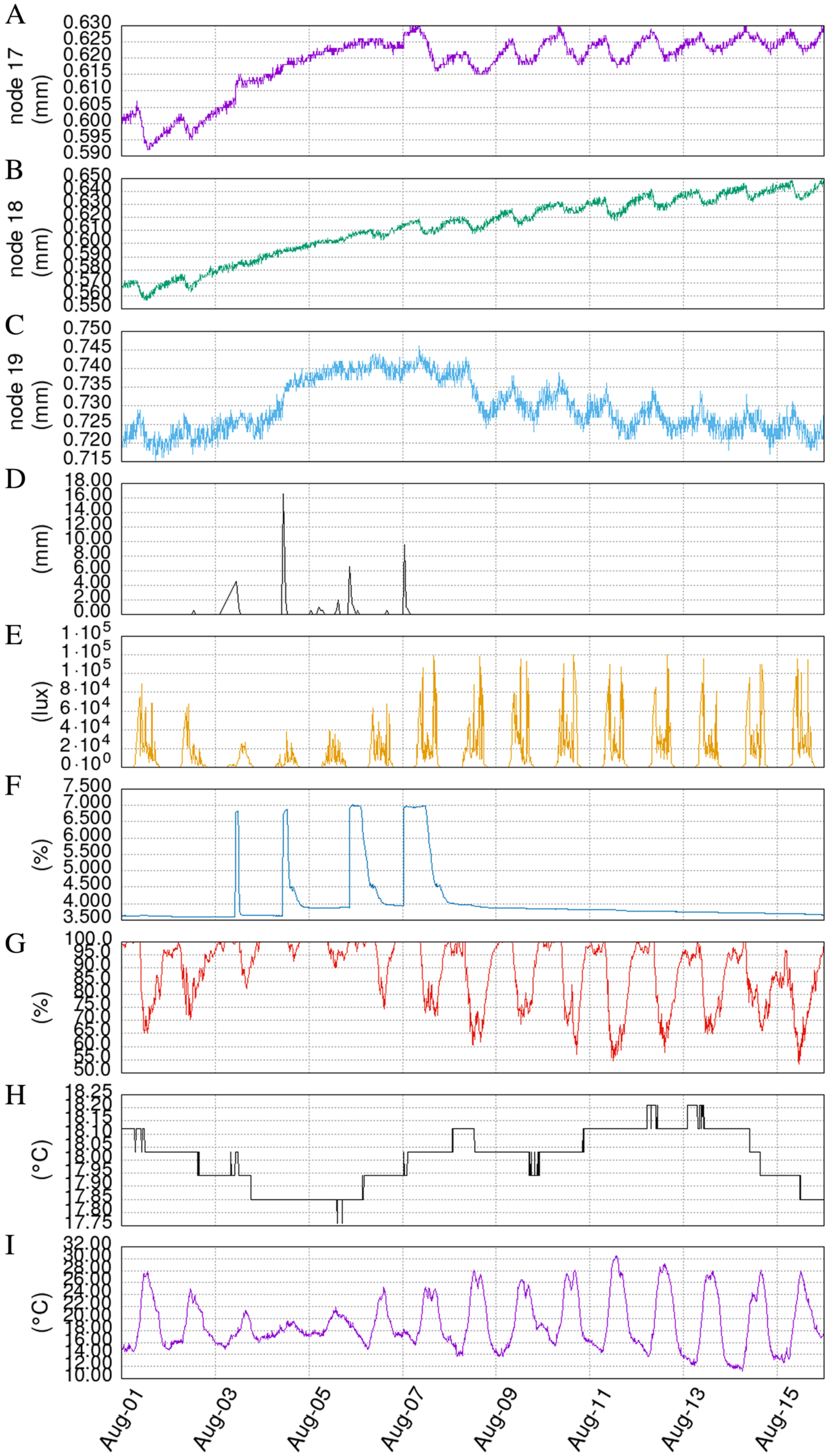

Fig. 7 (See legend on next page.)

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Fig. 7 The change of radial increment of trees and environmental factors at the study site for sensing micro-climate under the canopy of the Korean fir from 1 to 15 August 2016. In the figure, **a** the changing patterns of the radial increment with dendrometer node 17, **b** radial increment with dendrometer node 18, **c** radial increment with dendrometer node 19, **d** daily precipitation, **e** solar radiation, **f** soil moisture content at the depth of 50 cm, **g** relative ambient humidity, **h** soil temperature at the depth of 50 cm, and **i** ambient temperature were illustrated

Ambient temperature

As are shown in Figs. 6 and 7 from mid- to late growing season of the year in 2016, ambient temperature basically showed diurnal patterns. The diurnal patterns became more conspicuous when it did not rain and became less conspicuous when it rained because the precipitation lowered the ambient temperature regardless of the time of the day.

On the ambient temperature during the period in late April to early May when the radial growth seemed to initiate, it was observed that mean daily ambient temperature rose above 10 °C at the study site. On the ambient temperature during the period in late August to early September when the radial growth seemed to cease, it was observed that the ambient temperature went down below 15 °C at the study site.

