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The effects of irrigation on root density profiles of potato, celery, and wheat

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Abstract. Irrigation rate should correspond to the effective root depth, however, crop root growth is influenced by a number of factors, and little data is available on the impact of irrigation. This contribution presents the results of several experiments in which the influence of sprinkler or drip irrigations on root density distribution of shallow, medium and deep rooted crops within the soil profile were studied. Irrigation significantly increased the root density of potato, celery, and wheat in the topsoil zone. On the contrary, at most cases there was only a slightly reduced root density in the subsoil layers. Total root length, to maximum root depth, only increased significantly with drip irrigation in potato. The root depths of these crops were not significantly modified by irrigation. The results suggest that the use of a constant value for the calculation of maximum irrigation depth in a specific crop may not correspond to the variability of root depth nor the distribution in different years or fields.

Key words: drought, root distribution, root length, water depletion.

INTRODUCTION

In recent years drought has caused farmers in the Czech Republic (as well as in many other countries) losses of hundreds of millions of euros. Agro-climate models agree that water deficit, due to high evapotranspiration and uneven rainfall distribution throughout the year, will become increasingly common in Central Europe and elsewhere with impacts on yields (Středová et al., 2013; Spitz & Hemerka, 2014; Trnka et al., 2019).

At present in the Czech Republic, primarily vegetables and early potato are irrigated, as well as (to a different extent) fruit orchards, hops gardens, and vineyards (Agriculture and Horticulture Czech Republic, 2019). Most irrigation water is applied to field crops and vegetables by sprinkling; however, drip irrigation that is mainly applied in orchards and vineyards is more effective. The study of Duffková et al. (2019) showed that over 80% of spring crop regions in the Czech Republic were threatened with medium to severe water scarcity. The growing trend for the occurrence of dry periods, will lead to the expansion of irrigated fields. There is concern whether there will be enough water for irrigation in dry years. In addition, water is increasingly discharged from the landscape; and the water supply within both underground and surface resources (and often additionally its quality) has been declining.

This implies the need to improve the use of water in agriculture. The efficiency of irrigation water application depends on correctly determining both the current and estimated future water needs of plants, as well as the available water supply in the root zone. This subject matter has been described in a number of papers (Ahmadi et al., 2011, 2017; Haberle & Svoboda, 2015; Kirnak et al., 2017; Elzner et al., 2018; Assouline, 2019). If the irrigation dose is excessive, water can be lost by percolation below the root zones of the crops; while too low a dose increases the need for repeated application of water, thus increasing evaporation losses. Thus, actual crop root depth determines the maximum irrigation depths, and the volume of soil with the relevant water capacity. It is an especially important factor with shallow rooted potato, vegetables such as lettuce and radish, which are also often grown on shallow light soils.

In the Czech Republic, the calculation of the irrigation dose is determined by Czech national standard (ČSN 750434, 2017). The standard defines the maximum irrigation depth corresponding to the root depth for field crops, vegetables, and fruit trees. However, the root extent is only described in general terms; the effective root depth (for example, according to limit root density) not being defined. Based on this standard, the IRRIPROG expert system (Spitz et al., 2011) was created to calculate the terms and rates of irrigation. The calculation is based on: the FAO 56 evapotranspiration water balance methodology (Allen et al., 1998), infiltrating proportion of rainfall and irrigation water, decrease in available water supply in the root zone below the specified level, available soil water capacity, and possible water leakage below the root zone. Again, the maximum root zone depth of crops is fixed as an average value for a given species.

