Effects of intraspecific competition on growth, architecture and biomass allocation of Quercus Liaotungensis

Xiao-zhou Yang, Wen-hui Zhang and Qiu-yue He

College of Forestry, Northwest A&F University, Yangling, People’s Republic of China

ABSTRACT
Liaodong oak (Quercus liaotungensis) is an ecologically important tree species on the Loess Plateau in China that experiences strong intraspecific competition. Therefore, here, we aimed to clarify the strategies of Liaodong oak under intraspecific competition by examining the growth, architecture, and biomass allocation, and analyzed their relationships with the competition intensity. We found that intraspecific competition severely limited the accumulation of biomass in Liaodong oak and this competition was asymmetric among individuals. Intense competition among these trees resulted in a greater allocation of biomass to the belowground parts, allowing them to compete for moisture, which is a limited resource. Aboveground, the trees tended to allocate more resources to their trunks to ensure that tree height growth was not affected, resulting in a decreased diameter at breast height (DBH)/tree height ratio and tapering of the tree, thereby improving stem quality. By contrast, the amount of biomass that was allocated to the branches was greatly reduced through a reduction in the diameter and length of the branches rather than the number of branches.

1. Introduction

Competition occurs between individuals of the same or different species when the required environmental resources or energy are insufficient or a particular environmental factor is limited (Seifert et al. 2014). In trees, competition mainly occurs between neighboring individuals and usually involves the competition between crowns for light resources or between belowground root systems for soil water and nutrients (Cahill 1999; Song et al. 2012). This neighborhood competition has been shown to affect the growth, stem shape, crown shape, and biomass allocation of trees (Wu and Wang 2000; Liu et al. 2010; Cao et al. 2014).

The growth of plants is affected by the spatial location of the surrounding plants and competition by these plants for the available resources. Plant competition can be divided into two modes by competitors: intraspecific competition and interspecific competition. Intraspecific is competition between individuals of the same species, while interspecific is competition between individuals of different species. Since the same species has the same niche, intraspecific competition is usually the main mode of competition, and forest growth and yield models have generally just focused on intraspecific competition (Liu and Burkhart 1994). Plant competition also can be divided into two modes by evenness of competition: symmetric competition and asymmetric competition. Symmetric competition means plants that compete for resources allocate resources according to the size of the individual plants. But resources sometimes are not allocated according to the size of the individual plants, larger individuals have a disproportionate advantage in competition with smaller individuals and inhibit their growth, resulting in asymmetric competition. The intensity of competition has been found to be significantly negatively correlated with radial growth in Larix chinensis (Weiner 1990; Schwinning and Weiner 1998; Duan and Wang 2005) and biomass growth in stinky fir (Abies nephrolepis), Wang et al. (2012) indicating that strong neighborhood competition reduces the available resources and decreases the growth and biomass accumulation of trees.

According to Tilman’s competition theory, different plant communities have similar responses to competition but different forms of competition play a dominant role (Newman 1973; Tilman 1982, 1987). Under intense competition, plants show plasticity in response to different levels of resources competition through morphological changes (Mack and Harper 1977; Fowler 1982). This morphological change will directly affect the architecture of the plant. Architecture is the spatial distribution and morphological manifestation of plant components, including canopy area, branching, stem form, etc., it affects forests timber wood yield and fruiting. For example, under competition for light, plants balance their investment in leaves, which are the prime photosynthetic and shading components, and in supporting structures such as stems and branches, which place the leaves in the most advantageous position for competition (Caldwell 1987). Consequently, to obtain more light resources, plants shift the tradeoff between vertical growth and lateral growth, which eventually leads to architectural transformation (Clark 2010). Competition also promotes changes in the foliage area, branch angle, number of branches, and length of branches (King 1997; Stenberg et al. 1998), allowing plants to achieve a suitable crown length and crown area to maximize the interception of light resources.

In addition to morphological changes, plants can also acclimate to their external environment by changing the biomass distribution among various components (Mack and Harper 1977).
Changes in biomass partitioning of plant organs is an important mechanism to maintain productivity (Sebastia 2007). The ratio of the aboveground to the belowground biomass (T/R) reflects a plant’s demand for external resources, with fluctuations in environmental factors causing corresponding changes in the T/R ratio—for example, the T/R ratio decreases when water and nutrients are limited and increases when light resources are limited (Begon et al. 1986; Wilson 1988). However, Watt et al. (2003) and Casper et al. (1998) argued that competition intensity has no significant effect on the T/R ratio, observing that although plants under intense competition reduce the biomass of their branches, this is allotted to growth of the trunk, resulting in a generally stable aboveground biomass allocation. Many studies have also demonstrated that competition strongly influences tree productivity and biomass allocation. For example, Wang et al. (2012) reported that the biomass distribution of stinky fir accords with the optimal distribution theory of biomass, with an increase in light competition causing an increased biomass input to the leaves and a reduced input to the trunk. Furthermore, Whitelam et al. (1998) suggested that when plants are under intense competition or disadvantaged by competition, their phytochrome system will perceive a change in the ratio of red light to far-red light due to sheltering by neighboring trees, which will promote height growth and inhibit the growth of branches. Thus, it can be seen that the impact of competition on plants varies between species and that the extent of the impact is also constrained by the environment. Therefore, each of these patterns and mechanisms requires further research and analysis.

Liaodong oak (Quercus liaotungensis) is a native tree species on the Loess Plateau, China, that plays an important role in soil and water conservation and carbon sequestration due to its well-developed root system and high levels of carbon fixation. Since 1998 the inception of the Natural Forest Protection Project, there has been no management of Liaodong oak forests on the Loess Plateau, resulting in strong neighborhood competition. This intense competition has caused the low stem quality of the Liaodong oak and making it difficult for oak seedlings to regenerate. However, few studies have examined the effect of neighborhood competition on tree growth, stem shape, crown shape, and biomass allocation in broadleaved species, particularly on the Loess Plateau, so it remains unclear whether this high level of intraspecific competition will affect the growth and biomass accumulation of Liaodong oak in the future.