To check the validity of the data sensed at the study site, the ambient temperature data from the study site were compared with those measured from the AWS at the Jindallaebat Shelter nearby. A very high correlation was observed between the ambient temperature data from the site and those measured from the AWS at the Jindallaebat Shelter nearby ($r = 0.987$, $P < 0.001$). With this, it is reassured that the temperature data monitored at the study site can be safely used for further analysis in this study.

Soil temperature

Soil temperature is continuously measured using soil temperature sensors at the depths of 20 cm, 30 cm, and 50 cm belowground at 10 minutes interval.

Figure 10 shows a few important patterns of soil temperature during the growing season in 2016. It is interesting to note that the temperature of the deeper soil was lower than that of the shallower soil and that soil temperature was very sensitive to the events of precipitation during the growing season in 2016. In addition, it is very interesting to note that soil temperature dropped abruptly at the depths of 20 cm and 30 cm soon after the events of precipitation. As was shown in Fig. 10, soil temperature at the depths of 20 cm and 30 cm was very highly affected by the ambient temperature and, therefore, showed a very high correlation with ambient temperature on a daily basis.

As are shown in Figs. 6 and 7 during mid- to late growing season of the year in 2016, the patterns of soil temperature did not show any diurnal or seasonal patterns of change at the depth of 50 cm belowground but showed a delayed response to the events of precipitation.

On soil temperature during the period from late April to early May when the radial growth seemed to initiate, it was observed that the soil temperature at the depths of 20 cm and 30 cm belowground rose above 10 °C and

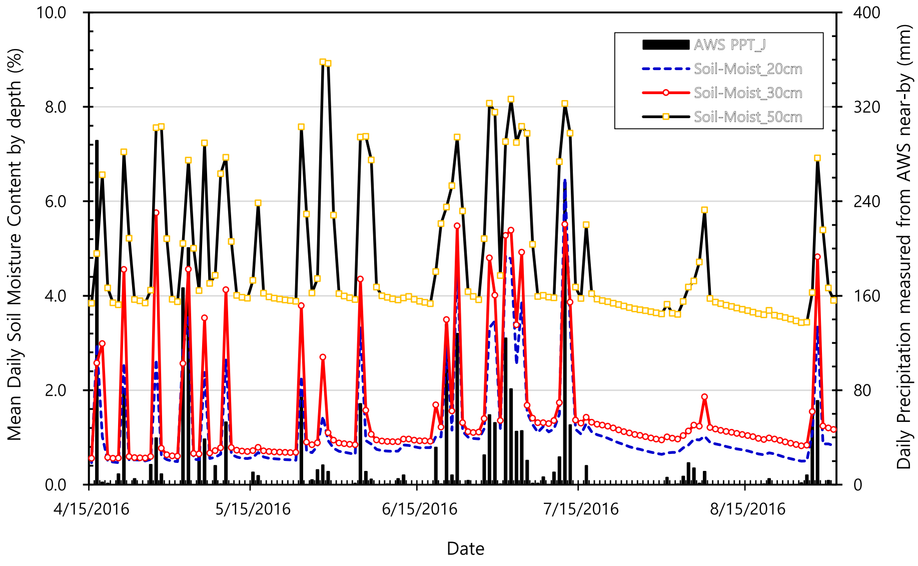

Fig. 8 Patterns of daily precipitation measured from the AWS located at the Jindallaebat Shelter nearby during the growing season in 2016 compared with mean daily soil moisture content at the depths of 20 cm, 30 cm, and 50 cm belowground at the study site

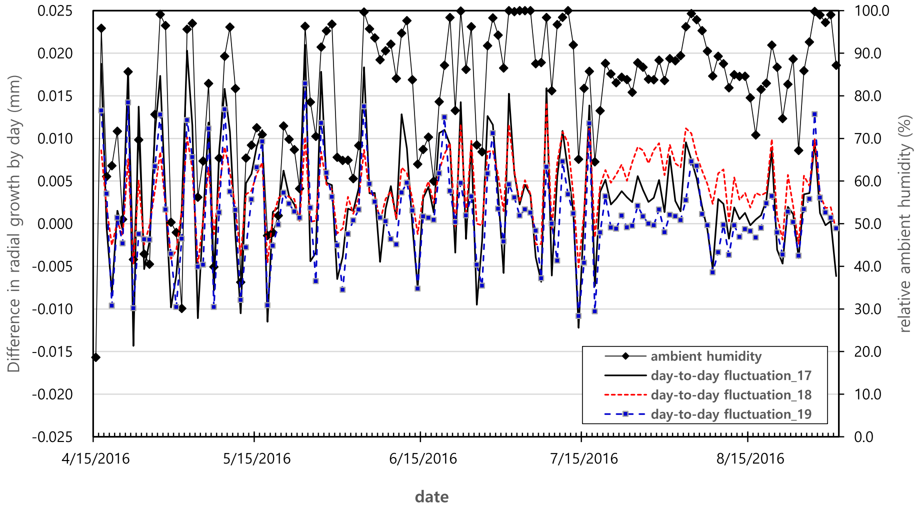

Fig. 9 The patterns of daily relative ambient humidity compared with the difference in the day-to-day fluctuation in radial increment of the three Korean fir trees on Mt. Hallasan

9 °C, respectively, at the study site. On soil temperature during the period from late August to early September when the radial growth seemed to cease, it was observed that the soil temperature at the depths of 20 cm and 30 cm belowground went down below 16 °C and 17 °C, respectively, at the study site.