Root growth is influenced by a number of factors, and the question is whether the root depth under farm conditions does not significantly deviate from the table values of maximum irrigation depth (Spitz et al., 2011; ČSN 750434, 2017). In addition to the expected impacts of soil site conditions, agronomic measures, or cultivar differences, there is concern that high soil moisture, due to irrigation or excessive fertilization (mainly nitrogen), could reduce root depth or density (Svoboda & Haberle, 2006). In such a case, too high an irrigation rate, calculated for an expected deeper root zone, might result in a percolation loss of irrigation water outside of the root zone. Potato and most vegetables have a high demand for nitrogen, but shallow roots and show a low efficiency of N utilization from fertilizers and a high risk of nitrate leaching into the groundwater (Haberle et al., 2018; Svoboda et al., 2018). It is especially important in regions also used for the accumulation of drinking water. These are often situated in areas with light soils near rivers where early potato and vegetables are produced. The on-farm experiments with potato and celery presented here were carried out in the lower Jizera river aquifer, source of 25% of the drinking water for Prague. Due to increasing nitrate concentrations in drainage waters the concerns about optimal irrigation are more pressing (Bruthans et al., 2019). To some extent the activities of these farms are regulated, but the growing of irrigated vegetables and potatoes is not prevented.

Optimal or supra optimum soil resource availability generally reduce plant investment in the root system, but there is little data on the effects of irrigation upon root depth. Tracking roots to the maximum root depth is difficult, so there is little relevant data to be found in the literature. We decided to determine the root density and depth in early potato and celery on farms in order to obtain data relevant for the conditions found in the area. This data should verify the recommended maximum irrigation depths for selected crops and to support the decisions of the farmers.

The aim of this research was to determine the effects of irrigation on the root density distribution of potato and celery (crops with shallow and medium deep root systems, respectively), and winter wheat (characterized by a large and deep root system).

MATERIALS AND METHODS

Site conditions

The basic descriptions of the crops studied, treatments, soils, irrigation systems, and total amount of irrigation water (mm) are shown in Table 1. The potato and celery roots were sampled at the farms, while the wheat was studied in a plot trial. Daily precipitation sums and average temperatures at the experimental sites and years are shown in Fig. 1. Soil moisture during the potato and celery experiments were monitored with EC10 (Decagon, USA) and CS616 (Campbell Scientific, USA) sensors. In wheat, the amount of water in the 0–90 cm zone was calculated from water balance data, corrected according to a standard determination of soil moisture (Raimanová et al., 2016).

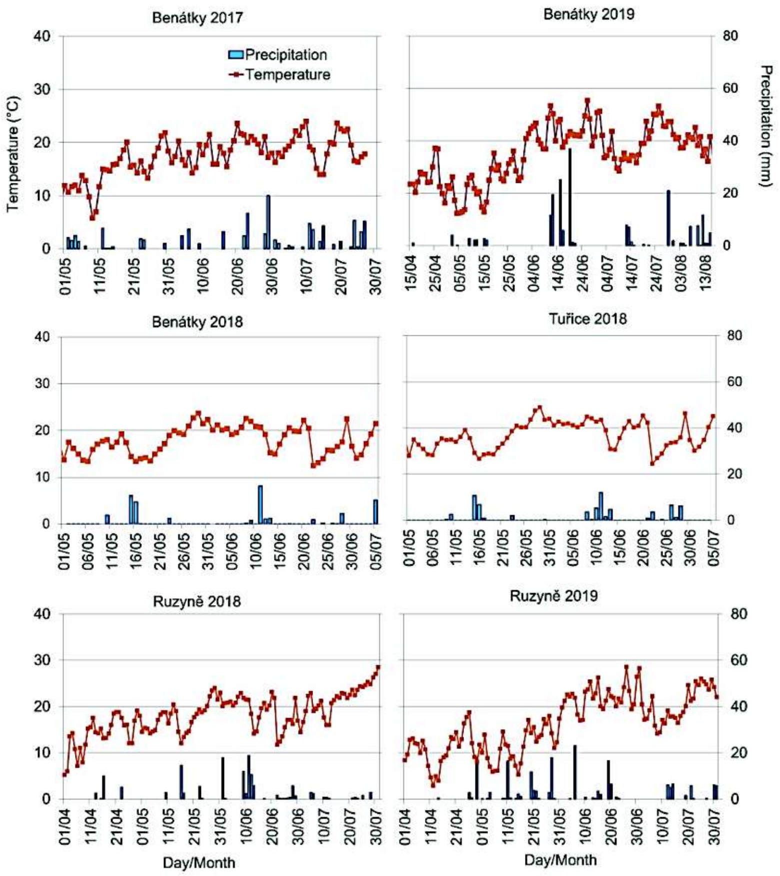

Figure 1. Temperature and precipitation in the experimental years and sites.

