Species-specific morphological and physiological characteristics and progressive nitrogen limitation under elevated CO₂ concentration

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Elevated atmospheric CO₂ (eCO₂) concentration initially enhances photosynthesis, growth and ecosystem productivity, but the excessive use of nitrogen due to the increased productivity causes uncertainty in long-term ecosystem responses. We exposed Korean red pine, Chinese ash, and Korean mountain ash to current atmospheric CO₂ concentration (aCO₂), 1.4 times higher CO₂ concentration (eCO₂,1.4), and 1.8 times higher CO₂ concentration (eCO₂,1.8) in an Open-Top Chamber (OTC) experiment for eight years (2010-2017) to investigate the effect on the morphological and physiological properties of trees. We also assessed whether nitrogen limitation occurred with time by comparing leaf and soil nitrogen concentration. CO₂ fertilization effect was observed on tree growth for the first two years (p < 0.05), but there was no difference thereafter. For photosynthetic properties, CO₂ effects were species-specific; no effects on Korean red pine and Chinese ash vs. significant effect on Korean mountain ash. However, maximum photosynthetic and carboxylation rates significantly decreased by 24.3% and 31.3% from 2013 to 2017, respectively. Leaf nitrogen significantly decreased by 21.0 % at eCO₂,1.4 and 18.5 % at eCO₂,1.8 compared with aCO₂ treatment. This study showed the decline of leaf nitrogen and species-specific responses to long-term high CO₂ concentration, which will effect on species competition and ecosystem succession.

Keywords: Elevated CO₂, Photosynthetic Properties, Down-regulation, Progressive Nitrogen Limitation, Carbon dioxide

Introduction
Elevated CO₂ concentration has become a common phenomenon in the Earth’s atmosphere over the last half-century (IPCC 2013). The indiscriminate use of fossil fuels and deforestation has raised the atmospheric CO₂ concentration, thus promoting photosynthesis and growth (Drake et al. 1997, Ainsworth & Long 2005, Sang et al. 2019) and affecting the productivity of plants (McCarthy et al. 2010, Norby et al. 2010), which is referred to as the CO₂ fertilization effect (Norby et al. 2010). However, there are conflicting opinions on whether such an effect will continue with increasing CO₂ concentration (Hungate et al. 2003). In general, the productivity of terrestrial ecosystems is affected by nutrient availability in the soil (Terrer et al. 2018). It should be taken into account that, if CO₂ fertilization promotes plant growth, the excessive nutrient use will result in insufficient nutrients in the soil, failing to meet the nutrient requirements needed for plant growth (Hungate et al. 2003, Wang & Houlton 2009) and decreasing the CO₂ fertilization effect. Therefore, the expected increase of ecosystem productivity and carbon storage due to CO₂ fertilization is still uncertain (Terrer et al. 2018).

Early studies using pots and growth chambers hardly reflected the real forest ecosystem conditions (Curtis & Wang 1998, Norby et al. 2010), therefore experiments with Open-Top chamber (OTC) and Free Air CO₂ Enrichment (FACE) techniques have been widely employed (Norby et al. 2010). Many OTC and FACE experiments reported an increased growth and photosynthesis under elevated CO₂ (Hungate et al. 2015, Talhelm et al. 2014). However, whether these effects would last for a long time is questioned. In particular, experiments on elevated CO₂ and soil nitrogen fertilization (Finzi et al. 2007), which were conducted at the Duke-FACE and Oak Ridge-FACE, confirmed that nitrogen can directly limit the increase in forest productivity due to the carbon fertilization response, highlighting the relevance of nitrogen on forest productivity.

