Effect of experimental climate change and soil moisture content on germination and early growth response of *Quercus dentata* seedlings

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**ABSTRACT**

This study was conducted to investigate the effect of changes in soil moisture content under climate change conditions on the growth response of *Quercus dentata*, a representative species of the genus *Quercus* on the Korean peninsula. The results showed that *Q. dentata* germination increased by 9.4% under climate change conditions (RCP 4.5 scenario), whereas the below-ground biomass and plant biomass increased by 1.3 and 1.2 times, respectively. However, the soil moisture treatment condition solely affected the leaf area, below-ground biomass, and plant biomass but not the germination percentage, germination speed, above-ground length, and above-ground biomass. The variance across the measured growth variables was considerably higher in the control group than in the climate change treatment group, whereas the variance was lower for lower soil moisture content. The findings suggested that under climate change conditions, *Q. dentata* germinated rapidly and exhibited broader leaf area and increased development below ground, which may be advantageous for the early establishment of seedlings. However, the plants may face difficulties in conditions with low soil moisture content. In conclusion, with continuous climate changes, *Q. dentata* seedlings are predicted to efficiently adapt to the altered soil moisture content to exhibit even more reliable growth than with the current condition. However, the growth of *Q. dentata* seedlings would be more difficult with severely low soil moisture content than with abundant soil moisture content, which is predicted to be detrimental to population maintenance in the long term.

**KEYWORDS**

Initial establishment; below-ground biomass; population variance; environment gradient; individual characteristics

**ARTICLE HISTORY**

Received 27 September 2022
Accepted 2 November 2022

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**Introduction**

*Quercus dentata* is one of the key temperate deciduous broad-leaved trees distributed throughout East Asia, including South Korea, in the northern hemisphere. In South Korea, the species is distributed from the lowland stone fields below 800 m altitude to the mountainsides across limestone zones, western coastal areas (Kim 2010), eastern coastal areas, and southern coastal lines (Chung and Lee 1965; Kim et al. 1990; 1991; D’Arrigo et al. 1997; Lee 2003; Menitsky 2005; Yi et al. 2007; Kim and Kim 2017; Hong et al. 2019; Peng et al. 2020). In the forests of South Korea, *Q. dentata* trees form a single community within a narrow area; therefore, they exhibit a low rate of occurrence (Kim 2013; Kim and Kim 2017). They are the representative successor trees in *Pinus densiflora* and *P. thunbergii* communities (National Ministry of Environment 2018; Hong et al. 2019). *Q. dentata* is known to inhabit areas with dry climate and soil (Lim 1995) or areas with low humidity that present somewhat dichotic growth conditions (Kim and Kim 2017) rather than areas with moderate moisture. Compared with other deciduous broad-leaved trees of the same genus, *Q. mongolica*, *Q. liaotungensis*, *Q. aliena*, and *Q. variabilis*, *Q. dentata* have been predicted to be more resistant to dryness as they are also found distributed in the southern hemisphere (Box et al. 2012). However, the distribution characteristics of *Q. dentata* and changes in its growth response according to the changes in soil moisture content in the continuum of climate change remain unknown. Thus, predicting the habitat environment of *Q. dentata* through indoor cultivation is crucial.

Following the industrial revolution, human activities have excessively increased the emission of greenhouse gases, causing global warming and rapid climate change, with serious effects on natural ecosystems. The entire global community is thus faced with the
problem of survival (Intergovernmental Panel On Climate Change 2007; Kim 2012; Ciais et al. 2014). In this situation, forest ecosystems have attracted increased interest as they can both adapt to and reduce climate change (Kim and Kim 2017). In South Korea, the rise in temperature due to climate change is predicted to have a complex impact on the growth of trees in forests and forest productivity (Adams et al. 2019; Kwon et al. 2020; Korea Meteorological Administration (KMA) 2011, 2020). Woody plants of the Quercus and Pinus genera are the dominant plant species in the forests of South Korea. However, a rise in forest temperature by only 2°C could alter the current climate zone of the central forest regions from temperate to subtropical (Lim et al. 2006). Quercus trees have been predicted to exhibit stronger resistance to temperature rise than Pinus trees (Byun et al. 2010; Chung and Lee 1965).