Treatments

Potato (*Solanum tuberosum* L.) was studied during years 2017–2019, celery (*Apium graveolens* L.) in 2018, and winter wheat (*Triticum aestivum* L.) during 2018–2019.

In 2017, the growth of roots of potato (cv. Impala), irrigated conventionally according to the estimated water need by sprinkling (wheel sprinkler irrigation), was compared with the control of a non-irrigated (rain-fed) potato crop at Benátky n. Jizerou. Irrigation increased the water supply in 2017 by 250 mm compared to the non-irrigated control. Due to technical problems, only the sums of irrigation water were recorded in potato (2017 and 2019), and not the individual water doses.

In 2018, on another part of the same field, the growth of potato roots (cv. Adéla) was monitored in two irrigation variants: the conventional empirical irrigation applied to this farm and the irrigation operated by calculation from the IRRIPROG program (Spitz et al., 2011) with the aim to save irrigation water use. Optimized irrigation in 2018 reduced the volume of water supplied to potato by 40 mm compared to the standard control (Table 1).

Table 1. Summary of experiments with observations of the effects of irrigation on crops root systems

Crop Year Irrigation system	Site Coordinates	Soil topsoil Subsoil	Treatments	Total amount of irrigation water (mm) [Precipitation (mm)] [4]
Potato 2017 Wheel[1]	Benátky n. Jizerou 50.2800797N 14.8443431E	sandy loam loamy sand	Without Irrigation Irrigated conventionally	nil 250 mm [151.4 mm]
Potato 2018 Wheel[1]	Benátky n. Jizerou 50.2829208N 14.8390903E	sandy loam loamy sand	Irrigated according IRRIPROG calculation Irrigated conventionally	195 mm 235 mm [80.0 mm]
Potato 2019 Drip[3]	Benátky n. Jizerou 50.2781683N 14.8378714E	loam loamy sand	Irrigation stopped at butonization phase Irrigated according IRRIPROG calculation	120 mm 270 mm [155.8 mm]
Celery 2018 Sprinkler[2]	Tuřice 50.2450472N 14.7544764E	loam sandy loam	Irrigated conventionally Irrigated according IRRIPROG calculation	150 mm 120 mm [68.9 mm]
Winter wheat 2018 Drip[3]	Ruzyně 50.0845428N 14.2994058E	silt loam clay loam	Stressed from heading Irrigated after heading	nil [31.7 mm] 230 mm [129.7 mm]
Winter wheat 2019 Drip[3]	Ruzyně 50.0845428N 14.2994058E	silt loam clay loam	Stressed from heading Irrigated after heading	nil [64.5 mm] 220 mm [141.4 mm]

[1]Wheel sprinkler irrigation, [2]Micro sprinkler irrigation, [3]Drip irrigation, [4]Precipitation was summed from start of April to harvest (celery), desiccation (potato) or to maturity (wheat).

In 2019, potato root distribution (cv. Antonia) was observed on the adjacent field with drip irrigation (driplines placed under a thin layer of soil). The drip irrigation was terminated at the start of butonization (BBCH 53–55, at visible bud inflorescence, 5th June) at two portions of the field, with the reduction in the amount of water compared to the irrigated crop being 155 mm of water.

For celery (cv. Asterix) in 2018 in Tuřice (micro sprinkler irrigation), the treatment with conventional irrigation was compared with the variant where the irrigation was adjusted by the IRRIPROG program's calculations.

The study of winter wheat was carried out in a field trial at Ruzyně in 2018 and 2019 as a part of experiments related to irrigation and the induction of water shortage during grain growth (e.g., Haberle & Svoboda, 2014; Raimanová et al., 2016). The growth of roots from drip irrigated and drought-stressed plants was studied; the lack of water was induced from heading (BBCH 58–60) with the help of a mobile cover (Table 1).