Relationships among the environmental factors affecting the growth of Korean fir trees during the growing season in 2016

In order to understand the relationships among the environmental factors affecting the growth of Korean fir trees during the growing season in 2016 at the forest site, correlation analyses were applied to the daily values of the precipitation, mean solar radiation, mean relative ambient humidity, mean ambient temperature, mean soil moisture content, and mean soil temperature observed for 139 days, between 16 April and 1 September 2016.

Table 1 shows the results of the correlation analyses among the factors. From Fig. 8, it was very clearly shown that daily precipitation was the factor that positively affected mean daily soil moisture content at the depths of 20 cm ($r = 0.809$, $P < 0.0001$), 30 cm ($r = 0.701$, $P < 0.0001$), and 50 cm ($r = 0.488$, $P < 0.0001$), and mean daily relative ambient humidity ($r = 0.363$, $P < 0.0001$) and negatively affected mean daily solar radiation ($r = -0.490$, $P < 0.0001$) and mean daily soil temperature at depth of 20 cm

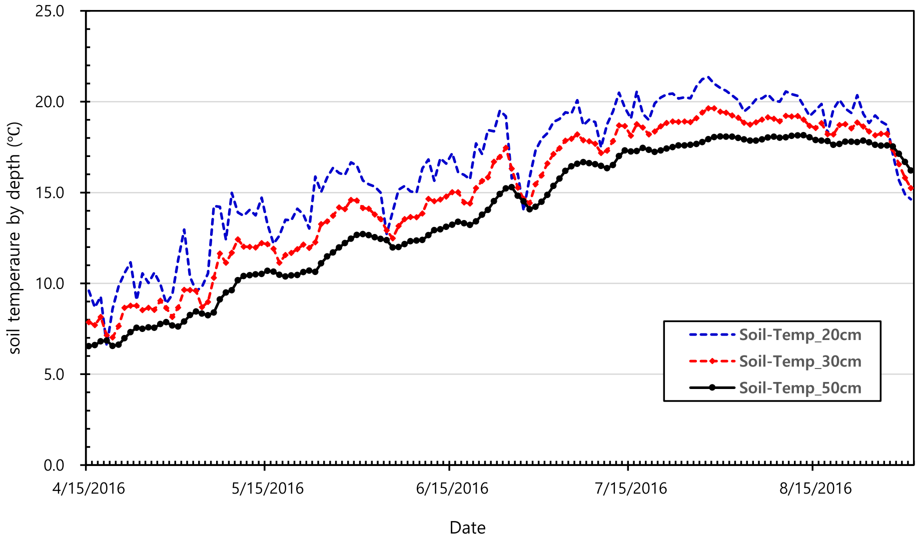

Fig. 10 The patterns of mean daily soil temperature at different depth during a growing season on Mt. Hallasan in 2016

Table 1 Correlation coefficients and the levels of significances among the environmental factors

	Mean daily soil temp. at depth of 20 cm	Mean daily soil temp. at depth of 30 cm	Mean daily soil temp. at depth of 50 cm	Mean daily ambient temp.	Mean daily relative humidity	Mean daily solar radiation	Mean daily soil moist. Content at depth of 20 cm	Mean daily soil moist. Content at depth of 30 cm	Mean daily soil moist. Content at depth of 50 cm
Daily precipitation	−0.170 $P = 0.05$	− 0.148 $P = 0.08$	− 0.158 $P = 0.06$	− 0.144 $P = 0.09$	0.363 $P < 0.0001$	− 0.490 $P < 0.0001$	0.809 $P < 0.0001$	0.701 $P < 0.0001$	0.488 $P < 0.0001$
Mean daily soil temp. at depth of 20 cm		0.976 $P < 0.0001$	0.941 $P < 0.0001$	0.961 $P < 0.0001$	0.456 $P < 0.0001$	−0.216 $P = 0.01$	0.055 $P = 0.52$	0.019 $P = 0.83$	−0.158 $P = 0.06$
Mean daily soil temp. at depth of 30 cm			0.989 $P < 0.0001$	0.907 $P < 0.0001$	0.506 $P < 0.0001$	−0.285 $P = 0.001$	0.061 $P = 0.47$	0.029 $P = 0.73$	−0.180 $P = 0.03$
Mean daily soil temp. at depth of 50 cm				0.863 $P < 0.0001$	0.503 $P < 0.0001$	−0.277 $P = 0.001$	0.038 $P = 0.66$	0.0098 $P = 0.91$	−0.209 $P = 0.01$
Mean daily ambient temperature					0.377 $P < 0.0001$	−0.153 $P = 0.07$	0.053 $P = 0.53$	0.014 $P = 0.87$	−0.174 $P = 0.04$
Mean daily relative humidity						−0.763 $P < 0.0001$	0.475 $P < 0.0001$	0.491 $P < 0.0001$	0.407 $P < 0.0001$
Mean daily solar radiation							−0.545 $P < 0.0001$	−0.511 $P < 0.0001$	−0.387 $P < 0.0001$
Mean daily soil moist. Content at depth of 20 cm								0.942 $P < 0.0001$	0.707 $P < 0.0001$
Mean daily soil moist. Content at depth of 30 cm									0.758 $P < 0.0001$

