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Humulus lupulus – The Hidden Half

Optimising hop cultivation is a constant endeavour for the brewing industry, as it delivers one of the most important ingredients for beer production. Whereas a lot about hop production in general is known, there is only little knowledge available with regard to the morphology and extent of its root zone. However, for further improving the agricultural management, a deepened understanding of the root development and its dimensions is required for optimising irrigation, soil tillage and plant nutrition.

We therefore investigated the root distribution of hop (*Humulus lupulus* 'Herkules') in a sandy soil and described the spatial extension geometrically. The description is based on an excavation of the whole rootstock of a plant in the fifth year of yield. The measurements were documented by photos during the excavation procedure and subsequently illustrated by morphological drawings.

The root system of hop can be subdivided into three parts: A row section with adventitious roots, a disk surrounding the rootstock with horizontally growing roots and a block of vertical roots developing downwards. Both the horizontal and the vertical part are interspersed by two types of roots (perennial and fresh ones). The total amount of the rooted soil volume was about 4.1 m³, which indicates a large potential capacity for available water. An area of around 5.0 m² for each plant is being wetted by rainfall. These findings may contribute to optimised management decisions.

Descriptors: hop, *Humulus lupulus*, irrigation scheduling, root excavation, root zone

Abbreviations used: HR: horizontal roots; VR: vertical roots

1 Introduction

The dried inflorescences of hop are a very important ingredient of beer as they stabilise foam and bring typical flavour to beer. A worldwide beer production of more than $1.97 \cdot 10^9$ hl is dependent on a stable hop production. In 2013, 46,246 ha acreage of hops, with a portion of 36 % in Germany, was cultivated to satisfy the demands of the brewing industry [1]. But for hop cultivation, and to assure contracted deliveries, farmers require advice for optimising hop production.

Hop represents a special culture. From an agricultural managerial perspective, it is a challenging and work-intensive crop. From a botanical perspective, the plant is special as it can reach heights of up to 7 metres and build up an aboveground green biomass of up to 25 kg in less than four months (own unpublished results). However, while varieties, cultivation and management techniques have markedly progressed over the last decades, little effort has been given to focusing on the root system of *Humulus lupulus* [2]. Although there is a profound description of hop's root types and their functions [3], there is only little information available about their morphology [4] and the dimension of accessed soil [5]. But every metabolic essential substance, except carbon dioxide, is taken up by the roots. So knowledge of the root system is necessary for effective fertilisation, irrigation and soil tillage.

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Many studies have focused on irrigation and the dependent physiological traits of hop [6, 7, 8, 9, 10]. But findings are difficult to interpret [11, 12] and irrigation scheduling is confronted with difficulties without a specific knowledge of the available water reserves. Especially water balance models are dependent on such values, as they are balancing the amount of precipitation, transpiration and soil water storage.

Furthermore, the optimisation of irrigation systems and the positioning of irrigation emitters in hop yards remain speculative without knowledge of the expansion of the root system.

In this study, which is part of a multi-annual irrigation experiment, we have therefore characterised the root system of *Humulus lupulus*. The following questions were to be answered:

How does the phenotype of the hop's root system look like? What is the potential volume of soil in which hop roots can extend? Can this knowledge contribute to a more rational-based irrigation scheduling and what are the consequences for land management?

2 Materials and Methods

2.1 Site parameters

Root excavation was carried out on 23rd July 2013 under sunny weather conditions. The excavation site is nearby a multi-annual irrigation experiment which is located in the Northern Hallertau, Bavaria, Germany, near Neustadt an der Donau (48°46'49,44" N, 11°47'00,72" E), on a sandy soil. The field capacity is between 10.4 % and 15.6 % in average (e.g. Tab. 1). Analyses were taken in 2012 and were performed in the Department of Soil Physics of the Bavarian State Research Centre for Agriculture in Freising, Germany. Particle size distribution was analysed by sieving and sedimentation (DIN ISO 11277). The field capacity (water content at – 64 hPa) was measured in undisturbed samples with suction plates connected to a hanging water column.

Table 1 Soil properties of the hop yard, analysed at 0.3 m and 0.6 m soil depth. Particle size distribution as a weight percentage was obtained from a mixed sample. The field capacity was measured in six undisturbed samples (n = 6) and is shown as the average. Samples were collected in the row near the rootstock and in the middle of the tractor tramlines approximately 1.6 m away from the rootstock

Location	Depth (m)	Clay (%)	Silt (%)	Sand (%)	Field capacity (%)
Row section	0.30	4.6	6.8	88.6	15.4
	0.60	1.5	2.7	95.8	10.4
Middle of machine track	0.30	6.2	7.2	86.6	15.6
	0.60	1.8	2.5	95.7	10.7

Cattle slurry was applied twice a year. Application was carried out based on a previously-determined nutrient analysis in agreement with the recommended maximum rate of 245 kg N/year [13].