In South Korea, the recent changes in precipitation patterns and abnormal temperatures due to climate change have frequently caused ecological issues such as the seedling death of Pinus trees that represent the forest ecosystems on the Korean peninsula (Lee and Lee 2003; Lim et al. 2006; Shin and Lee 2008; Chun and Lee 2013; Kim and Kim 2017). The severe changes in precipitation pattern could influence the water penetrating the forest soil (Renard et al. 1996; Römken et al. 2002; Ahn et al. 2013), altering the soil moisture content and impacting the growth and survival of several tree species including Q. dentata (Tinker and Nye 2000; Koo et al. 2007; Byun et al. 2010). According to the RCP 4.5 scenario, the mean annual precipitation on the Korean peninsula at the end of the twenty-first century will increase by 4.5% nationwide, with a notable increase in southwestern coastal areas compared with that in eastern coastal areas (Korea Meteorological Administration (KMA) 2020). The altered temperature and precipitation are estimated to cause a relatively high level of vulnerability of vegetation distribution across the forests of South Korea in northeastern and southern regions but a substantially low level of vulnerability in southwestern regions (Kim and Kim 2017). Quercus dentata is mainly found naturally growing in western coastal areas in southwestern regions as successor trees of P. thunbergii and other tree communities (Lee et al. 2004; National Ministry of Environment 2018). Using geographical modeling, the area of distribution of Q. dentata trees has been predicted to rapidly decrease in eastern coastal areas but remain relatively unchanged in western coastal areas in response to increasing temperature and precipitation (National Institute of Forest Science 2015). The decline of coniferous tree communities in South Korea in the future due to the climate change is conjectured to induce a gradual increase in the relative importance of Q. dentata as successor trees of coniferous trees through increased density and cover rate (Korea Forest Research Institute 2014).

Germination, growth, and survival of seedlings are the most important steps in the plant life cycle that are directly connected to the plant’s survival (Corbineau and Come 2015). The successful occurrence of germination and seedling growth is essential for the maintenance of plant populations (Barbour et al. 1987; Burton and Bazzaz 1991; Donohue 2005; Han 2018; Park et al. 2019). Seedlings, in particular, display more sensitive responses to the environment than adult trees (Kim 2012). According to the RCP 4.5 scenario suggested by the IPCC, the temperature and mean annual precipitation on the Korean peninsula as part of the temperate zone throughout East Asia in the northern hemisphere, are predicted to rise by 2.1°C and 4.5%, respectively, at the end of the twenty-first century (Ciais et al. 2014; Korea Meteorological Administration (KMA) 2020).

The germination type of Q. dentata is a slow germination type (germination in January–February) (Matsuda and Mcbride 1989) and germination of Q. dentata was confirmed in January of the following year in Korea (Jeong et al. 2021). On the other hand, the root germination period of Q. mongolica is from September to October (Jeong et al. 2021), and it is a type of rapid germination (Germination in October–November) (Matsuda and Mcbride 1989). Depending on the dormancy state, the metabolic activity in the acorn increases (Yıldız et al. 2017). For example, red oak exhibits various dormancy properties. On the other hand, acorns and oaks of the subgenus Lepidobalanus do not show complete dormancy, but some white oak species show epicoxial dormancy (Urbietta et al. 2008; Tantray et al. 2017) In this way, the seeds germinate so that they can survive and grow in the seedlings at a favorable time and place (Urbietta et al. 2008). Even in plants of the same genus, many environmental factors are expected to be involved in relation to differences in seed dormancy, germination period, and seedling growth including soil moisture content (Yıldız et al. 2017).

To predict the changes in the Q. dentata population characteristics according to the increase in precipitation on the Korean peninsula with continuous climate changes, an investigation of the influence of the consequent increase in soil moisture content on the Q. dentata seedling germination percentage (GP), germination speed, and growth is a prerequisite (Danby and Hik 2007).