Therefore, the aim of this study was to address the following questions:

1. How does neighborhood competition affect the growth of Liaodong oak on the Loess Plateau?
2. How do Liaodong oak trees acclimate to this strongly competitive environment through morphological changes (stem form, crown shape)?
3. What are the biomass allocation strategies of Liaodong oak trees under different competition intensities?

2. Materials and methods

2.1. Site description

In June 2014, twenty 20 m x 20 m sample plots were randomly established at the Caijiachuan Forest Farm (35°45′–35°57′N, 109°48′–110°02′E) of the Huanglongshan Forestry Bureau in Yan’an City, which is located in the hilly and gully region of the Loess Plateau. The total area of Caijiachuan forest farm is 20,996.34 ha, and forest land is 17,111.41 ha, accounting for 81.5%. This is a warm temperate semi-humid forest area (Wu and Yang 1998; Tsunekawa et al. 2015), with a mean elevation of 1615 m, a mean annual temperature of 10.4°C, mean annual precipitation of 545.78 mm (from 1990 to 2016) and mostly occurred in July, August and September (54.2%), dry season (5 months from November to March) only accounts for 10.4% of the annual precipitation. The meteorological data is supplemented by the POWER Data Access Viewer weather database website data (https://power.larc.nasa.gov/data-access-viewer/) (Kang et al. 2008). Soil and water loss is prone to occur during the rainy season, and soil water stress is common in the dry season, which seriously affects plant growth (Xu et al. 1999).

The plots are established in uneven-aged forest, with multiple layers, which has grown after deforestation. Within each plot, all trees with a diameter at breast height (DBH) of >5 cm were numbered and located, and the tree species, tree height, DBH, crown width, and tree coordinates were measured. Canopy closure was measured by visual inspection. The competition intensity is calculated using the Hegyi competition index described in 2.4.1, and intraspecific competition is calculated only with Liaodong oak. In addition, we built a buffer outside the plot, and all the trees that overlapping with sample trees in the buffer were identified and recorded, including the DBH, tree height and species. The average stand density of sample plots is 1209 plants per hectare (Table 1), and the canopy closure is high (0.8–0.95). High stand density caused intense competition in the sample plots. Liaodong oak is the main tree species in the sample plots (Liaodong oak number percentage is 79.3%), with other species of Toxicodendron vernicifluum (8.3% on average), Pinus tabulaeformis (2% on average), Betula platyphylla (2.1% on average), Populus davidiana (1.3% on average), and Acer ginnala (5.8% on average) and other deciduous species (1.2% on average), with other shrub and herbaceous species such as Rosa hugonis, Euonymus porphyreus, Melampyrum roseum, Carex spp., and Elymus dahuricus. The mean DBH of Liaodong oak in the plots was 23.5 ± 1.5 cm (ranging from 5 to 45 cm), with most trees being between 15 and 35 cm, and the mean tree height was 12.4 ± 0.3 m (ranging from 3.4 to 20.2 m).

2.2. Tree measurements

In order to minimize the impact of the environmental factors on research, all subject trees will be selected in the same plot. Plot No. 16 was selected as the study plot because of its representativeness (DBH, competition situation and canopy closure close to average) and operability (Flat and close to the road); also, Liaodong oak surrounded only by Liaodong oak was selected as subject tree since we focus on the main competition mode (intraspecific competition). From July to August 2014, the Liaodong oak meet the requirements in No. 16 plot was divided into the following eight size classes based on their DBH (5–10, 10–15, 15–20, 20–25, 25–30, 30–35, 35–40, and >40 cm). Three sample trees were selected in each middle class (15–20, 20–25, 25–30, and 30–35 cm), and two sample trees in large class (>40 cm) was selected. One sample tree was selected in each other class (5–10, 10–15, and 35–40 cm), resulting in 17 trees of different DBH being selected for analysis in the study area. For each tree, the DBH, tree height, crown width, and crown length were recorded, and the tree height/DBH and crown length/tree height ratios
Table 1. Basic information of the 20 Liaodong oak (Quercus liaotungensis) sample plots.