The precipitation recorded until the root sampling amounted to 481.2 mm in 2013 and was measured using the meteorological field station "metos" (Pessl Instruments Inc., Austria). Total rainfall in 2013 was 863.6 mm, similar to the 10-year average across the whole hop growing region in the Hallertau with 863.1 mm [14].

2.2 Plant selection

For morphological root investigation of *Humulus lupulus* a plant of the cultivar Herkules was chosen. Herkules is described as a high alpha hop variety with alpha acid contents of up to 20 % [15]. It is known as a very massy plant with green biomass of up to 25 kg per plant. The hop garden was established in 2009 with rhizome production, so that, at the date of excavation, the hop plant was in its fifth yield year. The distance between the plants amounts to 1.6 m in the row, while the planting rows are 3.2 m far apart from each other. The examined hop was in the beginning of flowering at development stage BBCH 65 [16].

2.3 Root excavation

For root excavation, a 0.4 m wide trench with three flanks in form of a "U" was dug by a dredger encompassing the plant in the centre. The dimension of the trenched ditch was about 3.8 m x 3.2 m and extended from the middle of the machine track to the next one. The fourth side (south-directed) remained for stability of the ditch and to shade the exposed roots [17] (Fig. 1). The depth of the ditch was around 1.7 m. After digging the trench, roots were carefully cleared by hand using rakes, brushes and digging forks (Fig. 1). The dredger excavated the hand-cleared soil and dumped it on a trailer beside the hop yard.

2.4 Overview

The excavation was able to be done well, because of the stable structure and the porous property of the investigated sandy soil.

Fig. 1 Root excavation. The dimension of the trenched ditch was 3.8 x 3.2 m. Roots were prepared with digging forks

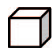
Firm roots were maintained, so that the whole root body could be extracted. Only thin roots were ripped off and had to be documented by photos. The whole root expansion was measured in the field. A pencil drawing was made based on observations, photos and measurements.

2.5 Volume calculations

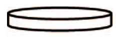
The volume of root expansion was calculated based on the following formulas. All volumes were accumulated.

$$\text{Volume}_{\text{triangular prism}}: 1/2 \text{ width} \cdot \text{height} \cdot \text{length} \quad \text{(Eq. 1)}$$

$$\text{Volume}_{\text{cuboid}}: \text{length} \cdot \text{height} \cdot \text{width} \quad \text{(Eq. 2)}$$

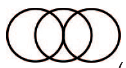


$$\text{Volume}_{\text{cylinder}}: \pi \cdot r^2 \cdot \text{height} \quad \text{(Eq. 3)}$$



Due to the fact that neighbouring plants share the space, and based on the assumption that every plant has the same dimension and occupies half of the shared volume, the amount for one plant was corrected with the formula of circle intersection with equal circles that intersect each other in their centre points:

$$\text{Volume}_{\text{intersection}}: r^2 \cdot (\pi \cdot \alpha / 180° - \sin \alpha) \cdot \text{height} \quad \text{with } \alpha = 120° \quad \text{(Eq. 4)}$$



3 Results

3.1 Root types

We could distinguish between three root types, which are mainly characterised by their age:

a) Roots developing shallow out of the rootstock – characterised as big, perennial, brown and lignified. The biggest diameter was about 2 cm near the rootstock.

b) White, young, fine roots emanating from the perennial roots – these roots used already penetrated channels remaining from older ones and developed root hairs for the exploitation of water and nutrients.

c) Roots developing out of the shoots above the rootstock in the tilled soil within the row – these roots were also

