Quantitative evaluation of the hop (*Humulus lupulus* L.) root system based on wall profile method

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**Abstract:** Hop cones are an indispensable raw material used for beer brewing. Since the hop plant is a minor crop, expansion habit of the hop root system has not been well investigated. In this study, we observed and analyzed the root systems of two major hop cultivars in Hokkaido, Little Star and Furano Special, using the wall profile method and root depth index. The results suggest differences in expansion habit of the hop root between the two hop cultivars, which has not been reported previously. The results also indicate that the different responses in cone yield to precipitation between the two hop cultivars may be derived from their differences in root expansion habit. The results of this preliminary study support the view that a better understanding of the hop root system could lead to improved productivity of hops via the development of agronomical techniques or genotypes.

**Keywords:** hops, *Humulus lupulus* L., root system

**Abbreviations:** RDI, root depth index

**Introduction**

Hop cones, the female inflorescence of hop plants, have been used as a raw material in beer brewing for over 1,000 years. Hop cones are used to impart a fresh aroma and crisp bitter flavor to beer. The hop plant is a perennial climbing herb grown primarily between latitudes 35°N and 55°N (Barth et al., 1994). In Japan, hops are grown in the Tohoku and Hokkaido regions.

Hop cultivation in Japan originated in the 19th century in Hokkaido. In the 1970s, more than 100 hop growers were located in Hokkaido, while only 4 were remaining as of 2014 (All National Hop Union, 2014). Although the cash income per unit area of hop production is good, the required long, intensive and heavy labor makes the industry less attractive to growers and is one of the major reasons for the decades-long decline in hop cultivation. Hop production would be more attractive if further improvements in productivity could be achieved. Improved growth of hop plants could also lead to better quality, which will benefit both brewers and beer consumers.

To improve productivity, a basic understanding of hop growth, including root system development and its distribution pattern in soil, is essential. Since the hop plant is a perennial that requires approximately 3 years to mature and produce full harvests with stable quality, the plants cannot be transplanted very often. Usually, hops are grown for more than 20 years after planting rhizomes. Although much research on root systems has been conducted in major crops, research on the hop root system is very limited. Hop roots reach a depth of approximately 150 cm and extend laterally 180 to 240 cm when grown in well-drained soil (Burgess, 1964). In addition, Beard (1943) reported that hop root systems cultivated under well-drained conditions are larger and deeper than those grown in poorly drained soil. He also conveyed that absorbing roots tend to be more prominent in the upper layers of the soil at depths of 0‒30 cm. While his report offers a basic understanding of the hop root system, it described only the morphology of hop roots.
The two hop cultivars used in this study, Little Star and Furano Special, were bred by Sapporo Breweries Ltd. and registered in 2005 and 2007, respectively. Furano Special has a medium maturity, high content of bitter acids in the cones, and a medium‒high yield. Little Star also has a medium maturity and high yield. Both are major hop cultivars that have been grown commercially in Hokkaido for more than 10 years. For both cultivars, 25 plants were planted in the spring of 2008. The width of each row was 3.2 m, and the distance between plants within a row was 1.2 m. We cultivated the crop according to the customary cultural practices for hops in Hokkaido. Hop cones were harvested at the mature stage of each cultivar during the crop years of 2009 to 2015. The hop cones were dried for approximately 5 hours at 55°C until the moisture content of the cones was.

Therefore, quantitative measurements of the root system have yet to be reported.

We performed a quantitative investigation of the expansion of hop root systems using the wall profile method. The hop cone yield in response to the expansion habit of root was also discussed.

**Materials and Methods**

*The hop cultivars and field survey method*  

We investigated hops grown in a research field on Abashiri farm at Tokyo University of Agriculture, Hokkaido, Japan (ca. 44°N 144°E). The size of the hop yard was 16 m × 16 m, and the height of the trellis was 5.4 m. The soil type in the research field is haplic andosol for both the top soil and the subsoil. The thickness of the top soil is ca 30 cm. The two hop cultivars used in this study, Little Star and Furano Special, were bred by Sapporo Breweries Ltd. and registered in 2005 and 2007, respectively. Furano Special has a medium maturity, high content of bitter acids in the cones, and a medium‒high yield. Little Star also has a medium maturity and high yield. Both are major hop cultivars that have been grown commercially in Hokkaido for more than 10 years. For both cultivars, 25 plants were planted in the spring of 2008. The width of each row was 3.2 m, and the distance between plants within a row was 1.2 m. We cultivated the crop according to the customary cultural practices for hops in Hokkaido. Hop cones were harvested at the mature stage of each cultivar during the crop years of 2009 to 2015. The hop cones were dried for approximately 5 hours at 55°C until the moisture content of the cones was.

**Fig. 1.** Distribution of vertical root densities of hop cultivars, Little Star and Furano Special, at three horizontal points (0, 50, and 100 cm) from the plant bases in the research hop yard in Abashiri in 2014 and 2015. Horizontal bar: standard error.
approximately 10%. The dried cones were weighed, and the cone yields per unit area were calculated based on a planting density of 2,600 plants ha⁻¹.