Nitrogen is an important component of plant photosynthetic organs and of functional and structural proteins (Kwon et al. 2019). In particular, nitrogen in the leaves constitutes the photosynthetic enzymes, such as chlorophyll and rubisco (ribulose-1,5-bisphosphate carboxylase/oxygenase), which determines the maximum carboxyla-
tion rate ($V_{\text{max}}$ – Makino & Osmond 1991, Hikosaka 2004), with a decisive influence on forest productivity (Harley et al. 1992, Harrison et al. 2009). However, owing to increased productivity by long-term exposure to a high CO₂ concentration, the consumption of nutrients may overcome the nutrients input, leading to a reduction in effective nutrients in the soil, and consequently to a reduction of plants’ photosynthesis ability. In particular, as the nitrogen concentration absorbed by plants decreases, its concentration in the leaves is lower, thus decreasing photosynthesis. This in turn results in a progressive nitrogen limitation (PNL), which offsets the CO₂ fertilization effect (Drake et al. 1997, Luo et al. 2004, Cai et al. 2018). This phenomenon is more common under nitrogen deficiency in the soil (Petterson & McDonald 1994, McCarthy et al. 2010).

Under PNL, an increase in productivity due to the CO₂ fertilization effect is a short-term phenomenon, whereas in the long term, the ecosystem productivity might decrease again and return to its original state (Luo et al. 2004, Finzi et al. 2007). This suggests that increased forest productivity due to a high atmospheric concentration of CO₂ might be inhibited by soil nitrogen deficiency (Feng et al. 2015). Reich et al. (2006) and Feng et al. (2015) confirmed that the response of plants to CO₂ fertilization was limited by nitrogen deficiency. Moreover, PNL is expected to be more prominent when the high CO₂ concentration environment is maintained for a long time (Rüttig 2017).

The main objective of this study was to determine the occurrence of nitrogen limitation under long-term CO₂ fertilization on three major species of the Korean temperate region: Korean red pine (Pinus densiflora), Chinese ash (Fraxinus rhynchophylla), and Korean mountain ash (Sorbus alnifolia). When the high CO₂ scenario (Chamber 2, eCO₂) was introduced, the CO₂ concentration (Chamber 1, aCO₂) is expected to be the atmospheric CO₂ concentration by 2070 (Chamber 3, eCO₂,1.8). The exposure of CO₂ was conducted for 10 hours (08:00-18:00) a day during the growing season (April-November). Pest controls were conducted every year and weed controls were conducted for four years of the experiment. The annual average, minimum and maximum monthly temperature in chambers were 12.4 ± 0.2 °C, -1.3 ± 0.4 °C, 22.5 ± 0.2 °C, respectively. The annual rainfall range was 751.16 mm yr⁻¹ to 1975.96 mm yr⁻¹ over the 9 years of the experimental period.

In each chamber, the same three clones for each species were tested. Four-year-old seedlings of Korean red pine (Pinus densiflora), two-year-old seedlings of Chinese ash (Fraxinus rhynchophylla), and two-year-old seedlings of Korean mountain ash (Sorbus alnifolia) were planted in September 2009. The density within the OTC was 2547 seedlings ha⁻¹.

Growth measurements

Growth measurements (height and diameter) on trees started in May 2010 and were repeated every year until 2017 at the beginning (mid-April), mean daily temperature: -10 °C) and the end (end of October), mean daily temperature: -5 °C of the growing season. The annual increase in growth was obtained as the difference in these two measures. Also, the lack of differences in diameter between the last measurement of the previous year and the first of the subsequent year was verified.

Tree height was recorded using a measuring rod (A-15, SENSINH Industry Co., Ltd., Osaka, Japan), while the tree diameter was measured twice in orthogonal directions 10 cm above the root collar using a digital Vernier callipers (CD-10CPX, Mitutoyo, Kawasaki, Japan), and the average value was used. Exceptionally, since 2016, Korean red pine and Chinese ash trees were measured using a diameter tape (F10-02DM, KDS, Malaysia) because of their large diameters.

Gas exchange measurements

The photosynthetic parameters were measured on tree leaves using a portable device Li-6400 (LI-COR Inc., Lincoln, NE, USA). From 2013 to 2017, except for 2015, the parameters were measured 1-3 times a year from June to August on 3 sunlit leaves for each species. The temperature of the leaves was set at 25 °C and the relative humidity at 55%-60%. The leaves were stabilized before measurements. The area of leaves was set at 6 cm² for all the species except Korean red pine. For this species the leaf area was recalcualated by measuring the actual leaf area using a scanner after all measurements.