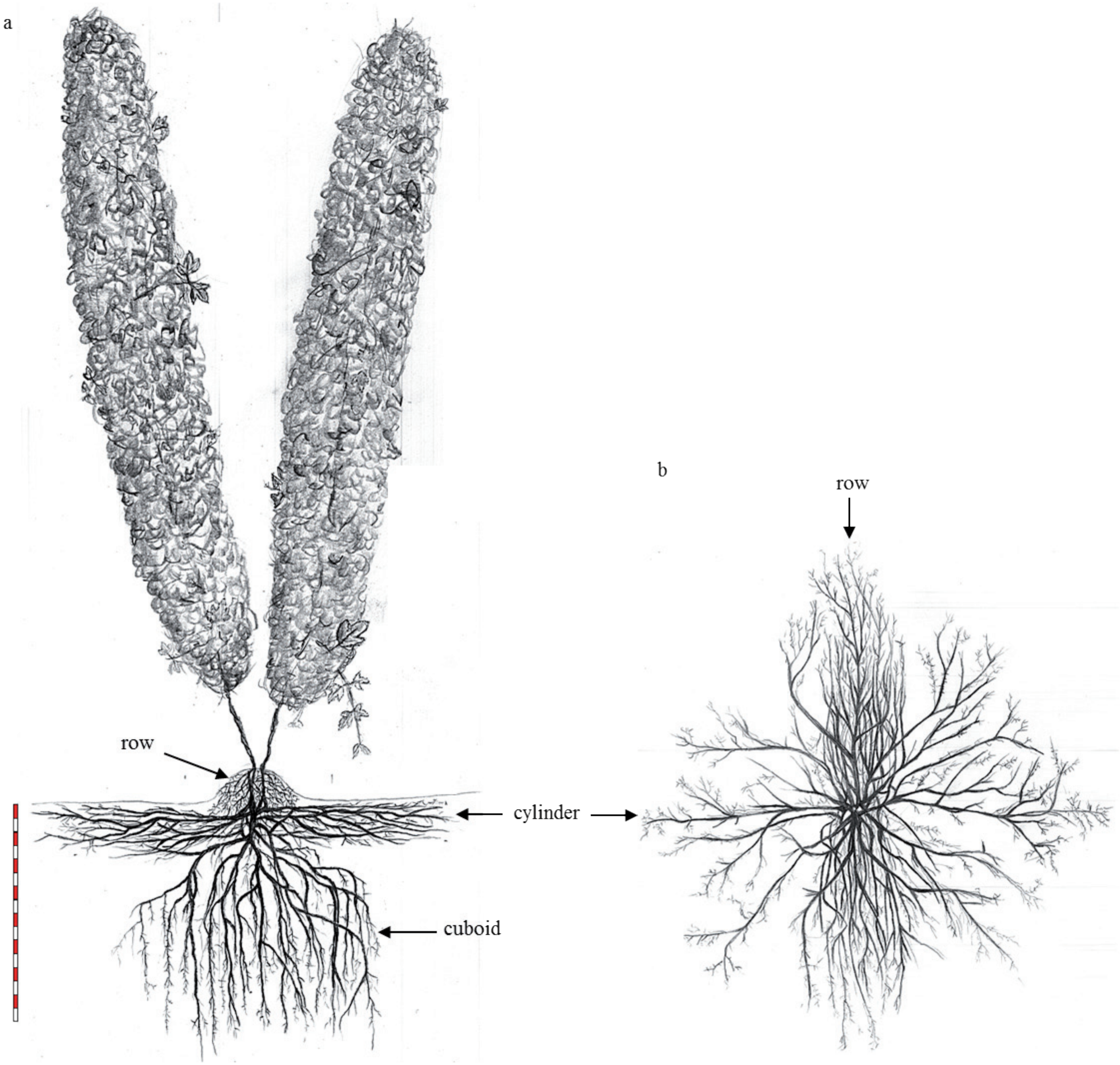


Fig. 2 **Morphological root development, transverse section through the rootstock (a) and aerial perspective of the hop's root system (b). Three different root zones are described: 1) The hilled up row section, with a high number of fibrous adventitious roots. 2) A cylinder-shaped region with flat-growing roots (HR) around the rootstock down to a depth of 0.4 m. 3) A cuboid-shaped region with deeper growing roots (VR) forming a large downward directed block. Young roots potentially active in water and nutrient uptake were detected on most of the perennial roots. For measurements see table 2. The bars indicate 10 cm respectively**

white and young, but were directly associated with the shoot.

3.2 Root morphology and calculated volume of root filled soil

A second distinction was given to the three-dimensional growth of the roots where there was differentiation between vertical roots (VR) and horizontal roots (HR).

The main part of VR ended in a depth of about 1.6 m. The geometrical shape of all VR could be described by a cuboid (e.g. Fig. 2 and Eq. 2). This zone contained old perennial roots and young white roots. The root "block" extended from below the rootstock and stretched out and encompassed a volume of about 2.0 m^3 (e.g. Tab. 2). The deepest roots were found at a depth of 1.7 m, where, however, only a few roots were traceable.

Besides VR, we found a lot of outstretched HR crossing the A-horizon (Fig. 2a and b). Young and perennial roots could also be found. These roots formed a cylinder-shaped zone around the root stock with a radius of about 1.6 m and reached a depth of about 0.4 m (e.g. Eq. 3). The volume of this "disc" was calculated as a cylinder amounting to 2.0 m^3 (e.g. Tab. 2).

A third zone was found within the row which is normally hilled up at the end of spring. The entire volume of the hilled row was interspersed with young white roots, which grew in horizontal and

Table 2 Root zones found and described as geometric solids and measurements of lengths with correspondingly-calculated volumes. The volume of the cylinder has been corrected under the assumption that plants occupy half of the shared space by the formula of intersection. For calculations of volume see 2.5.