Commercial compost (ORGANIC, 2.8–3.2% N dry matter) was applied during autumn soil tillage for both potato and celery at the rate of 5–10 t per hectare. Nitrogen fertilizers in the form of ammonium nitrate were applied before potato planting. In total, from 135 kg to 175 kg N ha^{-1} was applied in organic and mineral fertilizers. For celery, 180 kg ha^{-1} of nitrogen in the form of ammonium nitrate and calcium nitrate was applied together with complex fertilizers with micronutrients in several doses during growth. For wheat, 150 kg of nitrogen per hectare in the form of nitrate ammonium with limestone was divided into a regenerative early spring dose of 35 kg ha^{-1}, and a production dose of 115 N ha^{-1} at the start of stem elongation (BBCH 31–33).

RESULTS AND DISCUSSION

Root study

Soil samples were taken using a hand sampler with a diameter of 36 mm, in 10 cm increments, with at least in six replicates, down to the root-free depth. The roots were separated with water on sieves, cleaned, and their total length determined according to Tennant (1975), after which the root density was calculated (in cm per cm^{-3} of soil). The density distribution of the roots in potato was determined before desiccation of the plants (BBCH 85-91); and for celery before the harvest, when the target size of the bulbs had been reached. The roots of wheat were sampled during the grain filling period (BBCH 78-83). For potato and celery, soil with roots were taken on the ridge, row of plants, and between the ridge and furrow. For wheat, the soil was sampled on and between plant rows.

Statistical data evaluation was performed by the analysis of variance (ANOVA) and by the Tukey’s HSD test (significance level $P < 0.05$). Statistica 13 (Stat-Soft Inc., Tulsa, USA) software was used.

The impact of irrigation upon yields

The weather during the experimental years were among the hottest of the last several decades in the Czech Republic. The precipitation was mostly low (Fig. 1), water shortage created conditions for a positive effect of irrigation on yields. In 2017, the irrigation of potato, compared to the non-irrigated control increased the yield by 10.8 t ha^{-1} (50.4 t ha^{-1} against 39.6 t ha^{-1}), while the impact on the roots was weak. Also, in 2019, drip irrigation greatly increased tuber yield (from 10.7 kg per ten plants in the non-irrigated treatment, to 18.3 kg per ten plants); in agreement with the strong impact of drought on canopy and reduction of the root density in the stressed plants. The positive effect of irrigation on potato yields has not only been reported in drier areas, but also in areas with higher rainfall, where potato is grown on lighter soils (e.g., Elzer et al., 2018). The irrigation increased yields in wheat by 50.7% and 49.8% in comparison with stressed crop (3.81 t and 3.66 t ha^{-1}) in the experimental years 2018 and 2019, respectively. On the contrary, the effects of a relatively small reduction in supplemental irrigation on potato in 2018 (34.3 t ha^{-1} and 34.7 t ha^{-1}), as well as on the celery yields (average weight of bulb with tops 0.85 kg and 0.91 kg) were not significant.

The effect of irrigation on total root length and root distribution

In spite of different experimental conditions, the root distributions of the experimental crops showed similar trends. However, the differences of the root density between variants were not significant, in some cases, due variability in root density.

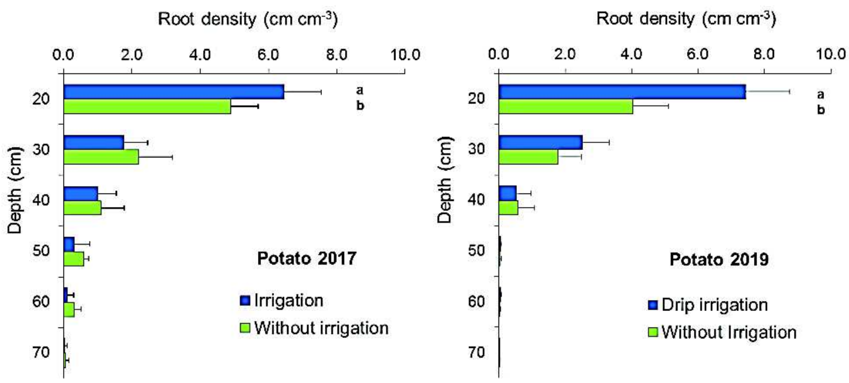

Figure 2. Root density of potato without irrigation and with irrigation (Benátky and Jizerou - 2017) or with drip irrigation (Benátky n. Jizerou - 2019). Here and further, the effect of irrigation is significant ($p < 0.05$) at layers with different letters.

