https://doi.org/10.17221/672/2019-PSE

Distribution of root system of hop plants in hop gardens with regular rows cultivation

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Citation: Brant V., Krofta K., Kroulík M., Zábranský P., Procházka P., Pokorný J. (2020): Distribution of root system of hop plants in hop gardens with regular rows cultivation. Plant Soil Environ., 66: 317–326.

Abstract: Spatial distribution of the root system of hop (*Humulus lupulus* L.) in the soil profile is a less explored issue. However, it is known that it can play an important role in the development of new tillage technologies, fertilisation and irrigation, including the use of precision farming principles. In the period from 2015 to 2018, the distribution of the hop root system was evaluated on twelve hop plants of five Czech hop cultivars. The age of the plants ranged from 3 to 15 years. The evaluation took place in the Saaz region at regularly cultivated hop gardens. As part of the evaluation, the root systems of hop plants were removed from the soil profile and subsequently spatially reconstructed. With the help of infrared image analysis, the root intensity in the soil profile and the morphology of the root systems were determined. The root depth of the plants ranged from 1 m to 2.25 m. The lateral width of the hop root system ranged from 0.6 m to 1.5 m. As a result of the rows cultivation, the lateral development of the roots in the upper soil layers was limited. The results were confirmed using the infrared image analysis method to specify the distribution of the root system and the root density of hop plants in the soil profile.

Keywords: rooting depth; infra-red photography; root density map; hop cultivars

Hop (*Humulus lupulus* L.) is a perennial dioecious plant with wide industrial use. It has a dominant application in brewing (Zanoli and Zavatti 2008, Mongelli et al. 2015), mainly using its secondary metabolites, especially resins and essential oils (Moir 2000, Steenackers et al. 2015). Its importance for medicinal purposes cannot be neglected, either (Zanoli and Zavatti 2008, Shishehgar et al. 2012). It is also significant in food industry in the production of food supplements (Abram et al. 2015).

A considerable part of studies and literature are devoted to the issues of hop breeding (Patzak et al. 2010, Nesvadba et al. 2011, Mongelli et al. 2015), qualitative and quantitative parameters of hops (e.g. Stevens 1967, Van Opstaele et al. 2013, Almaguer et al. 2014) and protection against harmful organisms (Postman et al. 2005, Bedini et al. 2015). Recently, the issues of hop moisture demands, resistance to water stress and irrigation efficiency in hop gardens have been solved by Kučera and Krofta (2009), Korovetska et al. (2014), Kolenc et al. (2016) and Nakawuka et al. (2017). Less information is available on the influence of basic agricultural technologies on the development and production of hop, its growth and on soil properties (Lipecki and Berbeć 1997, Turner et al. 2011, Rossini et al. 2016). Also, sporadic information is available in scientific literature on erosion processes in hop gardens (Auerswald 2002, Stumpf and Auerswald 2006) and the possibilities of reducing erosion risks by the use of intercropping,

Supported by the Ministry of Agriculture of the Czech Republic, Project No. QK1910170.

https://doi.org/10.17221/672/2019-PSE

sown between the rows of hop plants (Wieser et al. 2007, Kabelka et al. 2019). Earlier data refer to the problem of soil compaction in hop gardens and the impact of soil compaction on infiltration processes, nutrient availability and crop development (Sachl 1974, Štranc 1984). Brant et al. (2016) reported a compacted soil layer in the hop garden at a depth of 0.2 m, which reduced infiltration processes and contributed to subsurface water runoff.

A generally limited amount of information is currently available concerning the distribution of the hop plants root system in the soil profile. Wample and Farrar (1983) report that hop plants produce a perennially highly branched root system. Miller (1958) points out that the issue of the hop root system has been neglected when compared to other directions of research. The distribution of the hop root system is influenced by the cultivation management of rows. Neve (1991) states that the rows cultivation restricts the lateral development of the roots in regularly cultivated soil. In non-cultivated systems, the top soil layer is rooted in the perpendicular direction to the row axis. Graf et al. (2014) describes intensive root growth of a five-year-old Hercules plant in uncultivated spacing in the soil depth of 0–0.4 m within 1.7 m from the centre of the plant. The roots reached a depth of 1.6 m. The use of irrigation affected the distribution and depth of hop roots. Sobotik et al. (2018) report that in case of the irrigated plot, the roots reached the depth of 1.3 m, while in the non-irrigated plots it was 3.7 m. They further report that in the non-irrigated plot, more intense root growth of multi-year roots in the soil depth of 0.2 m to 0.4 m was observed compared to the irrigated area.

Graf et al. (2014) report that knowledge of the root system is necessary for effective fertilisation, irrigation and soil tillage. Brant et al. (2016) point to the fact that knowledge of the hop root system distribution in soil is needed not only for targeted removal of soil compaction and promotion of rainwater infiltration to the roots, but also for development of zonal fertilisation systems in accordance with the principles of precision farming. Perennial cultures are generally considered appropriate for applying the principles of precision farming for their long-term monitoring and work with plant placement, driving trajectory optimisation, etc. (Hameed et al. 2012, Castillo-Ruiz et al. 2015, Sharma and Ashoka 2015). Data on the use of the precision agriculture principles in hop gardens are very limited in the scientific literature.