The light response curve was obtained using the photosynthetic rate recorded by sequentially varying the intensity of light irradiated on the leaves, using the following sequence in all the chambers: 1400, 1200, 1000, 800, 600, 400, 200, 100, 75, 50, 25, 0, and 1200 μmol m⁻² s⁻¹. The reference CO₂ concentration, supplied in each Li-6400 chamber was set at the atmospheric CO₂ in each OTC. The maximum photosynthetic rate ($A_{\text{max}}$) was estimated as the photosynthetic rate at light saturation (1200 μmol m⁻² s⁻¹) under the CO₂ concentration in the chambers, which was measured using the light response curve (Taiz & Zeiger 2010) and estimated in Excel® spreadsheet version 2.0 (Microsoft, Redmond, WA, USA).

Leaf total nitrogen analysis

Three sunlit leaves were chosen on the same branch and used for photosynthetic measurements ($n = 9$ for each species, three repetitions for three species), and 1 cm² leaf disk was collected in 2017. The leaves were dried in a 70 °C in the lab for more than 72 h, then crushed using a FastPrep-24™ crusher (MP Biomedicals, Solon, OH, USA), homogenized, and finally analysed for nitrogen content using CHNS Analyzer Flash EA 1112® (Thermo Electron Corporation, USA) at the National Instrumentation Center for Environmental Management (NICEM).

Soil nitrogen analysis

Before planting trees in 2009, the soil in the OTC was excavated to a depth of 1 m and replaced with forest soil to control the soil characteristics of all the treatment groups. Soil depth < 30 cm was composed of forest soil and sand with a ratio of 1:1 (Lee et al. 2012). For all treatment groups, samples of soil from 0 to 5 cm depth were collected at five randomly selected points in September 2017, air-dried for 3 days at room temperature, and then analysed using the CHNS Analyzer Flash EA
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1112 described above at the NICEM.

Statistical analysis
All statistical analyses were carried using the software R ver. 3.3.2 (R Core Team 2016). Growth, photosynthesis variables and leaf total nitrogen over time were analyzed by repeated-measures ANOVA with CO doubling treatments as a fixed factor and the recording year as the repeated-measure. When significant CO × Year interactions and CO or Year effect were detected, means were compared using Tukey post-hoc comparisons. In addition, one-way ANOVA of individual species and Tukey post-hoc comparisons were conducted to assess the CO effect for each year.

Results
To investigate the CO doubling effect on tree growth over the period 2010-2017, diameter and height increments of trees of different treatments and species were recorded (Tab. 1, Tab. 2). The cumulative increments for height and diameter over the 8 years of the experiment are presented in Fig. 1.

Diameter growth
Tab. 1 summarizes the annual diameter increase measured after CO doubling exposure. The results showed a significant increment in diameter growth under high CO doubling concentration due to the CO doubling fertilization effect (p < 0.001 – Tab. 3). On average, the difference between aCO , and eCO,1.8 was 47.7%, 25.3% and 3.1% in Korean mountain ash (41.4 ± 6.2 vs. 61.1 ± 7.9 mm), Korean red pine (144.7 ± 15.1 vs. 181.3 ± 13.5 mm), and Chinese ash (70.9 ± 9.2 vs. 73.1 ± 5.5 mm), respectively.

The annual diameter increment of individual species under eCO, was significantly enhanced in all the species in 2010-2011 (maximum p = 0.029 – Tab. 3). However, since 2012, there was no significant difference in diameter increment under eCO,. Korean red pine showed a significant difference in diameter growth under eCO, in 2011 in the order of aCO, < eCO,1.4 < eCO,1.8, an increase of about 100.0% (aCO, vs. eCO,1.8, p = 0.015 – Tab. 1). Korean mountain ash showed significant difference under eCO, in 2010, an increase of about 57.9% (aCO,: 5.7 ± 0.7 vs. eCO,1.8: 9.0 ± 0.5 mm; p = 0.02).