Irrigation significantly increased the total root length to the maximum depth (TRL) of potato only in 2019 (10.53 km m^{-2} under irrigation, vs. 6.42 km m^{-2} for the non-irrigated crop) thanks to great root proliferation in the topsoil (Fig. 2). We have not found similar results in the literature, and these observations should be verified with further experiments. The strong effect was probably the result of frequent drip irrigation, with relatively small amounts of water (about 5 mm every day) in contrast to the strong stress due to low precipitation in the phase of the greatest need for assimilates for tuber growth in the not irrigated treatment. Potatoes, due to their origin, have a dense shallow root system aimed at the quick utilization of rainwater. Due to frequent small daily doses by drip irrigation, water was quickly evapotranspired at high temperatures. The moisture content was low in the top soil layers, except for periods with higher precipitation. (Fig. 3); however, the demand for water was satisfied. Soil moisture was only monitored in the irrigated treatment, but it can be deduced that the soil moisture was depleted to low levels in the treatment without irrigation, resulting in both low yield and reduced root growth in the top soil. The comparison of root distributions in years 2017 and 2019 shows significant year and site variability and it suggests difficulty in determining constant effective depths.

In 2017, the increase of TRL due to irrigation in potato was not significant (9.72 km m^{-2} and 9.20 km m^{-2}). Irrigation only significantly increased the root density of potato in the topsoil; and it slightly (but insignificantly) reduced the density in layers below a depth of 20 cm (Fig. 2). It was seemingly not fully consistent with the impact of the water shortage on potato roots in 2019, but in 2017 irrigation was not applied from the beginning of growth, and the potato plants probably adapted to the lower water content. The soil moisture data (Fig. 4) suggest lower water consumption of stressed plants in 2017. In 2019, irrigation was stopped at butonization when the canopy was fully developed, LAI was high, and the plants were accustomed to a regular supply of water from the drip irrigation. Shallow roots in 2019 (Fig. 2) could not compensate for the water input reduction.

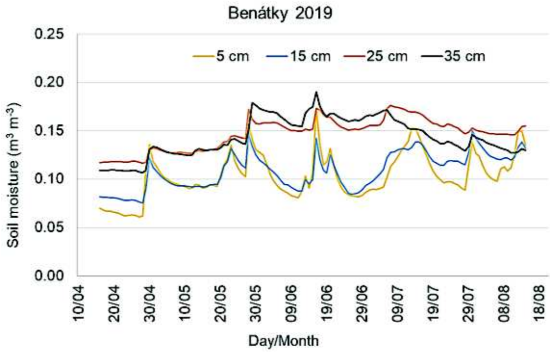

Figure 3. Soil moisture in irrigated potato (Benátky - 2019).

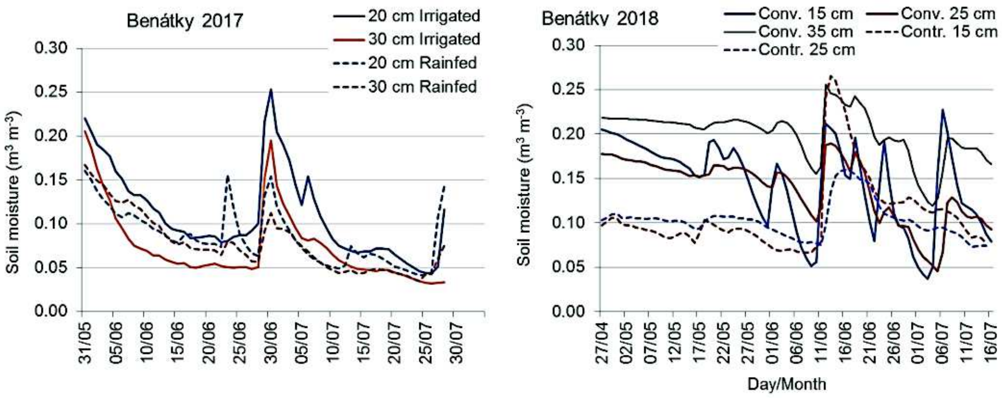

Figure 4. Soil moisture in potato (Benátky 2017 and 2018). Conventional (Conv.) and controlled (Contr.) irrigation in 2018.