The aim of the work was: (a) to specify the spatial distribution of the hop plants root system on the basis of its removal from the soil in *in-situ* conditions and recording of data for quantification of its parameters by image analysis; (b) to verify the use of the infrared image analysis of the hop root system to determine its shape and root density in soil; (c) to model utilisation of root systems biometric data to plan precise fertilisation and soil processing systems in hop gardens.

MATERIAL AND METHODS

Evaluation of the spatial distribution of the hop root system took place in the Saaz hop region (Czech Republic). The GPS coordinates of the evaluated sites (sampling points) in 2015–2018 are documented in Table 1. The altitude of the area is between 190 and 200 m a.s.l. The main soil type is Luvisol. The average annual air temperature is 9.4 °C and the average annual rainfall is 475 mm. In the evaluated years, the root systems of four hop cultivars, 3- to 15-year old, were monitored (Table 1). Two to three root systems were removed from the soil at each site. In all cases, these were always neighbouring plants in a row. The structure of hop plants placement was the same in all the hop gardens, the distance between plants in a row was 1 m and the spacing between the rows was

Table 1. Evaluated sites, term evaluation of root systems, number of plants and their designation and age of plants

Year	GPS of the site	Site code	Date of evaluation	Rated plants (number of plants)	Cultivar	Plant age (year)	Groundwater level (m)
2015	50.3145067N, 13.6058325E	AH 1	14. 04. 2015	1, 2 (2)	Harmonie	4	1.7
	50.3316075N, 13.6257506E	AH 2	14. 05. 2015	3, 4, 5 (3)	Saaz	3	> 2.5
2016	50.190158N, 13.3637704E	AH 3	15. 06. 2016	6, 7 (2)	Agnus	14	> 2.5
2017	50.3315514N, 13.6167431E	AH 4	10. 05. 2017	8, 9, 10 (3)	Saaz	15	> 2.5
2018	50.3267569N, 13.6206911E	AH 5	15. 06. 2018	11, 12 (2)	Sládek	15	> 2.5

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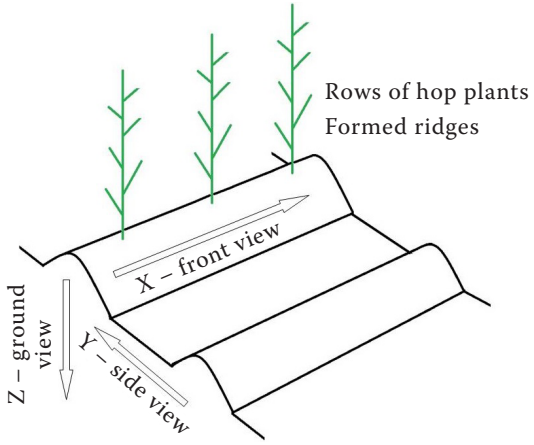

Figure 1. Representation of individual views of root systems

3 m. The root evaluation took place between April and June (Table 1). The same system of hop gardens cultivation was used in all evaluated cases.

Preparation of root system and visualisation. Heavy mechanisation removed most of the soil around the root system. The root system preparation itself was completed by manually removing the soil from the root zone. In the preparation of the roots, their spatial placement in the soil was recorded using the labels placed on the spinal roots. Thus, the position of the roots was determined based on the $x/y/z$ axial coordinates from the upper part of formed ridges and hereinafter referred to as front, side and ground views (Figure 1). The formed ridges were included in the evaluation because the root system was already present in those ridges. In addition to the roots, there are underground systems of stem organs situated in this part. The height of the ridge was around 0.2 m. The ridges were formed to a width of about 0.7 m.

From that point, the deposition and depth of roots in soil were measured. After removing the roots from the soil, they were spatially reconstructed using support and hanging wires. Subsequently, a photo of the root system was made using an infrared image. The roots were photographed in a direction perpendicular to the row and in the row direction. In the years 2015 and 2016, photos were taken from a ground view. Adjusted camera, model Panasonic Lumix DMC-G5 (Osaka, Japan) with Hoya R72 (Saitama, Japan) bandpass filter, was used.

Infrared photographs (8 Mpx resolution) of the roots were converted into a black (for background) and white (for roots) formats and following the circumference of the plates, all images were cropped in the Photoshop program (Adobe Photoshop CS5, Adobe Systems Software, Dublin, Ireland).