($r = -0.170$, $P = 0.045$). The reasons for negative but low correlations for the daily precipitation with mean daily ambient temperature and mean daily soil temperature were explained before due to the difference in magnitudes of scale of changes in precipitation and that of ambient temperature.

Solar radiation is another important factor which is being interrupted by precipitation ($r = -0.490$, $P < 0.0001$) and negatively correlated with mean daily relative ambient humidity ($r = -0.763$, $P < 0.0001$); mean daily soil moisture content at the depths of 20 cm ($r = -0.545$, $P < 0.0001$), 30 cm ($r = -0.511$, $P < 0.0001$), and 50 cm ($r = -0.387$, $P < 0.0001$); and mean daily soil temperature at the depths of 20 cm ($r = -0.216$, $P = 0.011$), 30 cm ($r = -0.285$, $P = 0.0007$), and 50 cm ($r = -0.277$, $P = 0.001$).

Ambient temperature is the factor that affects soil temperature at the depths of 20 cm ($r = 0.961$, $P < 0.0001$), 30 cm ($r = 0.907$, $P < 0.0001$), and 50 cm ($r = 0.863$, $P < 0.0001$) and that is positively related to relative ambient humidity ($r = 0.377$, $P < 0.0001$).

It is quite interesting to note that soil moisture content at the depths of 20 cm and 30 cm belowground is not significantly correlated with soil temperature at all depths and that soil moisture content at the depth and 50 cm belowground where all the factors are not abruptly changing affected by daily precipitation is negatively correlated with soil temperature at the depths of 30 cm and 50 cm belowground. In contrast, precipitation is a driving factor, which is a very stochastic and variable in frequency, amount, and patterns, affecting other factors including soil moisture content.

Relative ambient humidity is the factor that is being directly and positively affected by precipitation ($r = 0.363$, $P < 0.0001$) and that is negatively related to solar radiation ($r = -0.763$, $P < 0.0001$) and positively related to ambient temperature ($r = 0.377$, $P < 0.0001$); soil temperature at the depths of 20 cm ($r = 0.475$, $P < 0.0001$), 30 cm ($r = 0.491$, $P < 0.0001$), and 50 cm ($r = 0.407$, $P < 0.0001$); and soil temperature at the depths of 20 cm ($r = 0.456$, $P < 0.0001$), 30 cm ($r = 0.506$, $P < 0.0001$), and 50 cm ($r = 0.503$, $P < 0.0001$).

By evaluating the correlation coefficients among the factors shown in Table 1, the interrelationships among the factors are suggested in Fig. 11, which shows the affecting and interacting natures among the factors at the study site.

To summarize the interrelationships, while precipitation and solar radiation are the major driving factors affecting the other environmental factors at the forest site, soil moisture content and soil temperature are thought