| No. | Longitude | Latitude | Elevation (m) | Slope | Slope direction | Slope position | Tree species composition |
|-----|-----------|----------|--------------|-------|----------------|---------------|-------------------------|
| 1   | 109°      | 35°      | 1360         | 43°   | 105°           | Downslope     | Quercus liaotungensis, Betula platyphylla, Acer ginnala |
| 2   | 109°      | 35°      | 1365         | 35°   | 110°           | Downslope     | Quercus liaotungensis, Betula platyphylla, Acer ginnala |
| 3   | 109°      | 35°      | 1559         | 18°   | 96°            | Downslope     | Quercus liaotungensis, T. verniciflua, C. turczaninowii, Betula platyphylla |
| 4   | 109°      | 35°      | 1579         | 20°   | 290°           | Midslope      | Quercus liaotungensis, T. verniciflua, C. turczaninowii, Acer ginnala, C. turczaninowii |
| 5   | 109°      | 35°      | 1594         | 17°   | 233°           | Upslope       | Quercus liaotungensis, T. verniciflua, C. turczaninowii, Betula platyphylla, C. turczaninowii |
| 6   | 109°      | 35°      | 1588         | 14°   | 340°           | Upslope       | Quercus liaotungensis, T. verniciflua, C. turczaninowii, Acer ginnala, Betula platyphylla, C. turczaninowii |
| 7   | 109°      | 35°      | 1380         | 30°   | 330°           | Downslope     | Quercus liaotungensis, P. tabuliformis, P. betulifolia, Acer ginnala |
| 8   | 109°      | 35°      | 1367         | 16°   | 215°           | Downslope     | Quercus liaotungensis, P. tabuliformis, P. betulifolia, C. pinnatifida |
| 9   | 109°      | 35°      | 1465         | 11°   | 265°           | Upslope       | Quercus liaotungensis, P. tabuliformis |
| 10  | 109°      | 35°      | 1470         | 15°   | 270°           | Upslope       | Quercus liaotungensis, P. tabuliformis |
| 11  | 109°      | 35°      | 1557         | 16°   | 265°           | Midslope      | Quercus liaotungensis, T. verniciflua, Acer ginnala, Pyrus betulifolia, Ulmus macrocarpa |
| 12  | 109°      | 35°      | 1575         | 22°   | 328°           | Midslope      | Quercus liaotungensis, T. verniciflua, Acer ginnala, Pyrus betulifolia, Ulmus macrocarpa |
| 13  | 109°      | 35°      | 1532         | 10°   | 295°           | Downslope     | Quercus liaotungensis, T. verniciflua, Acer ginnala, Pyrus betulifolia, Ulmus macrocarpa |
| 14  | 109°      | 35°      | 1605         | 15°   | 330°           | Upslope       | Quercus liaotungensis, T. verniciflua, Acer ginnala, Pyrus betulifolia, S. walteri |
| 15  | 109°      | 35°      | 1644         | 9°    | 235°           | Upslope       | Quercus liaotungensis, P. betulifolia |
| 16  | 109°      | 35°      | 1635         | 0°    | 0°             | No slope      | Quercus liaotungensis, P. betulifolia, P. davidiana, C. pinnatifida |
| 17  | 109°      | 35°      | 1642         | 7°    | 150°           | Upslope       | Quercus liaotungensis, S. walteri, C. pinnatifida |
| 18  | 109°      | 35°      | 1637         | 16°   | 175°           | Upslope       | Quercus liaotungensis, P. betulifolia, C. pinnatifida, C. turczaninowii |
| 19  | 109°      | 35°      | 1650         | 33°   | 265°           | Upslope       | Quercus liaotungensis, P. betulifolia, C. pinnatifida |
| 20  | 109°      | 35°      | 1627         | 35°   | 235°           | Downslope     | Quercus liaotungensis, P. betulifolia, C. pinnatifida |

Table 2. Descriptive statistics of the 20 Liaodong oak (Quercus liaotungensis) sample plots (mean ± SE).

| No. | Stand Density (N ha⁻¹) | Canopy closure | Liaodong oak number percentage (%) | Mean DBH(cm) | Mean tree height(m) |
|-----|------------------------|----------------|-----------------------------------|--------------|---------------------|
|     |                        |                |                                   | Liaodong oak | Other species       |
| 1   | 1150                   | 0.85           | 88.0%                             | 23.7 ± 1.1   | 16.5 ± 3.1          |
| 2   | 1025                   | 0.87           | 83.9%                             | 28.4 ± 1.8   | 20.1 ± 1.5          |
| 3   | 1225                   | 0.88           | 78.9%                             | 22.2 ± 1.1   | 15.4 ± 1.2          |
| 4   | 1025                   | 0.82           | 82.3%                             | 27.9 ± 2.0   | 19.4 ± 1.7          |
| 5   | 1450                   | 0.95           | 69.3%                             | 18.2 ± 1.3   | 15.9 ± 0.9          |
| 6   | 1150                   | 0.92           | 77.9%                             | 20.2 ± 1.5   | 12.7 ± 1.8          |
| 7   | 1400                   | 0.91           | 64.0%                             | 19.8 ± 1.5   | 16.0 ± 1.4          |
| 8   | 1450                   | 0.91           | 64.6%                             | 20.2 ± 1.0   | 16.5 ± 5.0          |
| 9   | 1000                   | 0.85           | 87.5%                             | 26.2 ± 1.6   | 17.7 ± 3.0          |
| 10  | 975                    | 0.84           | 92.3%                             | 29.4 ± 1.2   | 19.6 ± 3.1          |
| 11  | 1350                   | 0.94           | 68.8%                             | 22.1 ± 1.5   | 21.4 ± 2.2          |
| 12  | 1175                   | 0.85           | 81.3%                             | 23.1 ± 1.6   | 17.3 ± 1.9          |
| 13  | 1325                   | 0.92           | 74.7%                             | 21.9 ± 1.2   | 16.2 ± 1.2          |
| 14  | 1475                   | 0.95           | 62.9%                             | 15.7 ± 0.9   | 12.0 ± 0.4          |
| 15  | 1250                   | 0.85           | 90.0%                             | 24.2 ± 1.4   | 18.5 ± 3.3          |
| 16  | 1050                   | 0.88           | 87.9%                             | 24.3 ± 1.6   | 17.5 ± 2.5          |
| 17  | 1000                   | 0.87           | 91.7%                             | 28.9 ± 1.1   | 19.7 ± 3.4          |
| 18  | 1475                   | 0.95           | 64.7%                             | 17.7 ± 1.5   | 14.7 ± 1.2          |
| 19  | 1150                   | 0.85           | 84.0%                             | 26.6 ± 1.9   | 17.8 ± 2.3          |
| 20  | 975                    | 0.89           | 91.3%                             | 29.3 ± 2.0   | 20.4 ± 3.2          |
| Mean| 1209                   | 0.89           | 79.3%                             | 23.5 ± 0.3   | 17.5 ± 0.4          |

were calculated (Table 2). In addition, the DBH and tree height of all competitors was recorded, the distance from the subject tree to the neighbor tree and the crown width in the direction of the overlap between the two trees. Examination of the overlap of areas of influence has proven useful for identifying local competition (Burkart and Tomé 2012). Crown width determines the area of influence of each tree, with overlapping crowns indicating that two trees are competing with each other. Thus, the neighbor j is a competitor if:

\[ \text{dist}_{ij} < CR_i + CR_j, \]

where \( \text{dist}_{ij} \) is the distance between the subject tree i and the neighbor j, CR_i is the crown radius of subject i, and CR_j is the crown radius of neighbor j (Figure 1 and Table 3).
2.3. Biomass determination

The biomass of each sample tree was measured using the whole plant harvesting method. Each sample tree was cut at 5 cm above the ground and separated into stems, branches, foliage, and roots. The fresh weight of each component was weighed using a platform scale in the field, following samples of each component was taken back to the laboratory and dried to constant weight at 105°C. The dry weight and moisture content of each component was then calculated.