Location	Geometric body	Height (m)	Width (m)	Length (m)	Radius (m)	Volume (m^3)
Row section	Triangular prism	0.3	0.4	1.6		0.1
A-horizon (around the rootstock)	cylinder	0.4			1.6	2.0 (excl. intersection)
B-horizon (below the rootstock)	cuboid	1.2	1.3	1.3		2.0
Accumulated volume						**4.1 m^3**

Considering a circular intersection, we found that an area of around 5.0 m^2 for each plant is being wetted by rainfall as shown in Figure 2 b. This corresponds with the plant density typical for the hop growing region Hallertau, where 2000 plants per hectare are planted [13], and is also based on the assumption that the water porous space available to the whole plant will be exploited by the plant's roots.

vertical directions (Fig. 2a and b). They formed many ramifications of further roots. The total volume of the row can be described as a triangular prism with 0.1 m^3 of outstretched volume (e.g. Eq. 1).

The total accumulated amount of the root zone volume of *Humulus lupulus* was thereby approximately 4.1 m^3.

4 Discussion

As a member of the plant order Urticales, the roots of *Humulus lupulus* can be compared with other known morphologies of the species *Urtica dioica* and *Cannabis sativa*. Although the dimensions of the root zones are smaller in size, those species also develop roots with horizontally-growing offshoots and downwards-directed roots [18, 19].

The HR are necessary to collect water from rain and surface-applied nutrients [20, 21]. Due to the fact that they develop close below the surface, rain water can be absorbed. While the topsoil is exposed to radiation, it loses water quickly by evaporation. We assume that VR represent a kind of life assurance in times of drought and missing rainfall. With such meteorological conditions, plants can exploit deeper regions and use these reserves.

Both root zones seemed to be exploited simultaneously at the time of excavation which is shown by occurrence of young fresh roots in all the described root zones. We assume that perennial roots can produce fresh roots very rapidly in time of need, as the growth of the aboveground shoot biomass also takes place very quickly and is proliferative. We detected many points where younger white fresh roots were emanating from the older ones and growing inside their already previously-penetrated root channels to reach moist zones. The whole volume was traversed by active white young roots.

4.1 Available water storage and irrigation scheduling

For irrigation scheduling, it is very important to know the amount of available water [22]. At our study site, with a field capacity of about 15 % in the upper layer (e.g. Tab. 1), there are approximately 300 litres of water contained in the soil and available to the plant, by regarding the supposed geometrical shapes. By further assuming a 10 % field capacity in the cuboid directing downwards, 200 litres can be accounted. Thus, the soil water available to the plant may reach up to 500 litres, based on the assumption that, after the winter period, the soil reaches field capacity which is rather the norm in this region.

Considering the two-dimensional wetting zones realised under drip irrigation emitters, only a relatively small zone is moistened [23] in contrast to the potential extended root zone found in the investigated sandy soil (compare Fig. 2 b). Irrigating the whole potential root zone would sustain root growth in a considerably larger zone. This cannot be achieved by drip irrigation.

Due to technical constraints, and partly to limited water disposal, it is difficult to satisfy the water requirements to increase yield. In areas with high rainfall yield and quality of hop can vary in combination with irrigation [11, 12, 24, 25, 26, 27], what is associated with own findings at the described study site.

A sustained effect of irrigation is however expected in drier years [6, 7], particularly when the previous root development is also confined by soil wetness due to a previous wet period.

Soil water tension measurements are frequently used for the irrigation controlling of plants [24, 28]. The extended root system of hops indicates that such point measurements are imprecise to assure water requirements of hop and further research is needed to investigate the positioning of the drip irrigation systems and their objective controlling. We suppose, if subsurface drip lines are used, installation should ideally be done before planting, in order to avoid root damage of the HR.

4.2 Consequences for land management

Findings from this study may be relevant to several aspects oriented to hop management. In spring, when the upper layer is getting pruned, it should be ensured that no parts of the HR, or as little as possible of them, get destroyed by the implements. Shallow soil tillage is therefore recommended, what is contradictory to former studies [29].

Since the expansion of roots is mainly limited by the penetration resistance of the soil [30, 31, 32, 33], soil compaction in the rooting zone should be avoided. Heavy machinery poses such a risk, particularly under wet soil conditions.

5 Conclusion/Summary

In the current study, the phenotype of the root system of *Humulus lupulus* grown on a sandy soil and cultivated for five years has been investigated. To the best of our knowledge, this may represent the first overall morphological description of the whole root habitus of hop and a calculation of the rooted soil volume. Clearly a generalisation is difficult, since the study was confined to one sampling of hop grown on a sandy soil.

Nevertheless, it has allowed a better insight into the hidden part of the hop plant. The results indicate that a large volume of the water available to the plant is in the investigated sandy soil. First tentative conclusions for optimising the irrigation of hops could be drawn. These findings may contribute to optimised hop cultivation with regard to irrigation, fertilisation and tillage. Future work will be required and should address how the root habitus looks in other soil types and how varieties may differ in their root systems.

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