Numerous studies have experimentally modeled or predicted the effects of climate change conditions on Q. mongolica, Q. acutissima, Q. variabilis, Q. aliena, and Q. serrata but not on Q. dentata (Jeong et al. 2010; Cho et al. 2012; Cho, Jang, et al. 2013; Cho, Kim, et al. 2013; Cho 2014; Jeong et al. 2021). No study has comparatively analyzed the effect of changes in soil moisture under controlled climate change conditions on the germination and growth response of Q. dentata. Therefore, predicting the seedling germination and early growth response of Q. dentata based on the changes in the soil moisture content due to climate change is difficult. This study aimed to determine the effects of the changes in the soil moisture content under climate change conditions on the ecological characteristics of Q. dentata.
Materials and methods

Climate change and soil moisture content gradients

The present investigation was conducted in two semi-sealed glass greenhouses (12 m $L \times 7.8$ m $W \times 5$ m $H$) with a 46.8 m$^2$ surface area; one for the control group and the other for the climate change treatment group. For the control group, the air temperature and CO$_2$ concentration of the actual atmosphere were applied. Based on the 24-hour cycle, the mean temperature and CO$_2$ concentration throughout the study period were $22.2 \pm 5.0 ^\circ$C and $330.6 \pm 8.1$ ppm (Figure 1), respectively. For the climate change treatment group, we applied the conditions predicted in the RCP 4.5 scenario, according to which the mean annual temperature would increase by 2.1 $^\circ$C and the CO$_2$ concentration would be 540 ppm on the Korean peninsula at the end of the twenty-first century (Ciais et al. 2014). The LCS environment measure system (LCSEMS-002, Parus Co. Korea) was used to modulate the temperature and CO$_2$ concentration for the climate change treatment group, and measurements were taken at 10 min intervals. A ventilator was used to maintain higher temperatures than the control group by approximately $2.0 \pm 0.3 ^\circ$C. To control the CO$_2$ concentration, two liquid CO$_2$ gas barrels (Carbon dioxide extra dry 99.9% min (N30), SPECIALGAS, Korea) were connected to a plastic hose (0.2-mm diameter) to increase the concentration through spraying at 2 m above the ground. The conditions of the climate change treatment were controlled and maintained for 8 months from March to October 2017. The CO$_2$ concentration of the control and climate change treatment groups was estimated based on the data obtained during the hours without plant transpiration between 18:00 and 6:00. The concentration was approximately 2-fold higher in the climate change treatment ($536.7 \pm 14.9$ ppm) group than in the control group (Figure 1).

The RCP 4.5 scenario predicts that the precipitation in South Korea will increase by 5–15% by the end of the twenty-first century (Korea Meteorological Administration (KMA) 2014). Hence, the soil moisture content across the forests in South Korea is predicted to be 15% higher than the current content due to the increased precipitation (Lee 1981). To set the soil moisture content gradients, 100 mL of water was supplied to a pot ($24$ cm $W \times 23.5$ cm $H$) filled with dried soil (2 kg) up to 20 cm. After one hour, a soil moisture sensor (DM-5, Takemura, Japan) was inserted to a 15-cm depth toward the root from the surface at the maintained angle of 45$^\circ$, and the soil moisture content was measured three consecutive times. With a 100-mL water supply, the soil moisture content was $15 \pm 5.4$%, which was set as the lowest gradient of soil moisture content (M1). Based on this, 200 mL of water was supplied to increase the soil moisture content by 10% at a time to set the low ($25 \pm 8.9$%, M2), high ($35 \pm 11.0$%, M3), and highest ($45 \pm 12.1$%, M4) gradient conditions. For the highest gradient (M4), the criteria were the field moisture capacity immediately before the water leaks out at the bottom of the pot during water supply. The soil water was supplied when the error range was within 5% for the soil moisture content. The irrigation period was 3–4 days during summer with a high level of evapotranspiration and 6–7 days at all other times. The water for the treatment was tap water stabilized before use. In addition, soil moisture content was measured at least once a month during the study period. In addition, the statistical analysis to verify the supply of a constant level of soil moisture confirmed that soil moisture contents in the control and climate change treatment groups were maintained at a constant level based on the soil moisture gradient ($p > 0.05$, Figure 2).