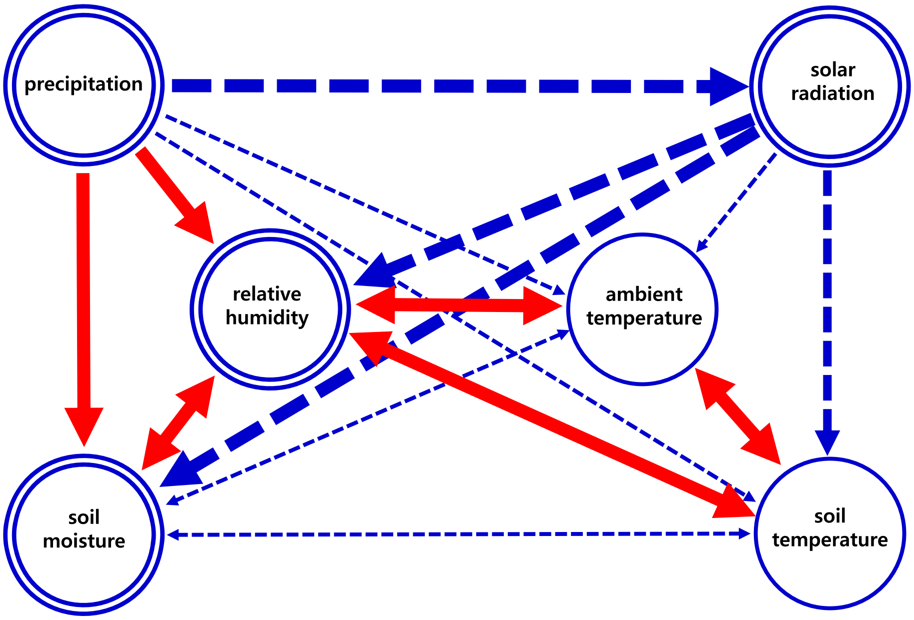

Fig. 11 Diagram showing the interrelationships among the environmental factors that affect the radial growth of trees at the study site, Jeju, Korea. In this figure, circles with double lines indicate abruptly fluctuating environmental factors; circles with single line indicate gradually changing environmental factors; solid lines (in red) indicate positive effects; dashed lines (in blue) indicate negative effects; thick lines indicate major and/or direct effects; thin lines indicate minor and/or indirect effects; and arrows show the directions of the affecting natures between the factors

to be the major contributing factors that directly affect the activities of the roots of the trees, which can eventually affect the radial activities of the trees.

The effects of micro-climatic factors to daily radial increment of Korean fir trees during the growing season in 2016

Daily precipitation

The results of the correlation analyses between the daily values of radial increment for each of the three trees of Korean fir and the daily precipitation indicate that all the three trees showed no significant correlations between them, which indicates that all the three trees do not grow linearly related to the amount of daily precipitation which is very stochastic and variable in frequency, amount, and patterns. The correlation coefficients (the level of significance in parenthesis) for the three trees with nodes 17, 18, and 19 are − 0.124 ($P = 0.144$), − 0.141 ($P = 0.097$), and − 0.075 ($P = 0.382$), respectively.

From Figs. 6 and 7, it is clearly shown that the increases in daily radial increment coincide with the events of the precipitation. The magnitudes of the increase in the daily radial increment do not correspond with the magnitudes of the daily precipitation during the growing season in 2016. It is natural to understand this because the range of the change of radial increment is very small compared to that of the daily precipitation which is quite big during the period. In fact, during the period of 139 days of the growing season in 2016, it did not rain for 70 days. While the maximum daily precipitation is 291.5 mm, the mean and the standard deviation of the daily precipitation for the period were 18.2 mm and 45.0 mm, respectively. Therefore, radial growth did not show linearly corresponding growth patterns to the amount of daily precipitation.

The results of the correlation analyses between the difference in the day-to-day radial increment for each of the three trees of Korean fir and the daily precipitation indicate that all the three trees showed very highly significant and positive correlations between them, which indicates that all the three trees showed highly sensitive growth responses in radius related to the amount of daily precipitation. In other words, the trees grew more in radius compared to the previous day when it rained more. The correlation coefficients (the level of significance in parenthesis) for the three trees with nodes 17, 18, and 19 are 0.482 ($P < 0.0001$), 0.396 ($P < 0.0001$), and 0.450 ($P < 0.0001$), respectively. Special attention should be paid to the fact that the amount of daily precipitation showed much higher correlations with the difference in the day-to-day radial increment than with the daily values of radial increment of the trees.

Daily soil moisture content

The results of the correlation analyses between the daily values of radial increment for each of the three trees of Korean fir and the mean daily soil moisture content at different depths indicate that all the three trees showed no significant correlations between them at the depths of 20 cm and 30 cm belowground, which indicates that all the three trees did not grow linearly related to the amount of daily soil moisture content at the depths of 20 cm and 30 cm belowground. It is interesting to note that the two trees with the nodes of 17 and 18 at the depth of 50 cm belowground showed significant but negative correlations with the coefficients (the level of significance in parenthesis) of − 0.202 ($P = 0.017$) and − 0.270 ($P = 0.001$), respectively, however.

The correlation coefficients with the levels of significance for the three trees between the daily values of radial increment for the three trees with nodes 17, 18, and 19 and the mean daily soil moisture content at different depths are shown in Table 2.

The results of the correlation analyses between the difference in the day-to-day radial increment for each of the three trees of Korean fir and the daily soil moisture content indicate that all the three trees showed very highly significant and positive correlations between them, which indicates that all the three trees show highly sensitive growth responses in radius to the amount of daily soil moisture content. In other words, the trees grew more in radius compared to the previous day when soil was with more moisture content. The correlation coefficients with the levels of significance for the three trees with nodes 17, 18, and 19 are shown in Table 3. In terms of the effects of the daily soil moisture content, it is interesting to note that the trees showed much higher correlations in the difference in the day-to-day radial increment than in the daily values of radial increment.

Daily solar radiation

The results of the correlation analyses between the daily values of radial increment for each of the three trees of Korean fir and the mean daily radiation indicate that all the three trees showed significant and negative correlations between them, which indicates that the trees grew more in radius when solar radiation was lower and grew less when solar radiation was higher. The correlation coefficients (the level of significance in parenthesis) for the three trees with nodes 17, 18, and 19 are − 0.276 ($P = 0.001$), − 0.178 ($P = 0.036$), and − 0.375 ($P < 0.0001$), respectively.