The distance of the lens to the object depended on the size of the root system. Subsequent root size quantification was performed based on the presence of size calibration points in the background. The principle of image creation of the root system was based on the methodology of infra-red photography (Brant et al. 2017). The workflow is illustrated in Figure 2. Figure 3 shows an example of a graphical representation of the root system of hop after converting the infra-red image into a black-and-white format (B/W format) with a scale imaging. A side views of a row, front views and ground views are documented. In 2016, two hop root systems (plant 6 and 7, locality AH 3) were prepared. Due to the interconnection of hop plant root systems in 2016,

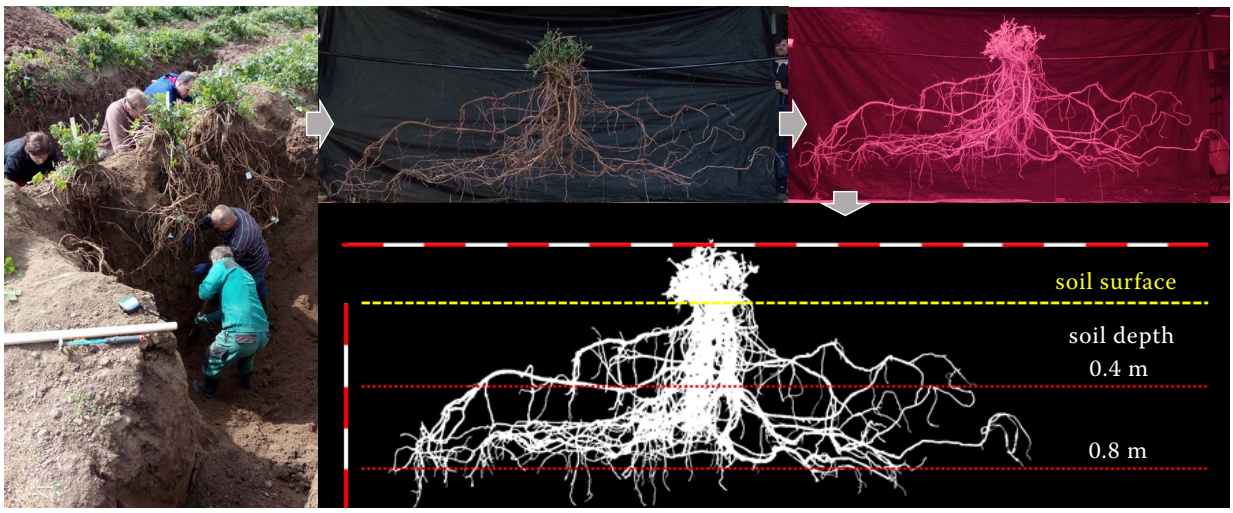

Figure 2. Preparation, reconstruction and visualisation of the hop root system

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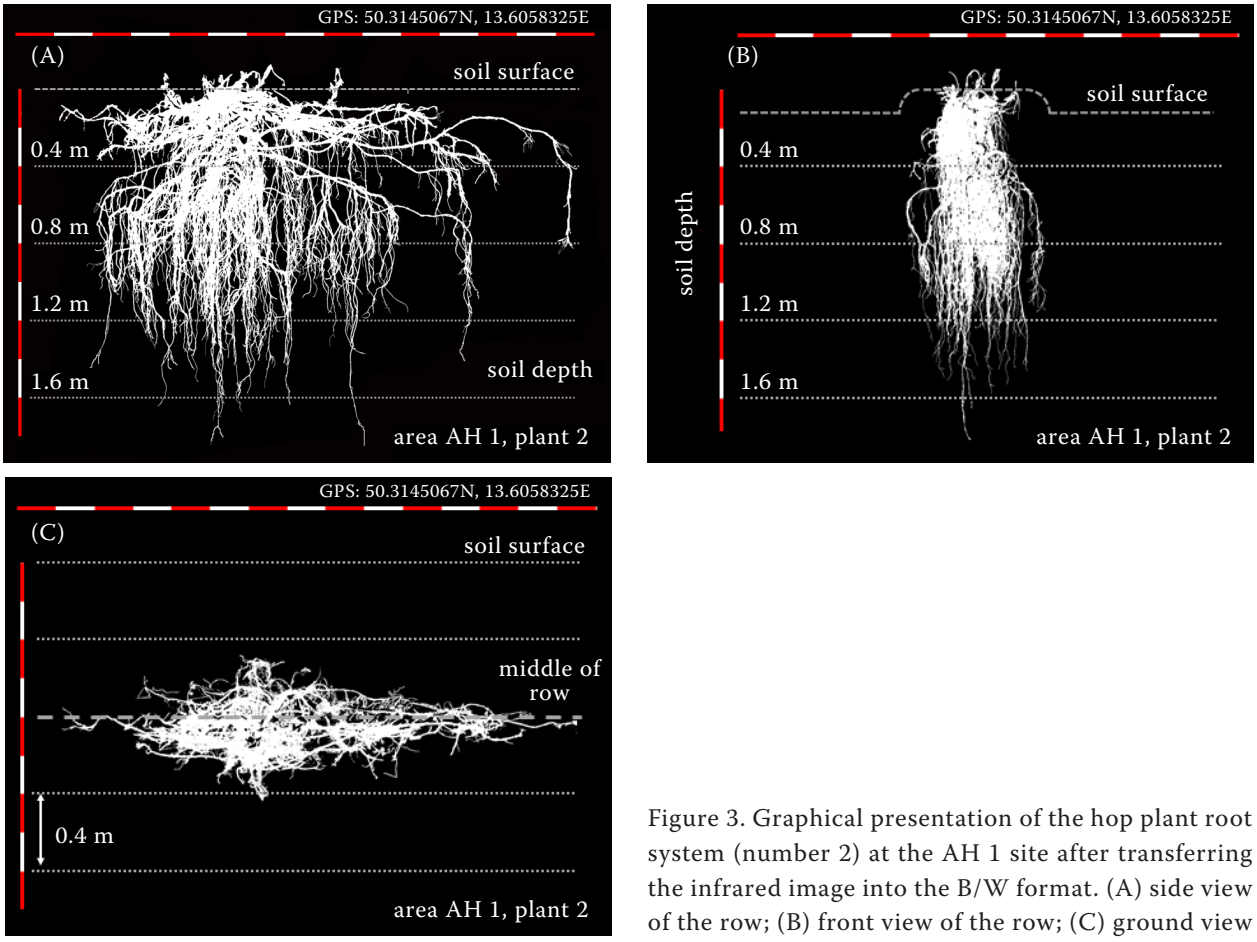