Height growth
Similarly to growth in diameter, annual increase in tree height was recorded each year from 2010 until 2017 (Fig. 1). For all the species, the increase in height was high under eCO, (p < 0.01 – Tab. 2). On average, the difference between aCO, and eCO,1.8 was 22.01%, 18.3% and 14.3% in Korean red pine (470.7 ± 22.8 vs. 574.3 ± 72.5 cm), Chinese ash (585.3 ± 39.1 vs. 692.3 ± 48.1 cm) and Korean mountain ash (299.3 ± 40.5 vs. 342.0 ± 8.2 cm), respectively.

Tab. 2 summarizes the annual growth of tree height measured after CO doubling exposure. For all the species, results were similar to the diameter growth. Chinese ash showed a significant difference in height growth under eCO, in 2010 (p = 0.029). Differences were observed under eCO,1.8 and aCO, which was increased about 57.9%. Korean red pine showed a significant increase under eCO, in 2011, an increase of about 110.7% (p = 0.006). However, after 2012, there was no difference in the increase in height due to CO doubling concentration for all the species.

Maximum photosynthetic rate (Amax)
The average Amax under eCO, measured from 2013 increased in the following order: aCO, (12.7 ± 0.7 μmol m⁻² s⁻¹) < eCO,1.4 (15.6

**Fig. 1** - Effects of elevated CO doubling concentration (aCO, Chamber 1; eCO,1.4, Chamber 2; eCO,1.8, Chamber 3) on average tree diameter (a, b, c) and height (d, e, f) growth per year from 2010 to 2017. There were no significant differences among CO doubling treatments (p > 0.05).
### Tab. 2 - Annual growth in height (cm, mean ± SE) of Korean red pine (Pinus densiflora, Pd), Chinese ash (Fraxinus rhynchophylla, Fr) and Korean mountain ash (Sorbus alnifolia, Sa) in response to aCO₂ (Chamber 1), eCO₂,1.4 (Chamber 2) and eCO₂,1.8 (Chamber 3) during 8 years. Different lowercase letters indicate significant (p < 0.05) multiple comparison results among CO₂ treatments (one-way ANOVA followed by Tukey post-hoc test). (ns): not significant.

| Parameter | Treatment   | Year | Height growth (cm) |
|-----------|-------------|------|-------------------|
|           | aCO₂        | 2010 | 6.5 ± 0.9         |
|           | Pd          | 2011 | 6.2 ± 1.6         |
|           | eCO₂,1.4    | 2012 | 5.9 ± 1.1         |
|           | eCO₂,1.8    | 2013 | 6.3 ± 1.6         |
|           | aCO₂        | 2014 | 7.0 ± 1.0         |
|           | Pd          | 2015 | 6.0 ± 1.0         |
|           | eCO₂,1.4    | 2016 | 7.3 ± 1.1         |
|           | eCO₂,1.8    | 2017 | 7.3 ± 1.1         |

### Tab. 3 - Results statistics for diameter, height, Amax, Vcmax, Jmax and leaf total N of all species with F statistics and p-values from two-way repeated-measure ANOVA.

| Parameter | Factor | F     | p     |
|-----------|--------|-------|-------|
| Diameter  | CO₂    | 58.03 | < 0.001 |
|           | Year   | 19.08 | < 0.001 |
|           | CO₂ × Year | 1.04 | 0.982 |
| Height    | CO₂    | 17.727 | < 0.001 |
|           | Year   | 9.201 | < 0.001 |
|           | CO₂ × Year | 0.367 | 0.416 |
| Amax      | CO₂    | 2.942 | 0.06 |
|           | Year   | 13.474 | < 0.001 |
|           | CO₂ × Year | 0.771 | 0.594 |
| Vcmax     | CO₂    | 1.662 | 0.194 |
|           | Year   | 2.791 | 0.030 |
|           | CO₂ × Year | 0.545 | 0.819 |
| Jmax      | CO₂    | 0.192 | 0.825 |
|           | Year   | 0.628 | 0.644 |
|           | CO₂ × Year | 0.251 | 0.979 |
| Leaf Total N | CO₂    | 3.701 | 0.026 |
|           | Year   | 5.295 | 0.002 |
|           | CO₂ × Year | 0.945 | 0.464 |