The trunk of each sample tree was cut at a height of 0.3 and 1.3 m above the ground and a 5-cm disc was taken from each section to determine the annual ring width and age using WinDENDRO (He 2005). Bark samples were also collected by stripping a piece of bark from each trunk segment, and their length, width, and thickness were recorded. The biomass of each sample was then obtained by drying and weighing the entire bark area.

The number of branches and the diameter and length of each branch on the trunk were recorded and used to calculate the total number of branches, mean branch length, and mean branch diameter.

Finally, we excavated the root systems follow the taproot and the depth was assessed based on the deepest root. We cut off all the fine root (diameter < 5 mm) and only coarse root is retained – since fine roots have little effect on the total biomass of the roots (Wang 2006) and it is very difficult to excavate them all. Part of the sample of coarse roots was then returned to the laboratory to calculate the root biomass.

2.4. Data analysis

2.4.1. Selection and calculation of the competition index

In this study, we used the Hegyi competition index to indicate the strength of neighboring competition (Hegyi 1974), as this has been shown to have wide applicability. This index is calculated using the equation:

\[ CI_i = \frac{\sum_{j=1}^{n} D_j / (D_i \times L_{ij})}{n} \]

where \( CI_i \) denotes the Hegyi competition index for subject tree \( i \), \( D_j \) (cm) denotes the breast diameter of subject tree \( i \), \( D_j \) (cm) denotes the breast diameter of the competitor \( j \), and \( L_{ij} \) (m) denotes the distance between the competitor and the subject tree. The 17-object tree Hegyi competition index is shown in Table 2.

2.4.2. Selection and calculation of the growth indicator

Biomass is the main representation of the accumulation of energy by plants, with an increase in biomass reflecting the capture of external resources to a certain extent. Mean annual biomass increment is an indicator to measure the speed of biomass acquisition, and it can also reflect the resources occupied by plants to a certain extent.

The biomass of the three plants is B1, B2, and B3, and the total resource is A, if the resources occupied by the three plants are: \( A_1 = A \times B_1 / (B_1 + B_2 + B_3) \), \( A_2 = A \times B_2 / (B_1 + B_2 + B_3) \), \( A_3 = A \times B_3 / (B_1 + B_2 + B_3) \), or \( A_1 / B_1 = A_2 / B_2 = A_3 / B_3 \), then the three plants is symmetric competition, otherwise asymmetric competition. So, we choose Mean annual biomass increment /Total biomass as an indicator to determine whether it is a symmetric competition.

Current annual height increment and current annual DBH increment in recent five years is an indicator to measure the speed of longitudinal growth and radial growth recently. Current annual height increment- current annual DBH increment ratio is used to reflect the growth strategy of the trunk of Liaodong oak.

Table 3. Dendrometry characteristics of the 17 Liaodong oak (Quercus liaotungensis) sample trees.

| No. | Age (years) | DBH (cm) | Height (m) | Crown width (m) | Crown length (m) | Total dry biomass (kg) | Competition index |
|-----|-------------|----------|------------|-----------------|------------------|-----------------------|-----------------|
| 1   | 19          | 6.5      | 4.6        | 3.0             | 2.5              | 9.80                  | 3.395           |
| 2   | 40          | 10.6     | 9.6        | 2.1             | 3.5              | 31.00                 | 2.247           |
| 3   | 61          | 16.9     | 9.0        | 3.9             | 5.8              | 123.94                | 2.897           |
| 4   | 45          | 17.7     | 8.3        | 3.5             | 5.6              | 105.72                | 0.763           |
| 5   | 54          | 18.8     | 13.6       | 4.7             | 4.1              | 111.36                | 1.117           |
| 6   | 53          | 21.3     | 13.4       | 6.9             | 7.4              | 320.80                | 1.159           |
| 7   | 54          | 21.8     | 13.5       | 5.5             | 7.9              | 212.84                | 1.336           |
| 8   | 64          | 22.6     | 12.6       | 6.9             | 6.2              | 246.75                | 2.672           |
| 9   | 68          | 24.5     | 15.8       | 4.3             | 10.2             | 275.65                | 1.282           |
| 10  | 58          | 25.0     | 13.2       | 5.8             | 12.2             | 445.24                | 0.736           |
| 11  | 61          | 26.3     | 10.6       | 8.1             | 8.9              | 191.88                | 1.433           |
| 12  | 85          | 30.2     | 10.4       | 10.6            | 9.1              | 532.47                | 1.416           |
| 13  | 67          | 31.0     | 15.6       | 6.8             | 12.0             | 757.64                | 0.873           |
| 14  | 81          | 34.2     | 13.0       | 9.0             | 11.1             | 395.02                | 0.902           |
| 15  | 89          | 36.4     | 13.2       | 4.7             | 11.9             | 853.11                | 0.754           |
| 16  | 103         | 40.5     | 17.9       | 8.8             | 11.8             | 1083.41               | 0.507           |
| 17  | 67          | 41.2     | 16.7       | 9.8             | 12.4             | 1060.93               | 0.817           |
2.4.3. Selection and calculation of the biomass allocation indicator

The relative proportion of biomass in the stem, foliage, live branches, roots, and bark are used to reflect the allocation strategy of each component, aboveground/belowground biomass ratio (T/R) to reflect the biomass allocation strategy between aboveground and belowground. Stem-branch biomass ratio is to reflect aboveground biomass allocation.