The results of the correlation analyses between the difference in the day-to-day radial increment for each of the three trees of Korean fir and the mean daily radiation indicate that all the three trees showed very highly significant and negative correlations between them, which indicates that the trees grew more in radius compared to the previous day when solar radiation was lower and grew less when solar radiation was higher. The correlation coefficients (the level of significance in parenthesis) for the three trees with nodes 17, 18, and 19 are − 0.586 ($P < 0.0001$), − 0.622 ($P < 0.0001$), and − 0.497 ($P < 0.0001$), respectively. In terms of the effects of the daily solar radiation, it is interesting to note that the trees showed much higher correlations in the difference in the day-to-day radial increment than in the daily values of radial increment.

Figure 5 shows the relationships very well between the difference in the day-to-day radial increment of Korean fir trees and the mean daily solar radiation during the growing season in 2016.

Daily relative ambient humidity

The results of the correlation analyses between the daily values of radial increment for each of the three trees of Korean fir and the mean daily relative ambient humidity indicate that all the three trees showed very highly significant and positive correlations between them, which indicates that the trees grew more in radius when it was more humid and grew less when it was drier. The correlation coefficients (the level of significance in parenthesis) for the three trees with nodes 17, 18, and 19 are 0.530 ($P < 0.0001$), 0.453 ($P < 0.0001$), and 0.602 ($P < 0.0001$), respectively. It is quite interesting to find that all the three trees showed higher correlations in daily radial increment with the mean daily relative ambient humidity than with the daily precipitation. This is explained with the fact that mean daily relative ambient humidity is less variable in amount and patterns than those of daily precipitation.

Table 2 The correlation coefficients and the levels of significances between the daily values of radial increment and the mean daily soil moisture content

Trees	Soil moisture content at depth of 20 cm belowground	Soil moisture content at depth of 30 cm belowground	Soil moisture content at depth of 50 cm belowground
Korean fir tree with node 17	$r = 0.045$	$r = 0.031$	$r = -0.202$
	$P = 0.598$	$P = 0.717$	$P = 0.017$
Korean fir tree with node 18	$r = -0.030$	$r = -0.026$	$r = -0.270$
	$P = 0.729$	$P = 0.758$	$P = 0.001$
Korean fir tree with node 19	$r = 0.150$	$r = 0.122$	$r = -0.082$
	$P = 0.078$	$P = 0.152$	$P = 0.335$

Table 3 The correlation coefficients and the levels of significances between the difference in the day-to-day radial increment and the mean daily soil moisture content

Trees	Soil moisture content at depth of 20 cm belowground	Soil moisture content at depth of 30 cm belowground	Soil moisture content at depth of 50 cm belowground
Korean fir tree with node 17	$r = 0.415$	$r = 0.445$	$r = 0.341$
	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$
Korean fir tree with node 18	$r = 0.398$	$r = 0.400$	$r = 0.237$
	$P < 0.0001$	$P < 0.0001$	$P = 0.0049$
Korean fir tree with node 19	$r = 0.392$	$r = 0.457$	$r = 0.434$
	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$

The results of the correlation analyses between the difference in the day-to-day radial increment for each of the three trees of Korean fir and the mean daily relative ambient humidity indicate that all the three trees showed very highly significant and positive correlations between them, which indicates that the trees grew more in radius compared to the previous day when it was more humid and grew less when it was drier. The correlation coefficients (the level of significance in parenthesis) for the three trees with nodes 17, 18, and 19 are 0.552 ($P < 0.0001$), 0.666 ($P < 0.0001$), and 0.577 ($P < 0.0001$), respectively. In terms of the effects of the daily relative ambient humidity, it is interesting to note that the trees showed similarly high correlations in the difference in the day-to-day radial increment to those in the daily values of radial increment. Figure 9 showed the relationship between the day-to-day fluctuation in radial increment of the three Korean fir trees and mean daily relative ambient humidity during the growing season in 2016.

Daily ambient temperature

The results of the correlation analyses between the daily values of radial increment for each of the three trees of Korean fir and the mean daily ambient temperature indicate that all the three trees showed highly significant and positive correlations between them, which indicates that the trees grew more in radius when ambient temperature was higher and grew less when ambient temperature was lower. The correlation coefficients (the level of significance in parenthesis) for the three trees with nodes 17, 18, and 19 are 0.812 ($P < 0.0001$), 0.732 ($P < 0.0001$), and 0.825 ($P < 0.0001$), respectively. It is natural to find that all the three trees showed very highly significant and positive correlations between the daily values of radial increment and the daily ambient temperature changes because the fluctuating patterns of the daily ambient temperature showed the similar patterns of daily fluctuation in radial increment.