Figure 3. Graphical presentation of the hop plant root system (number 2) at the AH 1 site after transferring the infrared image into the B/W format. (A) side view of the row; (B) front view of the row; (C) ground view

it was not possible to evaluate the individual plant roots separately.

Biometric characteristics. For selected root systems, their dry weight was monitored. The root system was dried at room temperature to equilibrium moisture content of 8% wt., and subsequently weighed. Furthermore, the shape of the root system was evaluated from the front and side view of the row. The volume of the root system was determined by joining the terminal points of the root system and turned into black and white photograph in the Photoshop program. In this manner, a pattern documenting the shape of the root system distribution in the soil was created. The soil rooting depth and lateral spacing of the soil from the front and side view of the row was determined by visualising black and white photographs that were divided into pixels of the size of 0.05 × 0.05 m (for description of the processing, see below). Presence of white colour pixels was taken for maximum depth and width determination.

Stratification of roots in soil. Root photos were converted to black (soil) and white (root) colour. The "BMPtool" (Anken et al. 1999) program was used to analyse the presence of rooting, and the transformed pictures were processed into a point network. During the process, the representations of white colour per individual cells were counted. The size of single cells was 0.05 × 0.05 m. Percentage of the root surface to the cell surface was determined. The ground view, the side view and the front view were evaluated separately for each root system. The central axis of the formed point network was through the centre of the plant in side, front and ground view. Then these values were used for statistical evaluation of the rooting density from the plant row side view. To simplify the interpretation of the results, the root density was determined for the area of the soil profile of 1.2 m (depth) and 1.8 m (width), which was divided into 0.3 × 0.6 m (12 cells) (Figure 4). The root depth for the shallowest rooted plant was decisive for dividing of the evaluated profile into cells.

A map of the root density was created for roots taken in years 2015–2016. It represents a ground view of roots. The values of the roots density with

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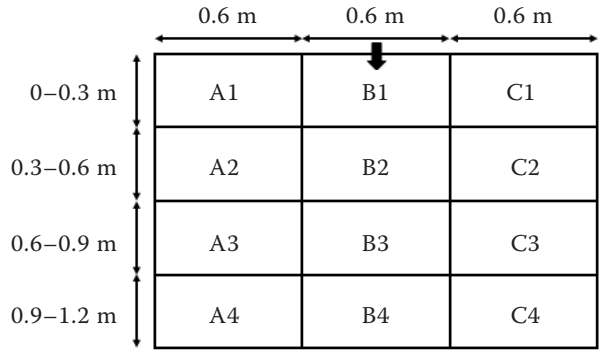

Figure 4. Distribution of soil profile zones (side view) used to assess hop plants root intensity. The black arrow indicates the centre of the plant

the resolution of 0.05 × 0.05 m were used for map creation as well. A root density map was created using the Kriging interpolation method and ArcGIS 10.4.1 software by Esri (Redlands, USA).

Statistical evaluation. Statistical analyses were carried out in Stat-graphics® Plus4.0 (Statgraphics, Warrenton, USA). The analysis of variance (ANOVA, Tukey's test, α = 0.05) and simple regression were used.

RESULTS AND DISCUSSION

Table 2 illustrates the basic biometric parameters of a hop root system distribution in different soil depths. In the evaluation of biometric characteristics, the plant rooting depth ranged from 1 m to 2.25 m. This is consistent with Graf et al. (2014) and Sobotik et al. (2018). Unlike the results presented by Graf, our results did not show significant formation of lateral hop plant roots in the *y* axis direction for regularly cultivated hop gardens.

Table 2. Dimensions of the evaluated plants root system (m) and dry weight of the root system (g)

Plant	Parameter			Dry weight
	a	b	c	
1	1.80	2.75	1.06	1 420
2	1.85	2.65	0.71	–
3	1.25	1.00	0.80	–
4	1.05	1.25	0.78	–
5	1.00	1.95	0.59	1 581
8	2.10	1.60	0.53	604
9	2.25	1.75	0.87	1 330
10	2.20	2.10	0.93	1 624
11	1.00	3.15	1.41	–
12	1.00	3.10	2.27	–

Parameter a – maximum depth of soil root; b – longest root width at side view; c – longest root width at front view

On the basis of the analyses, excavated roots showed lateral rooting mostly at a distance of 0.5 m to 0.6 m from the centre of the formed ridge in the soil depth of 0–0.3 m below the ridge level. The cause is obviously a regular cultivation that disturbs the symmetrical formation of horizontal roots into larger distances. Regular deep cultivation is carried out during autumn to depth from 0.3 m to 0.6 m depending on soil conditions. During the growing season, shallow loosening is carried out to control weeds. The limitation of lateral root development to the rows of cultivated hop fields is reported by Neve (1991).