Soil, organic ingredients, and light were supplied using identical methods for both control and climate change treatment groups. For soil, the standard soil (K.S.L 5100, Joomoonjin Silica Sand, Co., Ltd. Korea) of similar particle sizes ($\leq 2$ mm) was used. For organic ingredients, the general organic content of oak forests based on dry sand (100%) (KLTER (Korean Long-Term Ecological Research) 2012) was used in the treatment based on volume ratios, while the organic fertilizer (Hanareum Soil, Shin-sung Mineral, Co. Ltd. Korea) containing 51.5% cocopeat, 15% perlite, 13% vermiculite, 10% peat moss, 10% Zeo-lite, and 0.4% fertilizers, of $< 0.3$ Mg/m$^3$ bulk density, pH 5–7, and 1.2 ds/m EC, was used. In addition, the pots were moved to different locations in 1-month intervals within the set greenhouse district to prevent the pot location effect, as there could be variations in the microenvironment, such as the light inside the greenhouse. The experiment was repeated four times for each soil moisture content gradient for the control and climate change treatment groups; in total, 32 pots were used.

Climate change and soil moisture content gradients

To conduct the seeding and cultivation experiment, Q. dentata fruits were collected from the Q. dentata colony growing naturally on Mt. Joryeongsan, located in
Goesan-gun, Chungcheongbuk-do, South Korea, in October 2016. The acorns were obtained from a single branch to minimize the influence of maternal inheritance, while those of similar size or biomass (2.82 ± 0.72 g) were selected and stored in a low-temperature storeroom (4°C, relative humidity 40%) for approximately 6 months.

To conduct the germination experiment, the seeds that had germinated during storage or been damaged by fungi or pests were excluded, and only the fresh seeds were selected. Four acorns in optimum conditions were seeded in a pot on March 4th, 2017. The criteria for germination were the first visible sign of the radicle from the planted seed shooting up through to the soil surface. The number of germinated seeds was counted for 83 days in total, from the first germinated seed to the last one. During this period, the state of germination was monitored from 15:00–17:00 in four-day intervals. In the germination experiment, the GP, mean germination time (MGT), and number of days to 50% of the final GP (T50) were measured. The final GP was calculated by dividing the final number of germinated seeds by the total number of planted seeds and estimating the percentage. The MGT was calculated using the following equation: MGT = \( \frac{\sum (t_n \cdot n_i)}{N} \), where \( t_i \) indicates the number of days after explanation, \( n_i \) indicates the number of germinated seeds on the day of investigation, and \( N \) indicates the total number of germinated seeds (Edwards 1934). The \( T_{50} \) was calculated using the equation suggested by Coolbear et al. (1984).

Growth variables were measured for the seedlings cultivated between March and October 2017. Overall, the leaf size was similar across Q. dentata seedlings. To measure the leaf area (LA) (cm²), three leaves (as the minimum unit of statistical analyses) were obtained from the topmost part of the stem. After removing the petiole, the LA was estimated using a LA meter (SI700, Skye, UK). The criteria to differentiate between above ground and below ground was the presence of cotyledon or cicatrix, while the length (cm) was measured using a plastic ruler. To measure the dry weight (g), the plant was taken out of the pot, washed with water to remove the soil completely and dried in a 70°C dehydrator for 48 h. The biomass was measured using an electronic scale (UX400H, SHIMADZU, Japan). The data measured for growth items were analyzed after calculating the average value for each pot.

**Statistical analysis**

Normal distribution was tested using Shapiro–Wilk test, and due to the lack of normal distribution (\( p < 0.05 \)), nonparametric analyses were performed on the differences in Q. dentata germination and morphological characteristics of seedlings for each environmental gradient. The significance of these differences per gradient was tested using Mann–Whitney U test and Kruskal–Wallis test. In addition, a factor analysis (varimax rotation method) was performed using the coefficients of mean values estimated for six morphological characteristics to identify the changes in morphological characteristics of Q. dentata seedlings according to the soil moisture treatment in the climate change condition (Cho et al. 2012). The data used in the factor analysis were standardized to remove the errors for the units of variables. And the relationship between the growth characteristics of Q. dentata seedlings and the temperature and moisture content were analyzed by Spearman’s correlation analysis. The Statistica 8 statistical package (Statsoft Inc. Tulsa, USA) was used for the statistical analyses.