### Tab. 4 - Results statistics of diameter, height, Amax, Vcmax, Jmax and leaf total N of the studied species with F statistics and p-values from two-way repeated measured ANOVA. (Pd): Korean red pine (Pinus densiflora); (Fr): Chinese ash (Fraxinus rhynchophylla); (Sa): Korean mountain ash (Sorbus alnifolia).

| Species | Factors | Diameter | Height | Amax | Vcmax | Jmax | Leaf Total N |
|---------|---------|----------|--------|------|-------|------|--------------|
| Pd      | Year    | 0.632    | 0.540  | 14.449 | < 0.001 | 0.266 | 0.771 | 0.618 | 0.554 | 0.719 | 0.506 | 1.459 | 0.247 |
| Fr      | Year    | 0.249    | 0.995  | 1.250  | 0.306  | 1.189 | 0.374 | 2.817 | 0.051 | 0.511 | 0.810 | 3.793 | 0.006 |
| Sa      | Year    | 0.373    | 0.010  | 0.010  | 0.010  | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 |
| Sa      | CO₂ × Year | 2.537 | 0.21  | 0.456 | 0.935 | 0.545 | 0.765 | 1.368 | 0.292 | 0.507 | 0.815 | 2.646 | 0.021 |

Maximum rate of carboxylation (Vcmax) and electron transport (Jmax) are not provided in the text. However, the increase was maintained at 28.6% under eCO₂,1.8 in 2013 and 27.5% in 2017 relative to the rate under aCO₂.
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For Chinese ash, no statistical differences were found. However, its annual $V_{\text{max}}$ decreased under eCO$_{2}$ by 55.7% compared with that under aCO$_{2}$. In 2015 ($p = 0.03$, Fig. 2e), but there was no difference thereafter. All species showed no significant differences in $V_{\text{max}}$ due to CO$_{2}$ enhancement (minimum $p = 0.094$). The $J_{\text{max}}$ showed no significant differences under eCO$_{2}$ and year (Tab. 3, Tab. 4). However, it had a decreasing tendency of about 23.4% from 2013 (100.2 ± 7.2 μmol m$^{-2}$ s$^{-1}$) to 2017 (76.8 ± 3.1 μmol m$^{-2}$ s$^{-1}$) with no significance. Depending on the CO$_{2}$ concentration, there was no significant differences and tendency (minimum $p = 0.210$). In terms of response by species, all species showed no statistical differences with CO$_{2}$ and year (Fig. 2g, Fig. 2h, Fig. 2i).

**Leaf and soil N**

The leaf total nitrogen was significantly different under eCO$_{2}$ and year (maximum $p = 0.026$ – Tab. 3). The leaf total N exposed to CO$_{2}$ significantly ($p = 0.026$) decreased in the following order: aCO$_{2}$ (1.14 ± 0.06 %) > eCO$_{1.4}$ (1.28 ± 0.04 %) > eCO$_{1.8}$ (1.24 ± 0.03 %).

Korean red pine showed significant differences in leaf total N under CO$_{2}$ exposure ($p < 0.001$ – Tab. 4). The leaf total N decreased significantly by about 24.4% from 2013 (1.31 ± 0.08 %) to 2017 (0.99 ± 0.03 %). The leaf total N under eCO$_{2}$ decreased in the following order: aCO$_{2}$ (1.45 ± 0.15 %) > eCO$_{1.8}$ (1.21 ± 0.09 %) > eCO$_{1.4}$ (1.07 ± 0.04 %) but it was not significant ($p = 0.247$). The eCO$_{1.4}$ treatment showed the lowest leaf total N and the difference between aCO$_{2}$ and eCO$_{1.4}$ were 31.0% in 2013, 27.9% in 2015, and 10% in 2017 (Fig. 3a).