The front view of the root system in the row is displayed in Figure 5A. For plants number 11 and 12 (locality AH 5), the width of the rooted soil was larger (Table 2, parameter c, Figure 5A). However, lateral rooting occurred in the lower parts of the topsoil profile – in the depth that was not regularly cultivated. This fact is not available in literature describing the root system distribution in soil. Lateral rooting is reported only for the topsoil in non-cultivated hop fields (Graf et al. 2014). The dry weight of the root system ranged from 604 g to 1 624 g (Table 2).

Determination of the effect of plant age on the rooting depth from the obtained data is problematic because there were four cultivars evaluated at different sites. The dependence of the root depth on the plant age can therefore be partially assessed only in cv. Saaz (plant age 3 years – AH 1 site and 15 years – AH 4 site). Older plants of this cultivar were found to have the highest root depth of 2.25 m, but due to different soil profiles of the sites, the dependence of the root depth on plant age cannot be exactly compared. The soil profile has an essential impact on the root depth. For example, at H5 (cv. Sládek), the maximum root depth was found to be 1.00 m only, although the plant was 15 years old. Rooting depth of 1.00 m corresponded to the topsoil thickness; roots were shallower in the impermeable clay layer beneath the topsoil. A positive correlation was established between plant age and depth of rooting. It can be expressed by the linear function: "root depth of the plant = 1.73542 + 0.0298611 × plant age". The correlation coefficient for this model is 0.961 and means a statistically significant relationship between both parameters at the 95.0% confidence level. However, literature data on time

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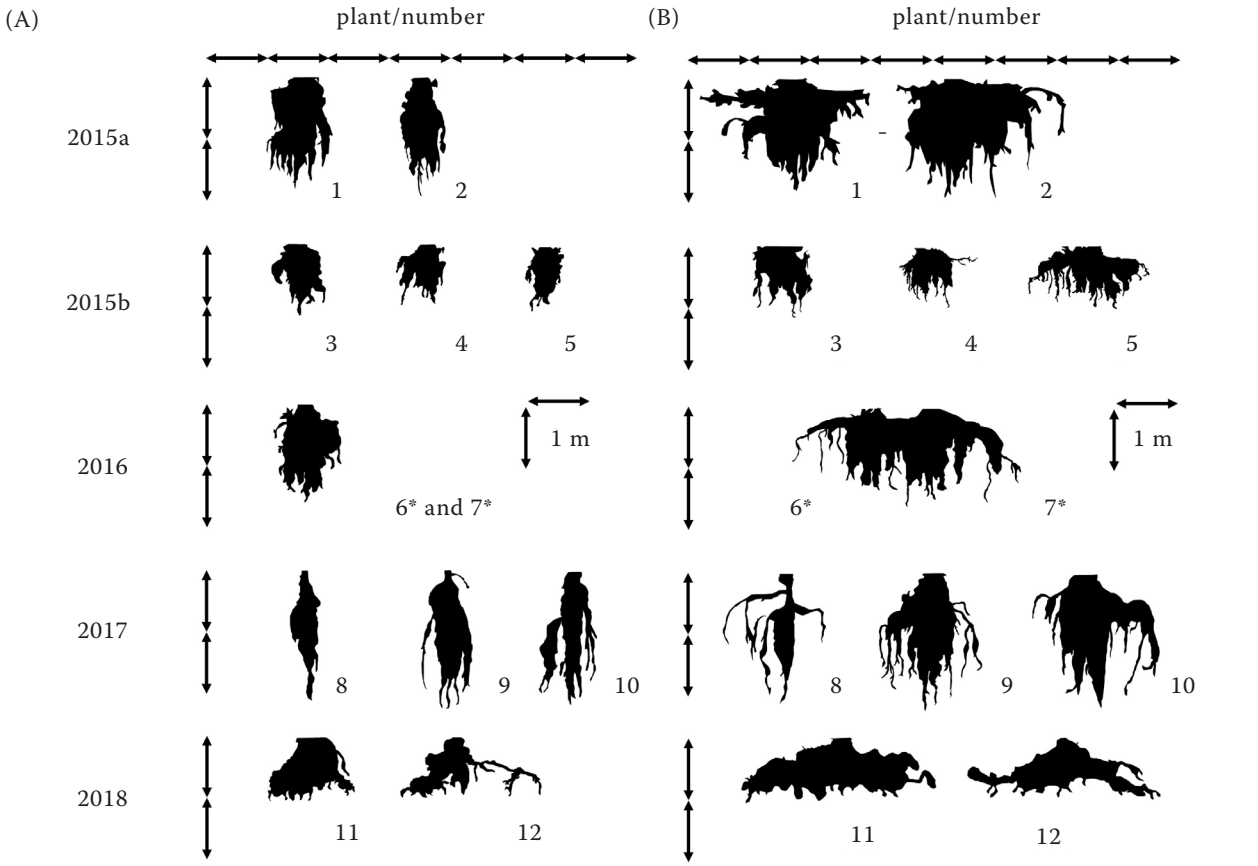