In 2018, the increase of TRL due to the slightly higher conventional irrigation in potato was not significant (6.29 km m^{-2} and 6.18 km m^{-2}), in agreement with the similar amounts of water applied in both treatments (Table 1). Conventional irrigation of potato, compared to lower irrigation (according to calculations) significantly increased root density in the top layers, and insignificantly reduced root density under 20 cm (Fig. 5). The soil moisture (Fig. 4) suggests periods of both low and high water supply that complicates the interpretation of small differences in root growth.

The exact calculation of effective depths, where the density drops (for example under 1 cm cm^{-3}) would demand interpolation of the root density curve in ten-centimetre segments. A simple comparison of potato root densities at these depths shows that the effective root depth was different in the experimental years (Figs 2 and 5). This suggests that the application of constant maximum irrigation depth for a species may cause irrigation doses that are either too low or too high.

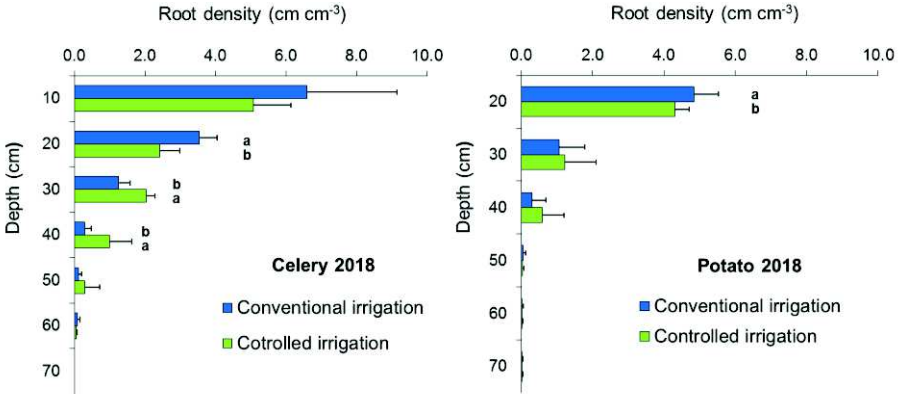

Figure 5. Root density of potato (Benátky nad Jizerou - 2018) and celery (Tuřice - 2018) with conventional empirical irrigation and with irrigation according to sensors and calculation with the IRRIPROG program.

Similar to potato in 2017 and 2018, TRL was (not significantly) greater at a greater water irrigation dose (with conventional irrigation) in celery (11.9 km m^{-2} compared to 10.9 km m^{-2}); however, the effect on root distribution and root length in both the top and subsoil layers was significant (Fig. 5). The soil moisture was slightly lower at the 15 cm depth, and slightly higher at the 25 cm in the conventional treatment in comparison with controlled irrigation; however, two different types of sensors were used (Fig. 6).

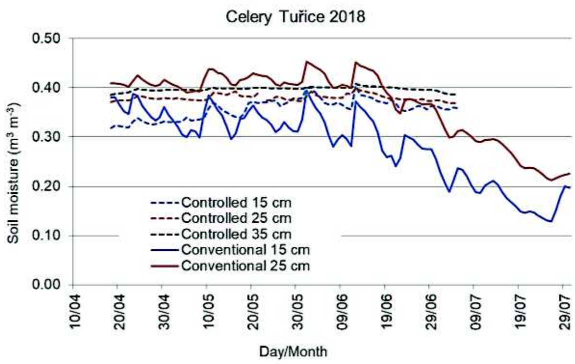

Figure 6. The soil moisture in celery (Tuřice - 2018). The data from controlled irrigation treatment (EC 10 sensors) are incomplete because the station with the sensors was stolen. Data from the conventional treatment were recorded with CS616 sensors.