Chinese ash showed a significant decrease in leaf total N under eCO$_{2}$ and year ($p = 0.021$ and $p < 0.001$, respectively). The
leaf total N under eCO₂ decreased significantly (p = 0.021) in the following order: aCO₂ (1.4 ± 0.04 %) > eCO₂ (1.4 ± 0.04 %) > eCO₂ (1.36 ± 0.05 %). In particular, the leaf total N was higher under eCO₂, and eCO₂ was higher than under aCO₂ in 2015 (p < 0.001), but it became significantly lower under eCO₂ and eCO₂ than under aCO₂ over time (Fig. 3b). The difference between aCO₂ and eCO₂ was 27.8% in 2016, and 18.8% in 2017 (maximum p = 0.04).

Korean mountain ash showed no significant differences under eCO₂ and year (minimally p = 0.522). But it decreased significantly by 15.4% under eCO₂ compared with aCO₂, only in 2017 (p = 0.03 – Fig. 3c).

There was no significant difference in soil total N under eCO₂, in 2017 (p = 0.125). The absolute concentration of soil total N was very low, and therefore, the variation depending on CO₂ concentration was negligible (Fig. 4).

Discussion

Relationship between the CO₂ fertilization effect and growth

Several studies have reported that elevated CO₂ concentration due to climate change directly affects photosynthesis, suggesting that eCO₂ promotes ecosystem production and biomass accumulation (McCarthy et al. 2010, Norby et al. 2010, Reich et al. 2018). For instance, the net primary production (NPP) increased by 22–32% in the DukeFACE experiment, which conducted the CO₂ exposure for more than 10 years. In the Pop-FACE experiment, the di- ameter increased about 5% and the 12 species leaf area increased about 8% in seven FACE (Ainsworth & Long 2005, Finzi et al. 2007, McCarthy et al. 2010). In this study, the annual growth of the three spe- cies was analysed, confirming a significant enhancement in height and diameter un- der eCO₂ for the first two years. However, the CO₂ fertilization effect was not sus- tained thereafter (Tab. 1, Tab. 2, Fig. 1). Temporary CO₂ fertilization effect was also reported by other studies. In the Oak-Ridge FACE and BioCON experiments, the reduc- tion of CO₂ effect was offset after 6 and 3 years, respectively, and nitrogen fertiliza- tion showed an immediate increase in NPP (Reich et al. 2006, Norby et al. 2010). In addition, there was no CO₂ effect in Picea abies growing on a very low-nutrient soil (Ward et al. 2008). Moreover, in the Duke FACE experiment, where the CO₂ fertiliza- tion effect remained for more than 10 years, soil N positively correlated with productiv- ity increment under eCO₂ (McCarthy et al. 2010). Thus, soil nutrients and CO₂ fer- tilization effect appeared to be closely re- lated. In particular, in our study site, the soil total N was very low because the nearby forest soil was mixed with sand and leaf total N decreased over time. For this reason, we argue that growth promotion through the CO₂ fertilization effect was not sustained.