The results of the correlation analyses between the difference in the day-to-day radial increment for each of the three trees of Korean fir and the mean daily ambient temperature indicate that the trees showed different correlations between them. It is interesting to note that the two trees with nodes 17 and 19 did not show any significant relationships between the difference in the day-to-day radial increment and the daily ambient temperature. Meanwhile, the tree with node 18 showed a very highly significant and positive correlation between them ($r = 0.286$, $P = 0.0007$), which indicates that the trees grew more in radius compared to the previous day when daily ambient temperature is higher and grew less when daily ambient temperature was lower. In terms of the effects of the daily ambient temperature, it is interesting to note that the trees showed much higher correlations in the daily values of radial increment than in the difference in the day-to-day radial increment.

When daily ambient temperature data collected from an automatic weather station (AWS), located at the Jindallaebat Shelter on Mt. Hallasan, were used in testing the correlation with the daily values of radial increment and the difference in the day-to-day radial increment, the results were very similar with the results used with the daily ambient temperature data collected at the study site. This can be explained rather easily because the two data sets were very similar in values.

Daily soil temperature

The results of the correlation analyses between the daily values of radial increment for each of the three trees of Korean fir and the mean daily soil temperature at different depths indicate that all the three trees showed very highly significant and positive correlations between them, which indicates that the trees grew more in radius when soil temperature was warmer and grew less when soil temperature was colder. The correlation coefficients with the levels of significance for the three trees with nodes 17, 18, and 19 are shown in Table 4.

The results of the correlation analyses between the difference in the day-to-day radial increment for each of the three trees of Korean fir and the mean daily soil

Table 4 The correlation coefficients and the levels of significances between the daily values of radial increment and the mean daily soil temperature

Trees	Soil temperature at depth of 20 cm belowground	Soil temperature at depth of 30 cm belowground	Soil temperature at depth of 50 cm belowground
Korean fir tree with node 17	$r = 0.887$	$r = 0.950$	$r = 0.980$
	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$
Korean fir tree with node 18	$r = 0.801$	$r = 0.877$	$r = 0.923$
	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$
Korean fir tree with node 19	$r = 0.903$	$r = 0.957$	$r = 0.974$
	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$

temperature at different depths indicate that the trees showed different correlations between them. It is interesting to note that the two Korean fir trees with nodes 17 and 19 did not show any significant relationships between the difference in the day-to-day radial increment and the daily soil temperature at all the depths. Meanwhile, the Korean fir tree with node 18 showed highly significant and positive correlations between them at all the depths (Table 5), which indicates that the Korean fir tree with node 18 grew more in radius compared to the previous day when daily ambient temperature was higher and grew less when daily ambient temperature was lower.

General discussion

Overall, the monitoring of the radial increment of Korean fir trees using the precision dendrometers and the micro-climate factors using sensors at the forest site was successful by carrying out the (1) monitoring of the radial increment and the micro-climatic factors at 10 minutes interval, (2) estimating the growth period by addressing the issues raised on the initiation and cessation of the radial growth of trees, (3) explaining the interrelationships among the micro-climatic factors, and (4) analyzing the effects of the micro-climatic factors on the radial growth of the Korean fir trees at the forest site on Mt. Hallasan, Jeju Island, Korea.

With the monitoring, it was made clear that trees showed diurnal patterns of expansion and shrinkage in radial growth affected by the daily change of ambient temperature during the growing season. In addition, the events of precipitation are the major factor that affects the abrupt changes in radius. Depending upon the frequency, magnitude, and duration of the events of precipitation, the diurnal patterns of expansion and shrinkage in radii become inconspicuous due to continuous wetting of the bark of the tree stems, which prevents the shrinkage of the radii of the trees. Shortly after the cessation of the events of precipitation, the bark of the tree stems become dry, from when the conspicuous diurnal patterns of expansion and shrinkage resume.

As the radial increment is invisible from outside, this kind of measurement of radial increment using precision dendrometers allows us to measure the radial increment of trees with the resolution comparable with the studies using automated point dendrometers (Biondi and Hartsough 2010; Wang et al. 2016).

In addition, simultaneous measurement of the environmental factors that can affect radial increment of trees provides us with important potentials to interpret the affecting nature of the environmental factors to the radial growth of the trees. This study showcases this potential very well by explaining the interrelationship among the micro-climatic factors and the effects of them to the radial increment of the trees at the forest site.

There are some points to be further considered and to be implemented. One of the important actions to be made in the monitoring the trees at the forest is to carry out simultaneous monitoring of the phenology of trees including the observation of such phenological features

Table 5 The correlation coefficients and the levels of significances between the difference in the day-to-day radial increment and the mean daily soil temperature

Trees	Soil temperature at depth of 20 cm belowground	Soil temperature at depth of 30 cm belowground	Soil temperature at depth of 50 cm belowground
Korean fir tree with node 17	$r = -0.033$	$r = -0.033$	$r = -0.064$
	$P = 0.697$	$P = 0.701$	$P = 0.453$
Korean fir tree with node 18	$r = 0.319$	$r = 0.325$	$r = 0.290$
	$P = 0.0001$	$P < 0.0001$	$P = 0.0005$
Korean fir tree with node 19	$r = -0.045$	$r = -0.051$	$r = -0.071$
	$P = 0.598$	$P = 0.552$	$P = 0.408$

as the opening of the dormant buds, flowering of strobili (small male and female cones), initiation of height growth, initiation of branch growth, and cessation of height growth and branch growth (Sheil 2003), which can provide researcher with further potential in interpreting the mechanisms and the dynamics of phenology of trees being affected by the changing climate.