2.4.4. Selection and calculation of the architecture indicator

We choose tree tapering to reflect the stem quality, crown width/DBH ratio, crown length/tree height ratio to reflect the whole crown architecture, lateral branch number/age ratio, lateral branch means diameter/DBH ratio and lateral branch mean length/tree height ratio to reflect crown architecture at the branch level.

2.4.5. Statistical analysis

The relationships between the competition index and the annual growth of tree height, DBH, and biomass were analyzed using exponential regression analysis (equation: \( y = a \times e^{bx} \)) and linear regression analysis (equation: \( y = ax + b \)). The relationships between the competition index and the biomass of each component and the tree height/DBH ratio, lateral branch mean diameter/DBH ratio, lateral branch mean length/tree height ratio, crown width/DBH ratio, crown length/tree height ratio, lateral branch number/age ratio, and tree tapering were analyzed using linear regression. All regression analyses were carried out using SPSS 23.0.

3. Results

3.1. The mode of competition

The results of competition analysis of Liaodong oak showed that the total competition index (sum of intraspecific competition index and interspecific competition index) of Liaodong oak in 20 plots is 1719.69 (Table 4), among them, the intraspecific competition was 1392.288, accounting for 82.6%, and the interspecific competition was 327.959, accounting for 17.4%. This indicates that intraspecific competition is the main competition mode of Liaodong oak in this region. For individual tree, the maximum competition index is 10.874, the minimum is 0.066, and the mean competition index is 1.753. The large difference of individual tree competition index also indicates that the competition environment of each tree is quite different. The mean competition index of intraspecific competition is 1.827, is greater than the mean competition index of interspecific competition (1.469), indicating that the same species make the competition more intense.

The mean competition index of 17 sample Liaodong oak is 1.753 (Table 3), and the minimum is 0.507, the maximum is 3.395. The range of competition index indicated that the sample trees are representative.

3.2. Competition effects on tree growth

The total biomass of the 17 Liaodong oak sample trees ranged from 11.044 kg to 1010.667 kg (Table 3). Mean annual biomass increment had a highly significant negative exponential correlation with the competition index (\( p < 0.01; \) Figure 2(A)), with the largest mean annual biomass increment (14.57 kg/annum) being 25 times greater than the smallest (0.58 kg/annum). Mean annual biomass increment/Total biomass was not a fixed value but significantly positively correlated with competition index (\( p < 0.01; \) Figure 2(B)), the proportion of resources occupied by competitive advantage trees is greater than the proportion of biomass, that means the intraspecific competition of Liaodong oak in this region is asymmetric competition. Current annual DBH increment was also significantly linearly correlated with the competition index (\( p < 0.01; \) Figure 2(C)), indicating that competition from neighbors greatly affected DBH growth but in a proportional way; however, the largest Current annual DBH increment (0.63 cm/annum) was only 2.4 times higher than the smallest (0.26 cm/annum). The competition index was not significantly correlated with current annual height increment (Figure 2(D)) but was significantly positively correlated with the tree height/DBH ratio (\( p < 0.05; \) Figure 2(E)), suggesting that when to high competition intensity, Liaodong oak trees could not obtain sufficient resources to supply the growth of the trunk and so gave priority to increasing the longitudinal growth of the trunk.

3.3. Competition effects on biomass allocation

The biomass ratios of the components of Liaodong oak were, in decreasing order, stem (45.42%), branch (22.19%), root (19.39%), bark (10.59%), and foliage (2.41%) (Figure 3). The aboveground biomass accounted for 80.61% of the total biomass, while the belowground biomass accounted for 19.39%, with a T/R ratio of 4.16.

The intensity of competition was closely related to the biomass allocation to the components of Liaodong oak (Figure 4). There was highly significant showed a positive correlation between competition intensity and the root biomass ratio (\( p < 0.01; \) Figure 4(E)), indicating that the trees allocated more resources to the belowground parts under more intense competition, this also led to aboveground/belowground biomass ratio decrease as the competition intensity decreases. Competition intensity had no significant effect on the stem biomass ratio (Figure 4(C)) but was significantly showed a negatively correlated with the branch biomass ratio (\( p < 0.01; \) Figure 4(E)) and significantly showed a positively correlated with the stem/branch biomass ratio (\( p < 0.05; \) Figure 4(G)), showing that aboveground, Liaodong oak trees preferentially allocated resources to their trunks and reduced the allocation to the branches under increased competition. The biomass ratios of the bark and foliage were not show a significantly correlated (\( p > 0.1 \)) with the competition index (Figure 4(D) and (A)). The bark biomass ratio showed the same trend as the stem biomass ratio, but the foliage biomass ratio showed the different regulation as the branch biomass ratio as the competition index changed.

3.4. Competition effects on architecture

The architectural indices of the 17 Liaodong oak are shown in Table 5. In terms of the whole canopy, as the competition index increased, the crown length/tree height ratio tended to decrease, albeit not significantly (\( p < 0.1; \) Figure 5(A)).
Table 4. Intraspecific competition and interspecific competition index of Liaodong oak (*Quercus liaotungensis*) in 20 plots.