**Results**

**Germination**

GP values in the control group were, from the lowest gradient (M1) of soil moisture content to the highest gradient (M4), 81.25 ± 12.50%, 87.50 ± 14.43%, 93.75±12.50%, and 62.50 ± 32.27%, while those in the climate change treatment group were 87.50 ± 14.43% for M1, M2, and M3 and 93.75 ± 12.50% for M4. GP was not affected by temperature or soil moisture content (\( p > 0.05 \)) (Figure 3).

MGT values were, from the lowest gradient (M1) of soil moisture content to the highest gradient (M4), 66.92 ± 15.24 day, 60.42 ± 12.00 day, 55.89%±14.35 day,
and 57.25 ± 5.74 day in the control group and 49.89 ± 1.64 day, 56.17 ± 4.69 day, 47.25 ± 9.84 day, and 49.60 ± 4.14 day in the climate change treatment group. GP was not affected by temperature or soil moisture content (p > 0.05). The mean MGT was 60.12 ± 11.83 days in the control group and 50.73 ± 5.08 days in the climate change treatment group, with the latter showing a higher rate by approximately 9.39 days (p < 0.05).

Number of days to 50% of the final GP (T50) values were, from the lowest gradient (M1) of soil moisture content to the highest gradient (M4), 66.50 ± 15.28 day, 59.13 ± 13.85 day, 57.88±13.83 day, and 55.13 ± 5.51 day in the control group and 47.50 ± 9.65 day, 53.88 ± 9.65 day, 45.50 ± 9.17 day, and 44.50 ± 4.60 day in the climate change treatment group. T50 was not affected by temperature or soil moisture content (p > 0.05). The mean T50 was 59.66 ± 12.12 days in the control group and 47.84 ± 8.13 days in the climate change treatment group, with the latter showing a higher rate by approximately 11.81 days (p < 0.05).

The results indicated that the climate change treatment had changed the Q. dentata germination characteristics so that both MGT and T50 were facilitated by at least 9.4 days, while the soil moisture treatment had had no influence on GP, MGT, or T50.

**Growth response**

The LA did not vary according to the soil moisture content in either control or climate change treatment group. In the condition of the highest gradient of soil moisture content (M4), the LA was higher in the climate change treatment group than in the control group (p ≤ 0.05) (Figure 4). The above-ground length (AGL), below-ground length (BGL), and above-ground biomass (AGB) did not vary according to the soil moisture content in either control or climate change treatment group, and no between-group variation was found (p > 0.05) (Figure 4).

The below-ground biomass (BGB) did not vary according to the soil moisture content in either control or climate change treatment group. The control group and the climate change treatment group were heavier in the climate change treatment group than the control group in all soil moisture content conditions (p ≤ 0.05). In addition, the average underground weights of the control group and the climate change treatment group were 3.77 ± 0.13 g and 5.01 ± 0.18 g, respectively, and the climate change treatment group was 1.24 ± 0.05 g heavier than the control group (p < 0.001) (Figure 4).

The plant biomass (PB) did not vary according to the soil moisture content in either control or climate change treatment group. In all soil moisture conditions except M3, the PB was higher in the climate change treatment group than in the control group (p ≤ 0.05). The mean PB was 5.26 ± 0.16 g in the control group and 6.43 ± 0.16 g in the climate change treatment group, with the latter being heavier by 1.17 ± 0.00 g (p < 0.001) (Figure 4). The results indicated that the climate change treatment had increased the BGB and PB among the Q. dentata growth characteristics, while the soil moisture treatment had increased the LA, BGB, and PB in the condition of M4; however, no significant change in AGL, BGL, or AGB was found (Figure 4).
Relationship between Q. dentata growth and environment