Figure 5. Habitus of hop root systems of evaluated plants in 2015–2018. (A) front view of the row and (B) side view of the row. *connected root system

dynamics of hop rooting are not available and thus cannot verify the relevance of this result. Figure 5B illustrates the shape of root systems from a side view. The lateral width of the hop root system ranged from 1.0 m to 3.15 m (Table 2, parameter b). Plant 6 and 7 were excluded from the evaluation, because the plats were not possible to separate. The intensified development of the hop root system in the direction of the row and lower soil layers was confirmed by Graf et al. (2014) and Sobotik et al. (2018).

Table 3. Average root density (%) at soil profile zones (A–C); side view of the evaluated plants root systems

Year	Plant (number)	Area											
		A1	B1	C1	A2	B2	C2	A3	B3	C3	A4	B4	C4
2015	1	19.4^{bc}	78.8^{e}	19.1^{b}	20.9^{ef}	83.7^{e}	36.7^{e}	21.4^{cd}	76.4^{d}	24.0^{c}	7.1^{b}	51.5^{c}	21.6^{c}
	2	24.3^{c}	81.6^{e}	49.0^{c}	19.2^{de}	80.5^{de}	37.9^{e}	34.5^{e}	76.2^{d}	51.0^{d}	17.7^{c}	54.7^{c}	24.8^{c}
	3	8.0^{a}	83.1^{e}	7.2^{a}	4.7^{ab}	56.3^{bc}	15.1^{bcd}	2.5^{a}	16.9^{ab}	7.1^{ab}	0.3^{a}	1.3^{a}	0.4^{a}
	4	0.1^{a}	60.8^{cd}	19.4^{b}	0.1^{a}	50.7^{b}	17.8^{cd}	0^{a}	8.2^{a}	1.9^{a}	0^{a}	0^{a}	0.2^{a}
	5	38.5^{d}	67.6^{de}	6.6^{a}	22.1^{ef}	52.2^{b}	12.8^{abc}	4.0^{ab}	16.1^{a}	5.9^{ab}	0^{a}	0.4^{a}	0.4^{a}
2017	8	0^{a}	23.0^{a}	0^{a}	8.0^{ab}	22.8^{a}	2.8^{a}	7.3^{ab}	28.2^{b}	2.7^{a}	9.9^{b}	21.4^{b}	0.4^{a}
	9	0.1^{a}	47.0^{bc}	0.0^{a}	9.5^{abc}	53.8^{b}	4.7^{ab}	26.1^{de}	64.1^{c}	13.5^{b}	18.9^{c}	51.5^{c}	9.9^{b}
	10	1.4^{a}	60.2^{cd}	2.6^{a}	18.0^{cde}	52.2^{b}	23.6^{d}	13.5^{bc}	54.3^{c}	22.9^{c}	8.0^{b}	49.4^{c}	10.8^{b}
2018	11	10.1^{ab}	56.1^{bcd}	7.7^{a}	29.8^{f}	69.6^{cd}	19.6^{cd}	30.1^{de}	28.4^{b}	26.6^{c}	0.6^{a}	0.2^{a}	0^{a}
	12	2.3^{a}	42.9^{b}	2.4^{a}	9.9^{bcd}	30.6^{a}	18.0^{cd}	13.7^{bc}	14.6^{a}	6.3^{ab}	0^{a}	0^{a}	0^{a}

Different indices within the column document a statistically significant difference at the significance level $\alpha = 0.05$ (ANOVA, Tukey)