| No. | Hegyi competition index (individual tree) | Hegyi competition index (plot) |
|-----|------------------------------------------|--------------------------------|
|     | Intraspecific competition | Hegyi competition index | Interspecific competition | Total |
|     | Max  | Min  | Mean ± SE | Max  | Min  | Mean ± SE | Max  | Min  | Mean ± SE | Hegyi competition index | Proportion | Hegyi competition index | Proportion | Interspecific competition | Total |
| 1   | 7.583 | 0.152 | 1.933 ± 0.142 | 3.658 | 0.256 | 1.351 ± 0.286 | 7.583 | 0.152 | 1.887 ± 0.124 | 77.341 | 89.1% | 9.461 | 10.9% | 86.802 |
| 2   | 5.233 | 0.121 | 1.671 ± 0.157 | 3.256 | 0.118 | 1.555 ± 0.279 | 5.233 | 0.118 | 1.614 ± 0.105 | 56.843 | 85.9% | 9.331 | 14.1% | 66.174 |
| 3   | 5.697 | 0.113 | 1.855 ± 1.153 | 3.881 | 0.165 | 1.485 ± 0.185 | 5.697 | 0.113 | 1.742 ± 0.109 | 70.506 | 82.6% | 14.852 | 17.4% | 85.358 |
| 4   | 6.668 | 0.215 | 1.710 ± 0.186 | 2.561 | 0.224 | 1.420 ± 0.296 | 6.668 | 0.215 | 1.661 ± 0.098 | 58.158 | 85.4% | 9.943 | 14.6% | 68.101 |
| 5   | 9.207 | 0.085 | 2.204 ± 0.135 | 3.289 | 0.214 | 1.455 ± 0.201 | 9.207 | 0.085 | 1.972 ± 0.089 | 88.184 | 77.1% | 26.192 | 22.9% | 114.376 |
| 6   | 7.258 | 0.156 | 1.801 ± 0.126 | 4.154 | 0.240 | 1.511 ± 0.208 | 7.258 | 0.156 | 1.738 ± 0.106 | 64.838 | 81.1% | 15.110 | 18.9% | 79.948 |
| 7   | 9.533 | 0.195 | 2.330 ± 0.127 | 3.596 | 0.082 | 1.546 ± 0.167 | 9.533 | 0.082 | 1.986 ± 0.113 | 80.298 | 72.2% | 30.918 | 27.8% | 111.216 |
| 8   | 9.663 | 0.175 | 2.303 ± 0.129 | 2.684 | 0.126 | 1.524 ± 0.169 | 9.663 | 0.126 | 2.021 ± 0.124 | 85.217 | 72.7% | 32.001 | 27.3% | 117.218 |
| 9   | 5.412 | 0.153 | 1.642 ± 0.149 | 2.335 | 0.066 | 1.295 ± 0.286 | 5.412 | 0.066 | 1.662 ± 0.096 | 64.060 | 87.6% | 9.068 | 12.4% | 73.128 |
| 10  | 6.427 | 0.198 | 1.462 ± 0.134 | 4.815 | 0.195 | 1.620 ± 0.357 | 6.427 | 0.195 | 1.433 ± 0.088 | 52.646 | 94.2% | 3.241 | 5.8% | 55.887 |
| 11  | 8.875 | 0.214 | 2.052 ± 0.153 | 4.235 | 0.324 | 1.463 ± 0.185 | 8.875 | 0.214 | 1.921 ± 0.094 | 75.933 | 73.2% | 27.801 | 26.8% | 103.734 |
| 12  | 6.848 | 0.208 | 1.781 ± 0.159 | 2.694 | 0.157 | 1.465 ± 0.189 | 6.848 | 0.157 | 1.739 ± 0.087 | 67.675 | 82.8% | 14.058 | 17.2% | 81.733 |
| 13  | 7.625 | 0.286 | 1.894 ± 0.148 | 2.549 | 0.295 | 1.512 ± 0.204 | 7.625 | 0.286 | 1.800 ± 0.108 | 75.748 | 79.4% | 19.652 | 20.6% | 95.400 |
| 14  | 9.872 | 0.158 | 2.233 ± 0.138 | 3.259 | 0.267 | 1.428 ± 0.185 | 9.872 | 0.158 | 2.023 ± 0.107 | 82.237 | 68.9% | 37.120 | 31.1% | 119.357 |
| 15  | 7.958 | 0.186 | 1.689 ± 0.178 | 3.574 | 0.174 | 1.287 ± 0.395 | 7.958 | 0.174 | 1.700 ± 0.102 | 75.990 | 89.4% | 9.010 | 10.6% | 85.000 |
| 16  | 8.024 | 0.198 | 1.538 ± 0.168 | 3.698 | 0.149 | 1.537 ± 0.541 | 8.024 | 0.149 | 1.538 ± 0.096 | 56.909 | 88.1% | 7.687 | 11.9% | 64.596 |
| 17  | 6.598 | 0.202 | 1.465 ± 0.157 | 4.125 | 0.112 | 1.529 ± 0.412 | 6.598 | 0.112 | 1.470 ± 0.087 | 54.214 | 92.2% | 4.586 | 7.8% | 58.800 |
| 18  | 10.874 | 0.205 | 2.302 ± 0.129 | 4.285 | 0.079 | 1.421 ± 0.195 | 10.874 | 0.079 | 2.037 ± 0.102 | 87.493 | 72.8% | 32.690 | 27.2% | 120.183 |
| 19  | 6.489 | 0.152 | 1.709 ± 0.137 | 2.654 | 0.095 | 1.398 ± 0.310 | 6.489 | 0.095 | 1.662 ± 0.109 | 66.666 | 87.2% | 9.786 | 12.8% | 76.452 |
| 20  | 5.264 | 0.096 | 1.426 ± 0.167 | 2.597 | 0.179 | 1.363 ± 0.357 | 5.264 | 0.096 | 1.456 ± 0.125 | 51.333 | 90.4% | 5.451 | 9.6% | 56.784 |
| Sum | 10.874 | 0.085 | 1.827 ± 0.046 | 4.815 | 0.066 | 1.469 ± 0.069 | 10.874 | 0.066 | 1.753 ± 0.026 | 1392.288 | 82.6% | 327.959 | 17.4% | 1719.693 |
but the crown width/DBH ratio increased \((p < 0.05; \text{Figure 5 (B)})\). At the level of the single branch, the biggest factor affecting the branching situation is the age except the genetic factors, so we choose the branch number/age ratio, the branch mean diameter/DBH and branch mean length/tree height ratio to try to exclude the effects of age. The competition index was not related to the branch number/age ratio (\text{Figure 5(C)}) but was significantly negatively correlated with the branch mean diameter/DBH ratio \((p < 0.05; \text{Figure 5(D)})\) and branch mean length/tree height ratio \((p < 0.05; \text{Figure 5 (E)})\). The competition index was significantly negatively correlated with tree tapering \((p < 0.05; \text{Figure 2(F)})\), this means that the stem quality becomes higher as the competition becomes fierce.