The TRL of irrigated wheat was (marginally) significantly greater (22.51 km m^{-2}) than in stressed plants (20.70 km m^{-2}) thanks to significantly greater root length in the arable layer (Fig. 7) in 2018 (an extremely dry year), while in 2019, the effect of irrigation at the grain growth stage was practically nil (11.21 km m^{-2} and 11.16 km m^{-2}). Plants in the stressed treatment were strongly affected by a decrease of soil water content near the wilting point level (Fig. 8), as was also shown by the low yields in comparison with the irrigated treatment.

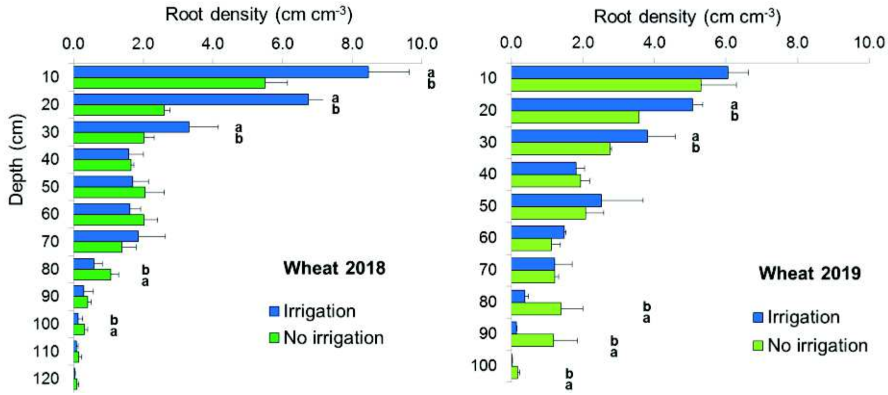

Figure 7. Root density of winter wheat with drip irrigation and stressed after heading (Ruzyně - 2018 and 2019).

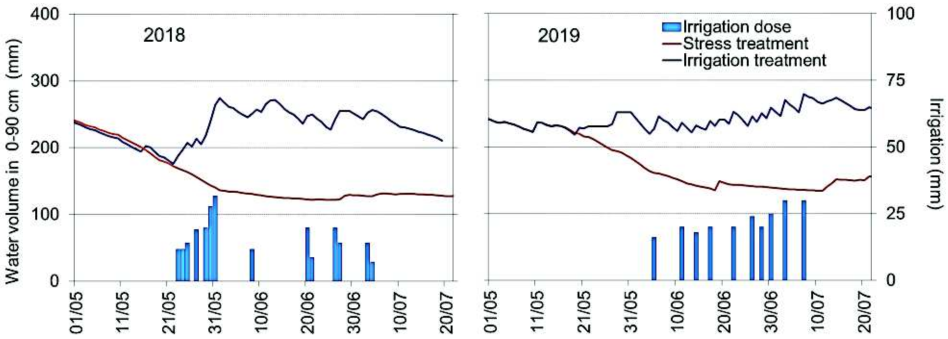

Figure 8. Soil water content in stressed and irrigation treatments in the 0–90 cm zone in wheat (Ruzyně - 2018 and 2019).

Despite different crops and locations, and great differences in the water supply, the results suggest a similar effect of irrigation on root distribution. An interpretation of the results is difficult. In the potato trials in 2017 and 2019, as well as in the wheat, the water deficit was much higher than in both potato and celery in 2018 (Table 1). There is very little literature data about the effects of irrigation on potato and celery root growth. Published results come mostly from different soil-climate conditions or pot experiments; thus, the described effects often differ. Ahmadi et al. (2017) observed greater total root length under a partial root drying irrigation regime when compared with full irrigation and deficit irrigation. On the other hand, Boguszewska-Mańkowska et al. (2019) found the root dry mass decreased in response to drought, but that the more drought-tolerant cultivars developed elongated roots. Zarzyńska et al. (2017) in a container experiment found that the greater the length and weight of potato cultivars' roots in the deeper layer (60–80 cm), the lesser was the decrease in yield due to (short term) drought. Further, in most experiments, root size was only determined during one term during growth. Generally, maximum root size in annual crops is attained after flowering and during seed development. We decided to sample the celery roots before harvest, upon attaining their target, retail, size of the bulbs; however, further root growth cannot be excluded.