In the climate change condition, the individual variance based on the soil moisture treatment was slightly higher in the climate change treatment group than in the control group (Figure 5). In addition, compared to the plants in the control group, those in the climate change treatment group exhibited more positive effects on growth characteristics. In the 2D coordinates, the distribution of the plants in the climate change condition was mainly detected in the second and third quadrants for the control group but in the first and fourth quadrants for the climate change treatment group (Figure 5). The distribution varied between the general atmospheric temperature condition and the temperature rise condition. Although the individual variance based on the soil moisture gradient showed an increasing trend from the lowest gradient (M1), low gradient (M2), high gradient (M3), to the highest gradient (M4), there was no distinct variation (Figure 5). Applying the ordination method, the key morphological characteristics that influenced the pattern of individual distribution were BGB and PB for Factor 1 (40.54%) and AGL and AGB for Factor 2 (22.68%) (factor loading ≥0.7) (Table 1). The correlation analysis of the environmental factors and morphological characteristics showed a positive correlation solely between the temperature and BGB and PB ($p \leq 0.001$), while the moisture content was not correlated with any of the morphological characteristics (Table 2).

The results indicated that individual plants varied between the general atmospheric condition and climate change treatment condition. The environmental factor that influenced the Q. dentata growth response was temperature rather than moisture content, with a notable correlation of temperature with the increase in BGB and PB.

Discussion

Germination

Germination is the first step in plant establishment and does not occur without successful germination establishment (Barbour et al. 1987). Seed germination is influenced by various factors, including environmental factors such as CO$_2$ and water levels, temperature, and seed storage conditions (Kim et al. 2005). The temperature rise condition in this study was shown to induce no variation in the GP of Q. dentata but to reduce the MGT and $T_{50}$ compared to the control to imply an effect on the germination speed (Figure 3). This was in line with a study reporting an increase in Q. dentata germination rate by 14 days under high...
temperature than under general atmospheric temperature (Jeong et al. 2021). Additionally, the germination speed of *Q. acutissima*, *Q. variabilis*, *Q. mongolica*, *Q. aliena*, and *Q. serrata*, the tree species of the same genus as *Q. dentata*, increases under global warming conditions (Park et al. 2019; Jeong et al. 2021). As the seed germination speed is directly related to interspecies competition on the use of resources required for establishment, *Q. dentata* is likely to be the dominant species in the competition for establishment when the temperature rises, against other herbs or trees whose seeds display weaker competitiveness over resources in the forest. However, the seeds of *Q. dentata* showed no variation in GP or speed from M1 to M4, a condition where the soil is periodically completely soaked in water (Figure 3). This agreed with the study reporting the lack of variation in GP according to varying soil moisture gradients in the investigation of other dominant *Quercus* species in the forests of South Korea; *Q. serrata*, *Q. mongolica*, and *Q. variabilis* (Beon 2000). Comparatively, the GP of *Q. dentata* is presumed not to have been significantly affected by the soil moisture content. However, an increase in seed germination speed may not always be advantageous in the establishment if the physical characteristics of the habitat are also taken into account, such as the seasonal

Figure 5. Distribution of factor scores according to the soil moisture content and temperature gradients (n = 32) between control (n = 16) and climate change treatment conditions (n = 16) and six growth characteristic variables of *Quercus dentata* seedling by factor analysis with the varimax rotation method. The arrows mean factor loadings of each variable on Factors 1 and 2. LA: leaf area; AGL: above-ground length; BGL: below-ground length; AGB: above-ground biomass; BGB: below-ground biomass; PB: plant biomass. The dotted line on the left surrounding the filled shapes indicates groups and encircles the objects in the control group, and the dotted line on the right surrounding the empty shapes indicates in the climate change treatment group. C: control; T: treatment; –M1: lowest soil moisture content; –M2: low soil moisture content; –M3: high soil moisture content; –M4: highest soil moisture content.