4. Discussion

In this study, we confirmed that the main competition mode of Liaodong oak in the region is intraspecific competition, which is mainly due to two inferences. First, the Liaodong oak species are the dominant species at the overstory. The average DBH and tree height are higher than other tree species. Pioneer species such as \textit{B. platyphylla} or small trees like \textit{Acer ginnala} is difficult to have an impact on the Liaodong oak individuals at the overstory, they only can affect the immature Liaodong saplings growth understory. The second reason is that the same tree species have similar ecological habits and more niche overlap. So the
tree species like *B. platyphylla*, *Crataegus pinnatifida*, and *T. verniciflua* usually was a clumped distribution (Wang et al. 2016), which also reduces the impact of these trees species on Liaodong oak. This is consistent with Liu et al. (2009) research results.

Biomass is the main representation of the accumulation of energy by plants, with an increase in biomass reflecting the capture of external resources to a certain extent. The results of this study show that the mean annual biomass increment/competition index of the Liaodong oak is a significant negative exponential correlated, indicating that competition severely inhibits the capacity of Liaodong oak to obtain resources and limits the growth, and the intraspecific competition of Liaodong oak in this region is asymmetric competition. This phenomenon appears to result from competition for light, which is ‘one-sided,’ with larger plants shading smaller plants and smaller plants having almost no effect on the amount of light available to their larger neighbors (Leeuwen and Etienne 2013). In addition, the spatial heterogeneity of soil nutrients in the Loess Plateau (Wang et al. 2002) will exacerbate this asymmetric competition (Facelli and Facelli 2002; Rajaniemi 2003, 2011). The asymmetric competition means that individuals who are oppressed by neighbor are difficult to obtain sufficient resources to meet normal growth and development, and need to make a trade-off to ensure future survival and enhance competitive advantage.

The first coping strategy for the oppressed Liaodong oak is to change the biomass allocation. In the present study, we found that Liaodong oak trees allocated more biomass to their belowground parts as the competition intensity increased, which differs from previous findings. For example, Newton and Cole (1991) and Watt et al. (2003) found that a change in competition intensity did not affect the aboveground and belowground biomass allocation ratios in Monterey pine (*Pinus radiata*). The observed response in Liaodong oak may be related to three factors. First, the short rainy season and severe soil erosion on the Loess Plateau mean that plants lack water for a long period of time and thus water is the main factor that restricts the growth of vegetation here (Xu et al. 1999). Second, average annual precipitation is the most important environmental factor affecting the distribution and growth of Liaodong oak (Yin et al. 2013), so a lack of water is the most important problem that needs to be addressed by this species in this region. Finally, the root system of Liaodong oak has good morphological plasticity and growth space, where Deng et al. (2018) found that the seedlings of this species meet the demand for soil moisture in this water-deficient environment by extending their root system.
allocating more biomass to the belowground parts and increasing the belowground biomass ratio.

As well as affecting the aboveground to belowground biomass ratio, the intensity of competition also significantly influenced the aboveground biomass allocation. Trees compete for both light and growing space, and we found that under strong competition, Liaodong oak trees reduced the biomass of their branches to allow the biomass of the belowground parts to be increased while also giving priority to high growth of the trunk. This is different from the conclusion of Wang et al. (2012) and Zhou et al. (2018), they suggested that the allocation of biomass accorded to the principle of optimal biomass allocation, which was the intense light competition will promote the biomass allocation to the foliage (components that receive lights) and branches (components that support foliage). The different findings for Liaodong oak may be explained as follows. First, the canopy closure of the Liaodong oak forest was between 0.8 and 0.95, it would be difficult for Liaodong oak trees in the lower layer of the canopy in our study area to obtain sufficient light resources simply by elongating their branches, most of the light would be intercepted by the broad leaves of the upper layer. Second, Liaodong oak trees have the potential to reach the upper layer of the canopy quickly, the stem analysis of the 17 sample trees showed that this species has a fast growth period over the first 5–10 years, during which time the tree height can increase by 70–100 cm per year, which is sufficient to reach the upper canopy by the end of this period. Finally, Liaodong oak has good shade tolerance (Wang 2014), with shading reducing the light compensation point, light saturation point, and dark respiration rate, and improving the light quantum efficiency (Schweitzer et al. 2006). Liaodong oak trees also exhibit plasticity in their photosynthetic response mechanism, which is regulated by the degree of shading, and can acclimate to changes in light intensity (Pemán et al. 2010). Consequently, smaller Liaodong oak trees are able to focus on tree height growth when distributing aboveground resources, which indirectly causes changes in the height/DBH ratio of the tree and reduces the level of tree tapering, improving the stem form quality. The bark is an external structure of the stem, so the proportion of bark biomass has the same change regulation with proportion of stem biomass. But the proportion of foliage biomass has the different change regulation with proportion of branch biomass, since the branch is the just support structure of leaves. Competition decreases the ratio of branch biomass, but has no significant influence on the foliage biomass, that is because the Liaodong oak need to maintain the photosynthesis capacity.