The importance of root modification for effective irrigation

Generally, plants adapt to water and nutrient scarcity by investing more in underground organs, increasing root density, and/or growing roots at depth - making it possible to exploit the water reserve in the deeper subsoil layers. In our experiments, the effect of the variants on the observed maximum root depth was both small (in the scale of 10 cm layer) and inconsistent among crops and variants. A possible reason may be that in spring, during the period of maximum root growth to depth, crops grow under a more-or-less sufficient water supply accumulated from winter precipitation, while in the latter period (when water shortage occurred) assimilates are preferentially used for seed and storage organs.

The root density in the deepest layers (mostly formed by individual unbranched root axes) is far below the levels considered effective (1.0–2.0 cm cm^{-3}) (Haberle & Svoboda, 2014; Haberle & Svoboda, 2015); therefore, the importance for water uptake is probably low. However, not only in wheat, but also in shallow and medium rooted crops, such as potato, varieties with deeper roots that are expected to be more resistant to drought (Ahmadi et al., 2017; Zarzyńska et al., 2017). Deep rooted crops, such as winter wheat or sunflower, adapt to resources shortage by extracting water (and nitrate nitrogen and other ions) from deep subsoil reserves (Haberle et al., 2006; Kautz et al., 2013; Haberle & Svoboda, 2014). The plant's demand for water is shifted downwards; a low root density in the deep layers may to some extent be compensated by an enhanced uptake per root unit. However, with irrigation depleted water is replenished in the densely rooted topsoil; therefore, small changes of root depth and density in the deep subsoil layers will probably not affect the water uptake and balance. The correct determination of the maximum depth of irrigation is a key input value for any calculation for both the optimum rates and timing of irrigation water. The possible reduction of the root depth of potatoes and vegetables, with both shallow and medium deep root systems, is more important than a lesser root density in the deeper subsoil zones. Soil compaction, impermeable layers of clay / pebbles, even a high ground water level are known factors limiting root penetration and the depletion of water and nutrients (e.g., Johansen et al., 2014). According to the monitoring of fields in the lower Jizera region, the soils are often highly variable due to their origins (Bruthans et al., 2019). In our experiment, potato root distribution and maximum depths were influenced by soil conditions in an interaction with the irrigation method. In those cases where fine tuning of the irrigation doses and its timing are priority due to water quality concerns, farmers should check for the possible reduction of root growth and accordingly adjust the maximum irrigation depth. However, farmers lack a simple method for the calculation or estimation of the effective root depth.

The lateral distribution of roots is another factor complicating standardization of input value of effective root zone for maximum depth of irrigation. The root density of wide-row crops varies according to the distance from the plant and the row. This aspect should be taken into account under irrigation conditions. For example, Ahmadi et al. (2011) found twice the amount of potato roots below furrows when compared with the corresponding layers below ridges. We observed a lower density between rows with potato, celery, lettuce, and other vegetables, as well as sunflower, or maize (not published). This means that for wide-row crops it is not possible to determine any one generally valid (effective) root depth to be used in standards and irrigation models. The uptake and use of water from the entire soil volume will depend upon the density and physiological properties of the roots at varying distances from the plant, with the soil properties affecting the movement of water to the roots and the crop's water demand. With drip irrigation the use of one constant effective root zone seems even more dubious. Our data did not support the idea about the local proliferation of roots only in the vicinity of a dripping hose; however, this subject needs more experimental data.

CONCLUSIONS

Irrigation stimulated root growth in the topsoil, while reduced irrigation or non-irrigation slightly enhanced growth in the deeper layer. The observed modifications of root depth and distribution in subsoil seem too small to affect the effectiveness of irrigation water utilization. These results suggest that the use of a constant value for the calculation of maximum irrigation depth of a specific crop may not correspond to the variability of root depth and distribution. When irrigation doses and timing are the priority due to water supply shortage and water quality concerns, farmers should check for any possible reduction of root growth and adjust the maximum irrigation depth accordingly. This is especially important with shallow rooted vegetables and soil limitations. However, a definition of effective depth has not yet been standardized.

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