This kind of monitoring of radial increment should be further extend to other tree species as well as other Korean fir trees at different forest sites to better understand the patterns as well as dynamics of radial growth of the tree species and the interrelationships among the factors that affect the growth of tree species under the regime of changing climate in Korea (Kim 2010).

In doing this study, we think it important for us to pay a special attention to the current status of the long-term ecological research (LTER) activities being carried out at local levels as well as the regional and international levels (ILTER 2006; Kim 2006; Müller et al. 2010; Kim et al. 2018). In addition, special attention should be paid to the National Ecological Observatory Network (NEON) activities of the USA, which are focused on the infrastructure of measurement and cyberinfrastructure that deliver standardized and calibrated data to the scientific community through an open data portal (Kim 2007). The activities of the NEON is designed to ask and to address important questions around the environmental challenges identified to understand the effects including the issue of climate change to the change of ecosystems (https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=13440). With these in consideration, we think it is needed for us to construct the upgraded version of the NEON in Korea. In this regard, further efforts should be made in discussing the ways to construct and promote the ecological observatories in Korea (Kim 2012).

Conclusions

To understand the dynamics of the radial growth and micro-climate at a site of Korean Fir forest on high altitude area of Mt. Hallasan National Park, Jeju Island, Korea, high-precision dendrometers were installed on the stems of Korean fir trees and the environmental sensors measuring micro-climate at the forest site at 10 minutes interval were also installed to interpret the affecting nature of the factors to the radial growth of trees. Data from sensors were sent to nodes, collected to a gateway wirelessly, and transmitted to a data server using CDMA (Code Division Multiple Access) communication method.

By analyzing the radial growth data for the trees for the growing season in 2016, radial growth of Korean fir trees seemed to begin in late April to early May and cease in late August to early September, which indicates that period for the radial growth was about 4 months in 2016. It was observed that the mean daily ambient temperature and the mean daily soil temperature at the depth of 20 cm coincided with the value of about 10 °C when the radial growth initiated from the trees in 2016. When the radial growth ceased, the values of the ambient temperature went down below about 15 °C and 16 °C, respectively, for the trees in 2016. To summarize the interrelationships among the micro-climatic factors, precipitation and solar radiation are the major driving factors affecting the other environmental factors at the forest site. Soil moisture content and soil temperature are thought to be the major contributing factors that directly affect the activities of the roots of the trees, which can eventually affect the radial activities of the trees at the forest.

While the ambient temperature and soil temperature are good indicators for the initiation and cessation of radial growth, it becomes clear that the diameter of tree stems showed diurnal growth patterns majorly affected by the diurnal change of ambient temperature. In addition, the wetting and drying of the surface of tree stems affected by relative ambient humidity after rainfall become the additional factors that affect the expansion and shrinkage of tree stems at the forest site. While it is interesting to note that the interrelationships among the micro-climatic factors at the forest site were well explained through this study, it should be recognized that these were made possible with the application of high-resolution sensors in the measurements combined with the observation of 10 minutes interval with aids of information and communication technologies (ICT) and with the application of the mobile phone technology for making real-time monitoring possible for ecosystem observation. Long-term studies including phenological observation for these kinds of studies will allow us to further understand the dynamics of the radial growth of various tree species in Korea including the Korean fir growing on Mt. Hallasan, Jeju Island, Korea.

Abbreviations

AWS: Automatic weather station; CBIS: Climate-sensitive Biological Indicator Species; CDMA: Code Division Multiple Access; ICT: Information and communication technologies; ILTER: International Long-Term Ecological Research; IPCC: Intergovernmental Panel on Climate Change; IUCN: International Union for Conservation of Nature; KEITI: Korea Institute of Environmental Science; LTER: Long-term ecological research; LVDT: Linear variable displacement transducer; MEA: Millennium Ecosystem Assessment; MOE: Ministry of Environment of Korea; NEON: National Ecological Observatory Network; SAS: Statistical Analysis System; UNESCO: The United Nations Educational, Scientific and Cultural Organization; US LTER: United State Long-Term Ecological Research

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Authors' contributions
ESK coordinated the research, carried out statistical analyses, drafted the article, and submitted the article to the Journal. DH, YSK, SHL, and HBC helped in various aspects of this study including study design, data collection and management, field survey, data analyses and graphics, and drafting and reviewing of the manuscript. NSK, KL, and JR carried out IT and sensor networking works for this study. All authors read and approved the final manuscript.

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Consent for publication
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Competing interests
The authors declare that they have no competing interests.

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