The second coping strategy option is to change the architecture. Through these changes, Liaodong oak can improve competitiveness. These findings show that the architecture

| No. | Age (years) | Lateral branch number | Lateral branch mean length (m) | Lateral branch mean diameter (cm) | Height/diameter ratio | Crown/height ratio | Tree tapering |
|-----|-------------|-----------------------|-------------------------------|----------------------------------|----------------------|-------------------|--------------|
| 1   | 19          | 10                    | 8.62                          | 4.18                             | 0.708                | 0.543             | 2.68         |
| 2   | 40          | 11                    | 4.95                          | 2.65                             | 0.908                | 0.365             | 2.36         |
| 3   | 61          | 11                    | 8.88                          | 5.14                             | 0.533                | 0.644             | 3.89         |
| 4   | 45          | 13                    | 5.76                          | 2.92                             | 0.469                | 0.675             | 1.21         |
| 5   | 54          | 13                    | 8.99                          | 4.34                             | 0.723                | 0.301             | 2.98         |
| 6   | 53          | 6                     | 7.62                          | 4.02                             | 0.629                | 0.552             | 1.73         |
| 7   | 54          | 14                    | 4.91                          | 2.58                             | 0.619                | 0.585             | 1.87         |
| 8   | 64          | 10                    | 11.18                         | 5.95                             | 0.558                | 0.492             | 3.85         |
| 9   | 68          | 14                    | 11.26                         | 5.46                             | 0.645                | 0.646             | 2.90         |
| 10  | 58          | 7                     | 3.73                          | 1.62                             | 0.528                | 0.924             | 1.40         |
| 11  | 61          | 3                     | 2.50                          | 1.20                             | 0.403                | 0.840             | 1.70         |
| 12  | 85          | 8                     | 3.46                          | 2.63                             | 0.344                | 0.875             | 2.03         |
| 13  | 67          | 12                    | 9.38                          | 4.94                             | 0.503                | 0.769             | 1.60         |
| 14  | 83          | 4                     | 2.50                          | 1.60                             | 0.381                | 0.854             | 1.44         |
| 15  | 89          | 15                    | 11.70                         | 5.40                             | 0.363                | 0.902             | 3.50         |
| 16  | 103         | 14                    | 7.51                          | 4.09                             | 0.442                | 0.659             | 2.62         |
| 17  | 67          | 6                     | 6.45                          | 2.92                             | 0.405                | 0.743             | 2.14         |

Figure 5. Relationships between competition intensity and the architecture in terms of the crown length (C)/tree height ratio (A), crown length (CL)/diameter at breast height (DBH) ratio (B), lateral branch number/age ratio (C), lateral branch mean diameter/DBH ratio (D), and lateral branch mean length/tree height ratio (E), tree tapering (F).
of Liaodong oak trees is strongly shaped by intraspecific competition. At the whole-tree level, as competition for light increases, the relative height of the canopy (crown length/tree height ratio) decreases, while the relative width (crown width/DBH ratio) remains unchanged because the trees keep most of their foliage at a high position to obtain light resources, thereby compressing the crown, as seen in *Quercus robur* (Peer et al. 2017). They ensure that the canopy has enough width to reach gap center, which is the same as the Muth and Bazzaz (2002) research results. At the individual branch level, although the number of branches/age does not change as competition increases, the relative length (branch mean length/tree height ratio) and base diameter of the branches (branch mean diameter/DBH ratio) are significantly reduced, mainly because gaps in the understory are small and fragmented. Thus, the trees are able to improve photosynthesis without allocating any additional resources to each branch by simply retaining the same number of branches to cover most of the gaps (King et al. 2006). This negative effect of aboveground competition on the branch diameter (Lintunen and Kaitaniemi 2010) and branch length (Jones and Harper 1987) had also been reported in *Betula pendula*. However, Umekia and Kikuzawa (2000) reported a negative effect of aboveground competition on the number of first-order branches in Asian white birch (*B. platyphylla*), this difference expression may be caused by the characteristics of tree species. As a fast-growing pioneer species, Asian white birch has a strong self-pruning ability and low crown plasticity with intense competition, while the Liaodong oak has a high crown plasticity (Longuetald et al. 2013) and no need to self-pruning. These morphological changes at the level of both the whole tree and the individual branch are to ensure the canopy area that can receive light is not affected by the decrease in branch biomass allocation (Sachs 2004; Mäkinen and Hein 2006).

5. Conclusions
In this study, we found the intraspecific competition is the major competition way for Liaodong oak in the Loess Plateau, it is an asymmetric competition, intense competition had greatly influenced the resources acquisition of Liaodong oak also, it would restrict the growth and biomass accumulation. In order to acclimate the intense competition, Liaodong oak would change architecture and biomass allocation, it would allocate more biomass to the underground parts to absorb more soil water, and the reduced part of biomass would be from branches rather than the stem, mostly based on reducing the diameter and length of branches, not the number of branches. These changes would reduce the canopy area. In addition, with the intensification of competition, Liaodong oak changed its stem form. The DBH/tree height ratio and tree tapering have decreased, in this case, the stem form quality also improved. Intense competition negatively influenced the growth of individual Liaodong oak, on the other hand, lower competition would reduce the stem quality. Considering the dual influences, the future research should be focused on the suitable competition intensity for timber capacity based on growth and yield model simulation, the suitable competition intensity would be a gist for objective tree select during the transformation to near-natural forest management in the future.

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Notes on contributors
*Xiao-zhou Yang*, 1990, is doctor of Northwest A&F University, Shaanxi, China. The authors’ major research directions are forest silviculture and plant interaction.

*Wen-hui Zhang*, 1954, is professor of forest cultivation at Northwest A&F University, Shaanxi, China, as long as he is engaged in teaching and research work in forest plants, forest management, forest ecology and so on.

*Qiu-yue He*, 1991, is doctor of Northwest A&F University, Shaanxi, China. The authors’ major research directions are watershed ecology and tree physiology.

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