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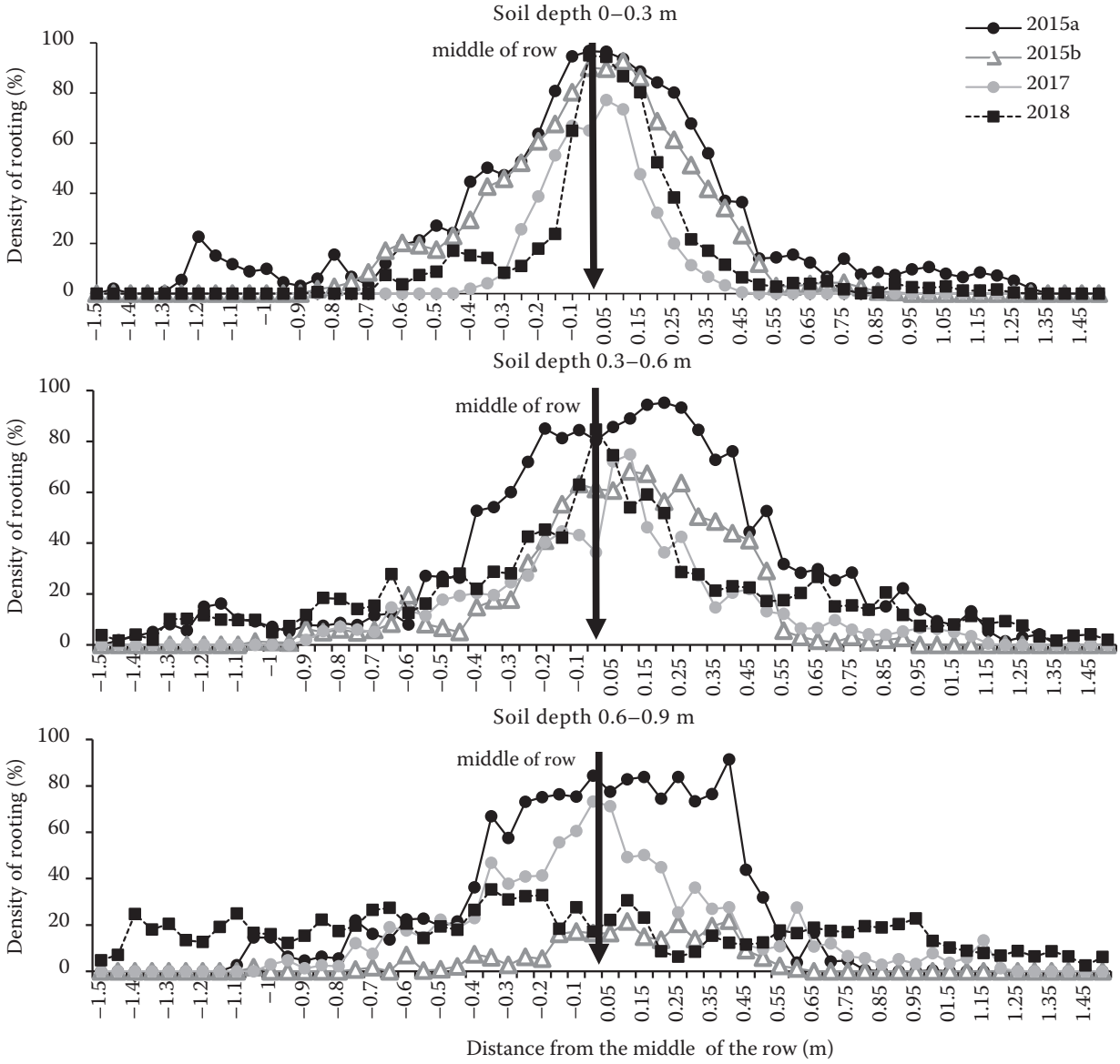

Figure 6. Average values of root density in soil depths 0–0.3, 0.3–0.6, 0.6–0.9 and 0.9–1.2 m in the monitored localities. The curve documents the average value of root density obtained as the average of all plants evaluated in a given locality in a given year

Average root density in soil profile, including formed ridges, from side view is summarised in Table 3. Distribution of soil profile cells and depth of profile is shown in Figure 4. The highest roots intensity in most plants was determined in zone B1 of 0.3 m from the left and right sides of the centre of the formed ridge to the depth of 0.6 m compared to other zones. Zones B1 to B4 showed higher root density values compared to zones A and C. There were statistically significant differences among individual plants in terms of the root density of the zone. Within the individual localities, differences among individual plants in zones B were mostly not statistically significant. The average values of root density in selected soil depths are shown in Figure 6. The curve illustrates the average value of root density obtained as an average of all the evaluated plants in a given locality in a given year. The Figure shows differences among localities. Of course, the actual root density in a given soil depth is higher due to overlapping of the root systems of individual plants.

Increased soil rooting in zones B1 to B4, including mostly perpendicularly downward growing roots,