Table 1. Factor loadings on the six growth characteristic variables of *Quercus dentata* seedling by factor analysis with the varimax rotation method.

| Variable | Factor 1 | Factor 2 |
|----------|----------|----------|
| LA       | 0.583    | 0.072    |
| AGL      | 0.138    | 0.872    |
| BGL      | 0.680    | −0.428   |
| AGB      | 0.190    | 0.700    |
| BGB      | 0.792    | 0.218    |
| PB       | 0.860    | 0.289    |

Eigenvalue 2.43 1.36
Cumulative variance explained (%) 40.54 63.22

LA: leaf area (cm²); AGL: above-ground length (cm); BGL: below-ground length (cm); AGB: above-ground biomass (g); BGB: below-ground biomass (g); PB: plant biomass (g). The number of samples for each growth item is 32, for a total of 192 samples for the 6 growth items.

Table 2. Spearman correlation coefficient between environmental and growth characteristics of *Quercus dentata* seedling.

| Variable | Temperature (°C) | Soil moisture content (%) |
|----------|------------------|---------------------------|
| LA       | 0.271            | 0.254                     |
| AGL      | 0.230            | −0.111                    |
| BGL      | 0.278            | 0.042                     |
| AGB      | 0.074            | −0.024                    |
| BGB      | 0.866*           | 0.106                     |
| PB       | 0.718*           | 0.221                     |

Notes. *Correlation is significant at the 0.05 level.

LA: leaf area (cm²); AGL: above-ground length (cm); BGL: below-ground length (cm); AGB: above-ground biomass (g); BGB: below-ground biomass (g); PB: plant biomass (g).
characteristics of the dominant colony in the habitat where the seeds have germinated (e.g. leaf openness and leaf falling of the dominant tree species) and the ecological disturbance. Therefore, to understand the impact of the rapid germination speed of *Q. dentata* seeds, the physical characteristics of the natural habitat of *Q. dentata* should also be taken into consideration.

**Growth response**

In this study, the climate change treatment caused an increase in the BGB and PB of *Q. dentata* but did not influence the AGL, BGL, or AGB (Figure 4). These findings coincided with the findings of a study reporting that the global warming phenomenon generally increased the leaf size of seedlings with incomplete xylem growth or below-ground rooting compared to that of adult plants (Kwon et al. 2020); additionally, the rate of growth was higher below ground than above ground (Kimball et al. 1993; Zhu et al. 1999; Onoda et al. 2009; Kim 2012). The broadening of LA due to increased temperature and CO₂ concentration was also displayed by *Q. serrata* and *Q. aliena*. The increase in LA is presumed to be the means to facilitate the CO₂ dispersion through leaf pores to increase the rate of photosynthesis (Cho, Jang, et al. 2013). In the condition of increased temperature and CO₂ concentration, compared to the control, the biomass and growth of *Q. acutissima* and *Q. variabilis* seedlings were not affected (Cho, Kim, et al. 2013) in contrast to the growth of *Q. dentata* seedlings observed in this study. On the other hand, the growth of the plant body and root of *Q. serrata* and *Q. aliena* was shown to have increased, which coincided with this study (Cho et al. 2012). Notably, *Q. dentata* seedlings across climate change conditions showed higher biomass below ground than above ground (Figure 4), which agreed with the study reporting that the accumulation of materials below ground increased compared to above ground when the seedlings inhabit a place exposed to several complex environmental changes (Tilman 1998). Based on the results, the increase in the BGB of *Q. dentata* seedlings in the climate change condition is presumed to be for reinforcing the support function toward establishment or extending the role of the root as a storage organ for the regeneration of the stem in subsequent years. In addition, compared to other *Quercus* species, *Q. dentata* exhibited the highest rate of regeneration of sprouts from the stubble in regions of frequent forest fire (Ha 1989; Menitsky 2005) to suggest that the below-ground response of *Q. dentata* may be sensitive to high temperatures. Until recently, growth responses of seedlings to climate changes in a greenhouse experiment involving various forest plant species have been shown to vary across species, while they may be positive (Skálová et al. 2015) or negative (Footitt et al. 2018). In this study, the results indicated that the rise in temperature had a positive effect on the early growth of *Q. dentata* seedlings (Enoch and Honour 1993; Byun et al. 2010; Albert et al. 2011).