Changes in photosynthetic properties under elevated CO₂ concentration

Elevated atmospheric CO₂ concentration increases the difference in the partial pres- sure of CO₂ between the atmosphere and leaf mesophyll tissues, increasing the maxi- mum photosynthetic rate (Curtis & Wang 1998, Ainsworth & Rogers 2007). Twelve FACE experiments showed that the aver- age Amax of all the tested species increased by about 31%. Depending on species, it was increased by about 31% in Pinus australis (Mozdzer & Caplan 2018), 67% in P. taeda, and 62% in Liquidambar styraciflua (Ells- worth et al. 2012). However, over time, the increase of Amax under eCO₂ was reduced by the acclimation of photosynthetic proper- ties (Ainsworth & Rogers 2007). In our study, the reduction of Amax under eCO₂ varied depending on the species (Fig. 2). Korean red pine and Korean mountain ash did not show a significant difference since 2013, which was only three years af- ter eCO₂ exposure. Chinese ash showed the enhancement in 2013, but the increase in Amax was reduced over time. Amax of Korean mountain ash under aCO₂ was maintained over time, but it was decreased in Chinese ash, which might have been due to the low soil nutrient (Fig. 2, Fig. 4). This decrease in the Amax resulted in the down-regulation of the Vcmax and Jmax. In other words, the Amax is usually measured under the CO₂ concentra- tion of each treatment, therefore no differ- ence or a decrease indicates that photosyn- thesis enhancement is not maintained, rather lowered over time. Similar to previ- ous studies (Drake et al. 1997, Martínez- Carrasco et al. 2005), we observed a reduct- ion in the Vcmax and Jmax under eCO₂. This reduction usually occurs after long term CO₂ exposure (Ainsworth & Rogers 2007, Norby et al. 2010). In P. ponderosa exposed to eCO₂ for 6 years, the Vcmax and Jmax were decreased by about 36% and 21%, respec- tively (Tissue et al. 1999), and the Vcmax was decreased by about 19% in P. abies (Uddling & Wallin 2012). However, in some cases, the reduction of photosynthetic ability un- der eCO₂ did not occur even in the long term (more than 6 years – Bader et al. 2010, Darbá et al. 2010, Warren et al. 2015). In an experiment on Fagus sylvatica, Quercus petraea, Carpinus betulus, Acer campestre, and Tilia platyphyllos in mature deciduous forests, the increase in the Amax was maintained even after 8 years of CO₂ treatment, and the down-regulation of Vcmax and Jmax did not occur. Similarly, in the Aspen FACE experiment, the increases in Vcmax (48%-85%) and Jmax (23%-34%) were sus- tained for 11 years, and no reduction oc- curred. Warren et al. (2015) also showed that the increase in photosynthesis was maintained during the first 8 years when the leaf N was 0.2 mg cm⁻² more, but af- ter a decrease of leaf N, the CO₂ fertiliza- tion effect disappeared. Thus, the increase in photosynthesis and the decrease in pho- tosynthetic ability are largely affected by the nitrogen available in the environment. These studies were conducted in well-de- veloped organic layer of forest floor, such as mature stands (Bader et al. 2010), or soil N of 3% or more (Darbá et al. 2010), i.e., environments with considerably higher N than normal forest soil. On the contrary, the long-term exposure under eCO₂ leads to nitrogen limitation in common forest soil, which results in PNL that decreases photosynthesis and growth increment (Reich et al. 2006, Norby et al. 2010, Feng et al. 2015, Rüting 2017).

Relationship between photosynthetic properties (Vcmax and Jmax) and leaf nitrogen

In general, the leaf total N is positively correlated with the photosynthesis ability (Evans & Seemann 1989). Several studies have shown that the leaf N decreased in re- sponse to long-term eCO₂ condition (Ells- worth et al. 2012). The elevated CO₂ con- centration increases the capacity of the ru- bisco enzyme to adsorb carbon dioxide, thereby causing carboxylation and a de- crease in the demand of nitrogen for ru- bisco (Nowak et al. 2004, Liu et al. 2012). Similarly, in this study, the leaf N was signifi- cantly lowered under eCO₂ over time (Fig. 3). In addition, studies have shown that the Vcmax and photosynthesis ability, decreased as the leaf N decreased (Ainsworth & Long
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2005, Warren et al. 2015). Thus, fertilization at the time of nitrogen limitation increased the CO₂ fertilization effect again or the decreasing rate was reduced (Liberloo et al. 2007, Crous et al. 2008, Terrer et al. 2018).

In general, there is a strong correlation between $V_{\text{Cmax}}$ and $J_{\text{max}}$ with $J_{\text{max}}/V_{\text{Cmax}} = 1.5-2.0$ at 25 °C (Medlyn et al. 2002, Walker et al. 2014, Cho et al. 2019). Similarly, $V_{\text{Cmax}}$, $J_{\text{max}}$, and leaf N showed correlation under eCO₂ (Crous et al. 2008, Warren et al. 2015). Therefore, when the leaf N and $V_{\text{Cmax}}$ were decreased after long-term eCO₂ treatment, the $J_{\text{max}}$ also decreased in some cases (Herrick & Thomas 2001, Medlyn et al. 2002, Sholts et al. 2004, Crous et al. 2008, Bader et al. 2010). As in our study, the decrease in $J_{\text{max}}$ (Tab. 4) was relatively lower than that of $V_{\text{Cmax}}$ in some cases (Liberloo et al. 2007, Warren et al. 2015). Moreover, these changes are different depending on species. Chinese ash and Korean red pine showed a decrease only in the $V_{\text{Cmax}}$ while Korean mountain ash did not show any decrease in both the above photosynthetic parameters (Fig. 2). These differences due to the change in intracellular nitrogen distribution under eCO₂ are dependent not only on the environment but also on the species. Further studies are needed to examine how species change the intercellular nitrogen distribution under elevated CO₂ (Evans & Seemann 1989, Hikosaka 2004).