**Hop cone yield and spatial distribution of the root system**

One plant in 2014 and three plants in 2015, grown in the center of the hop yard and exhibiting the average growth rate of each cultivar, were selected and used in this study. In 2014 and 2015, after harvesting the cones, the expansion habit of the root system was examined using the wall profile method (Böhm, 1979; Itoh et al., 2009). Trenches approximately 1.2 m long, 1.0 m wide and 1.0 m deep were excavated perpendicularly to the plant rows. After the surface of the trench wall was smoothed, a soil layer 5 mm thick was removed carefully from the smoothed wall using tweezers. All roots subsequently exposed were traced on a polyethylene sheet (root map) set on the wall. A thin paper sheet with 0.1 m grid lines was then placed over the polyethylene sheet, and the roots traced on the sheet were re-traced on the paper. The number of roots per cm² in each grid square was considered the root density.

The mean root depth, i.e., the root depth index (RDI), was estimated from the root density using the Oyanagi method (1998), modified by applying the root number instead of the root length. The calculation was conducted as follows: the root density in each 0.1 m horizontal layer was calculated as a percentage of the entire 1.0 m layer, then multiplied by the mid-depth value (in cm) of the corresponding layer, and then integrated. We investigated the roots at three distances with respect to the plant base: at the plant base and 50 cm and 100 cm from the plant base.

**Climatic data**

Climatic data were obtained from the Japan Meteorological Agency’s (Chiyoda, Tokyo, Japan) Abashiri Local Meteorological Observatory, located approximately 20 km from the Abashiri farm. The daily temperature, precipitation, and total solar radiation are recorded at the observatory.

**Results**

The root densities of the two hop cultivars Furano Special and Little Star are shown in Fig. 1. The root densities of both cultivars were high in the upper layer, decreasing with increasing depth at each horizontal distance point from the plant bases. Differences in Little Star root densities at depths of 0–50 cm compared with 50–100 cm were more pronounced than the differences in Furano Special root densities between these depth ranges. At the plant bases, the root densities of Furano Special in the top soil (0–30 cm) were less than those of Little Star during both years. However, the root densities of Furano Special at the depths of 40–100 cm were higher than those of Little Star. At horizontal distances of 50 cm and 100 cm from the plant bases, the root densities of Furano Special were higher than those of Little Star.

The RDIs of both cultivars are shown in Fig. 2. The RDIs of Furano Special and Little Star at the plant bases were 32.1 cm and 22.6 cm, respectively, although this difference was not significant at α = 0.05 ($P = 0.07$).
The yields of both hop cultivars were positively correlated with the precipitation amounts from 1 to 20 July during research period (Fig. 3), although the correlation coefficients between yield and precipitation amount were not significant at the 5% level of significance for either cultivar. The slope of the regression line for precipitation amounts versus hop yields was smaller for Furano Special than for Little Star.

**Discussion**

This study provides the first quantitative description of expansion habit of the hop root system. The results suggest the varietal differences in root expansion habit between the two hop cultivars. Beard (1943) investigated the root systems of different hop cultivars grown under different soil conditions and detected variations in the development of their root systems. However, he concluded that the soil condition was a more dominant factor in the development of the root system, while the contribution of genotypes was negligible. In our study, differences in expansion habit of the root systems of hop cultivars grown under similar soil, climatic, and cultivation conditions were suggested for the first time; i.e., the root system of Little Star was closer to the plant base than was that of Furano Special (Figs. 1, 2).

The data also suggest that the differences in the root systems between the cultivars could affect the response of cone yields to variations in climatic conditions. The cone yields of Little Star seem to be more sensitive to variations in precipitation from the beginning to middle of July than those of Furano Special (Fig. 3). Hamaguchi (1967) investigated the relationship between hop yields and precipitation amount in Japan and found that precipitation in July, especially during the first 20 days, affected hop cone yields more strongly than that in May or June. He suggested that hops are especially in need of water during early July, because blooms and cones start forming during this time of year in Japan. The different responses to precipitation between the two hop cultivars might be due to differences in water acquisition capacity during this critical period, which is influenced by the variations in root expansion habit. The contribution of varietal differences in root expansion habit to plant growth has also been observed in different crops. Itoh et al. (2008) reported that varietal differences in the root system distribution of sugar beets affected the responses of the plants to heat and dryness. More extensive and detailed studies are necessary to confirm the contribution of hop genotypes to cone yield as a result of root expansion habit.

A better understanding and knowledge of the genotypes, root system and agronomical characteristics of the hop plant would lead to further research and development to improve the productivity of hops. Clarification of the contribution of hop genotypes to root system distribution, responses to climatic conditions and crop yield would give hop breeders additional insights into the development of a new hop cultivar with better productivity under fluctuating climatic conditions. A clearer understanding of the hop root system will also help establish more efficient cultivation techniques.
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