The soil moisture treatment in this study, on the other hand, did not affect the growth of *Q. dentata* (Figure 4). This finding was in line with that of a previous study where the biomass of *Q. dentata* was compared according to soil moisture content (Lee et al. 2010), as well as a study reporting the lack of influence of precipitation on the biomass of *Q. dentata* seedlings (Han et al. 2009). However, the LA of *Q. dentata* increased in the temperature rise condition than in the general atmospheric condition when the soil moisture content was of the highest gradient (M4) in addition to the increased levels of BGB and PB (Figure 4). Similar findings have been reported by a study on *Q. mongolica*, where the BGB rather than the AGB increased under water stress conditions (Kim and Kim 1994). For *Q. dentata* seedlings, following the increase in temperature and soil moisture content to promote development, it is presumed that the absorption of soil moisture below ground is effective, implying that *Q. dentata* would show reliable growth in an environment of increased soil moisture caused by the changes in precipitation with the temperature rise.

The factor analysis on the variations in environmental factors and six morphological characteristics showed that the individual variance according to the soil moisture treatment in the climate change condition was slightly higher in the climate change treatment group than in the control group (Figure 5). The individual distribution distinctly varied between the general atmospheric temperature condition and the temperature rise condition. However, for the individual variance based on soil moisture content gradients, an increasing trend was found from the lowest (M1), low (M2), high (M3), to the highest (M4). The individual variance in morphological characteristics showed narrower variations as the temperature increased, possibly indicating that continuous climate changes would increase the BGB of *Q. dentata* seedlings. The scope of influence of the extreme climate with the increase in the mean temperature of the Earth is predicted to extend to the shaded layers of forests (Bassow et al. 1994) and with the decline of the species more vulnerable to climate changes, including *P. densiflora* and *P. thunbergii*, the seedlings of the successor species *Q. dentata* is likely to become more important as they have shown increased germination speed with positive effects on the growth with the rise in temperature (Lee et al. 2004; National Ministry of Environment 2018). In addition, although *Q. dentata* seedlings were not affected by the soil moisture content, the variance in morphological characteristics decreased as the soil moisture content decreased, which is presumed to pose a disadvantage in time for population maintenance. The results suggested that, for predicting the establishment of *Q. dentata* seedlings based on the soil moisture content in the climate change condition, several different characteristics are in play rather than a few key determinants regarding the growth and survival of *Q. dentata* (Cho et al. 2012; Cho 2014).
Conclusion
The findings in this study suggested that compared with the current conditions, the climate change conditions would result in an increase in germination speed, BGB, and PB of *Q. dentata*. The root development caused by the rise in temperature would be advantageous in utilizing and storing soil moisture content and nutrients so that the early growth of seedlings would be successfully accomplished. In addition, with continuous climate changes, *Q. dentata* seedlings are predicted to efficiently adapt to the altered soil moisture content to exhibit even more reliable growth than with the current condition; the plant population would be adequately maintained, and the distribution area would be widened. Nevertheless, less variations were observed in the morphological characteristics of *Q. dentata* under lower soil moisture conditions. This finding implies that the growth of *Q. dentata* seedlings would be more difficult in soils with severely low moisture content than in soils with abundant moisture, posing a disadvantage for population maintenance in the long run.

Disclosure statement
No potential conflict of interest was reported by the author(s).

Funding
This work was supported by Korea Environmental Industry & Technology Institute (KEITI) through Wetland Ecosystem Value Evaluation and Carbon Absorption Value Promotion Technology Development Project, funded by Korea Ministry of Environment (MOE) (2022003630003).

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Disclosure statement
No potential conflict of interest was reported by the author(s).

Funding
This work was supported by Korea Environmental Industry & Technology Institute (KEITI) through Wetland Ecosystem Value Evaluation and Carbon Absorption Value Promotion Technology Development Project, funded by Korea Ministry of Environment (MOE) (2022003630003).

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