CO₂ fertilization effect and PNL

The enhanced productivity of forest ecosystem due to the CO₂ fertilization is heavily influenced by the nutrients available in the soil (Finzi et al. 2007). PNL is a hypothesis that the increased forest productivity due to eCO₂ decreases over time because of the increased N accumulation in the biomass, resulting in a decrease of soil N availability, an increase of N immobilization and a decrease of N mineralization (Luo et al. 2004). In the long-term eCO₂ at Duke FACE, Oak-Ridge FACE, and BioCON experiments, N fertilization led to an immediate increase in NPP. Therefore, there seemed to be an interaction between eCO₂ and N in terms of increased productivity (Reich et al. 2006, McCarthy et al. 2010, Norby et al. 2010). In particular, the soil N is important and N deficiency leads to a decline in production due to PNL even under eCO₂ (Norby et al. 2010). Such N deficiency changes the N distribution in the plants’ organs for effective nitrogen utilization, resulting in a decrease of the N used for above-ground photosynthesis (Pettersson & McDonald 1994). In addition, N distribution in photosynthetic apparatus such as Rubisco is greatly reduced. Therefore, nitrogen-use efficiency is increased generally (Vicente et al. 2016, Sharwood et al. 2017), but the persistence of such an increase is controversial (Ainsworth & Rogers 2007, Leakey et al. 2009). There is limited information about N distribution in the above- and below-ground under eCO₂. Therefore, it is necessary to determine and quantify the distribution of N in the above- and below-ground through follow-up studies.

Conclusions

In this study, we investigated the physiological and morphological characteristics of Korean red pine, Chinese ash, and Korean mountain ash, which are native tree species in Korea, under eCO₂ over a period of 8 years. We also examined the longevity of CO₂ fertilization effect in our study sites. The CO₂ fertilization effect caused by eCO₂ led to an increased growth in the early stage of exposure, but there was no significant difference thereafter. Photosynthetic properties showed a decreasing tendency in all species and a down-regulation of photosynthetic capacity increase with time, especially in Korean red pine and Korean mountain ash. The analysis of leaf and soil N to identify the cause revealed a significant decrease of leaf N under eCO₂. We argue that the enhancement of productivity might have decreased due to low soil N.

In conclusion, progressive nitrogen limitation (PNL) caused by the N reduction might have already started or is about to start in our study sites. Further investigation is needed to clarify N use efficiency and nitrogen distribution according to species.

List of abbreviations

(OCT): Open Top Chamber; (aCO₂): current atmospheric CO₂ concentration; (eCO₂): 1.4 times higher CO₂ concentration than the current concentration (Chamber 2); (eCO₂): 1.8 times higher CO₂ concentration than the current concentration (Chamber 3); (A): maximum photosynthetic rate; (V_{\text{Cmax}}): maximum rate of carboxylation; (J_{\text{max}}): maximum electron transport rate.

Acknowledgments

This research was funded by the National Research Foundation of Korea, by the project “Evaluation of climate change adaptation mechanisms of native temperate tree species and its ecological effects using open-top chambers” (2014R1A1A2055127) and “Testing progressive nitrogen limitation and nitrogen use efficiency increment through the quantification of leaf nitrogen allocation” (2017R1A2B2012605). We thank members of forest ecophysiology laboratory for their assistance with field sampling.

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Supplementary Material

Fig. S1 – The Open Top Chamber (OTC) user in the experiment.

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