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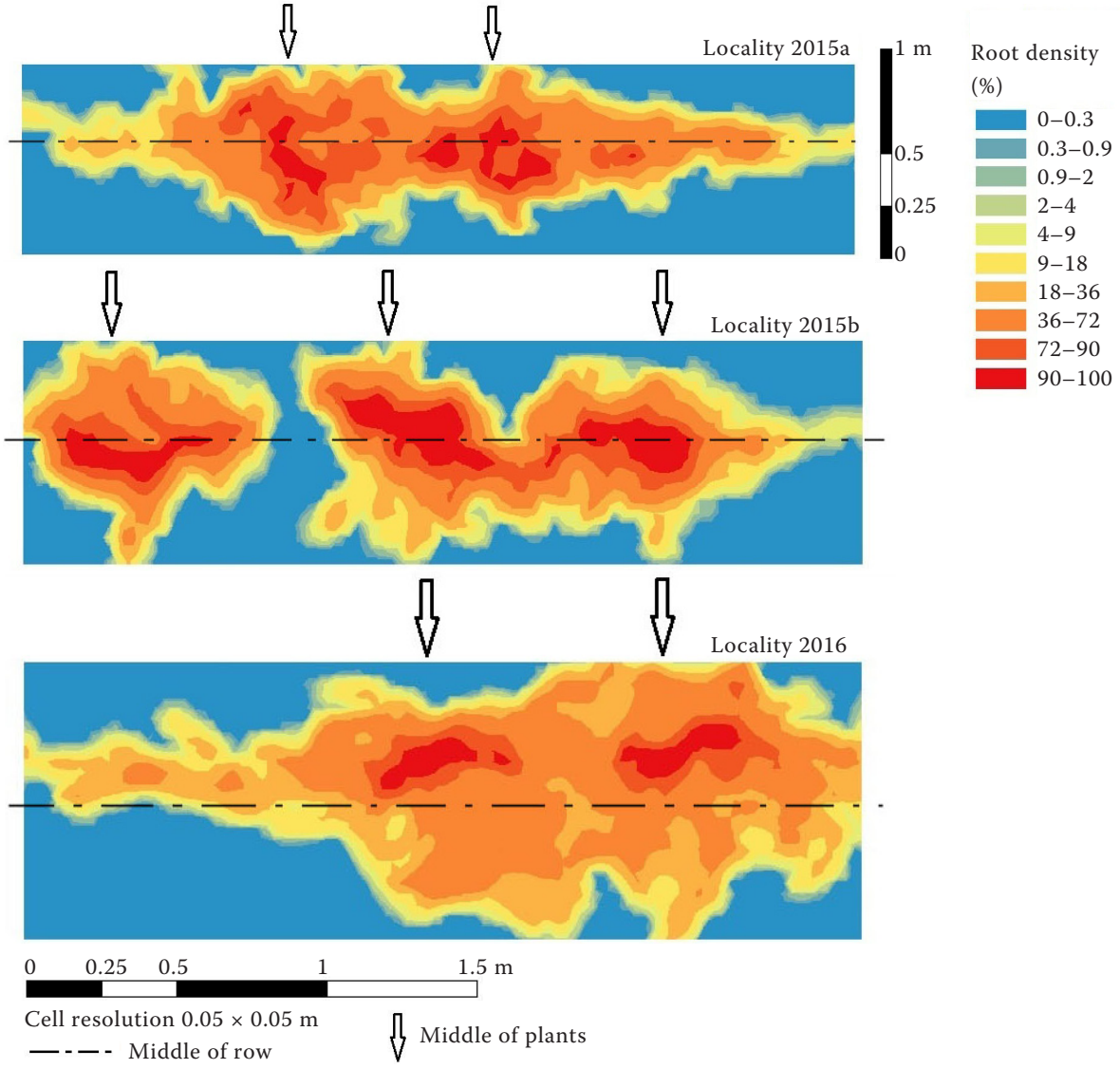

Figure 7. Soil rooting density at the ground view in 2015 and 2016. Root mapping includes soil rooting within the line of the observed plants

creates suitable conditions for infiltration of rainwater and irrigation water. A positive effect of the root system in the soil on water infiltration is described in the maize plants under field conditions (Brant 2016).

The intensive root-cropping of the soil around the centre of the crown, both in young and older plants, can also be used for zonal fertilisation of plants into the soil during cultivation. The possibilities of zonal deposition of fertilisers into the soil to plant roots are described by Rybáček (1980) and are considered as a suitable system by Brant et al. (2016). Based on the distribution of the plants root systems in the soil depth (Table 2, Figure 6), zonally deposited fertilisers can be considered optimal to a depth of 0.3 m on the sides of the plant row.

The distance of the fertiliser placement from the centre of the crowns to row space should be at least 0.5 m for regularly cultivated plots. Figure 7 illustrates the root density on the basis of the soil root map when looking at a row of hop from above. From the map it is evident that the lateral development of the root system on cultivated hop fields is limited in accordance with the results of Neve (1991). Furthermore, linking the root systems of neighbouring plants is clearly visible. Considerable interconnection of root systems of neighbouring plants was observed at sites older than 10 years (Figure 5B, plants number 6–12).

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This information can be used for zonal fertilisation systems, where the fertiliser can be deposited specifically in the centre of plants for young hop gardens, and continuously over the entire side of the row at later stages.

Root system deployment is also useful for irrigation planning. After the rows are fully developed, the irrigation can be directed to the entire surface of the row. On the sides of the row, it is necessary to create suitable conditions for rainwater infiltration, because in cultivated hop gardens it can be assumed that in the unrooted rows, the water intake of plants will be minimal.

The presented work confirmed the possibility of using the infrared image analysis to specify the distribution of the hop plants root system in the soil profile and to specify the intensity of soil root growth. The results show that in regularly cultivated hop gardens, the development of the root system of the hops is limited in a direction perpendicular to the row and in most cases the roots occur within 0.5 m of the centre of the plants row. The regular soil cultivation is the dominant technology used in the Czech Republic. Therefore, the results are of crucial importance for the development of zonal fertilisation systems in the lower soil layers and the root occurrence zone, because the distribution of roots is not sufficiently taken into account in terms of irrigation and fertilisation. It is necessary to consider the fact that pumping of water by the roots of plants occurring in a narrow strip of the line is considerably limited. The work was conceived as a pilot project for the application of precision agriculture principles, especially for the development of targeted positional fertilisation (directly to the plant's planting site at the beginning of vegetation), or continuously along the line for older growths.

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Received: December 10, 2019
Accepted: June 2, 2020
Published online: June 23, 2020