Received: 23 May 2020 | Revised: 27 September 2020 | Accepted: 3 October 2020

DOI: 10.1111/sum.12664

RESEARCH PAPER

Soil Use and Management | BRITISH SOCIETY OF SOIL SCIENCE | WILEY

Impact of water availability on root growth of sugar beet varieties

Tamara F. J. Fitters[1] | **Sacha J. Mooney**[2] | **Debbie L. Sparkes**[2]

[1]Plant and Crop Sciences, School of Biosciences, University of Nottingham, Sutton Bonington, UK

[2]Agricultural and Environmental Sciences, Biosciences, School of Biosciences, University of Nottingham, Sutton Bonington, UK

Correspondence
Debbie L. Sparkes, Biosciences, Agricultural and Environmental Sciences, University of Nottingham, Sutton Bonington Campus, South Lab. C330, College Road, LE12 5RD Sutton Bonington, Leicestershire, UK.
Email: debbie.sparkes@nottingham.ac.uk

Abstract

On average, sugar beet yield in the UK is reduced by 10% due to water limitation. The root system of a plant is responsible for water uptake and hence an extensive root system is crucial to mitigate drought stress. There might be varietal differences when it comes to plant root system architecture but so far none have been reported in sugar beet. This study shows the results of 2 years of field experiments, examining the rooting patterns and overall plant growth of sugar beet under both rainfed and irrigated conditions. In the first year, three varieties were assessed, and in the second year, five varieties. No significant yield differences were found between the rainfed and irrigated treatments, which is likely due to the applied drought stress only being mild in both years. There were, however, significant varietal differences in plant growth and rooting patterns in rainfed plants which were most distinct when plants were subjected to mild drought stress. Varietal differences observed might indicate the possibility of breeding for certain root traits to mitigate drought stress in sugar beet in the future.

KEYWORDS

drought, irrigation, ROOT growth, soil constraints, stomatal conductance, water uptake

1 | INTRODUCTION

Sugar beet (*Beta vulgaris*) yields across the UK are still rising despite stagnating yields in other crops (Supit et al., 2010). Previously Jaggard et al. (2007) showed an average 10% yield loss to drought in UK sugar beet which increased up to 25% loss in dry years. The main sugar beet growing area in the UK is in East Anglia, which is also an area where rainfall is relatively low compared with the rest of the UK (600 mm vs. 885 mm on average in the UK annually). UK sugar beet is generally sown in March and harvested anytime between September and the following March (Draycott, 2006). During this time, a storage root is produced in which sugar is stored in the form of sucrose, the beet normally has a sugar content of c. 17% (Draycott,). Growers aim to reach canopy closure as early as possible since radiation interception is directly related to yield (Jaggard et al., 2009). If drought occurs at any time it will result in negative effects on yield, but drought during June-July is most disadvantageous (Brown et al., 1987). To prevent yield losses due to drought, it is important to look at differences in root system architecture as a way of mitigating drought stress (Christopher et al., 2013; Comas et al., 2013).

Annual rainfall in the main sugar beet growing area of the UK is typically around 600 mm, and the soil type is predominantly a sandy loam with a maximum available water capacity of 130 mm in the top 100 cm (Scott & Jaggard, 2000). At the start of the growing season, it is assumed that the soil is at maximum water holding capacity, however, during the storage root bulking period (June–August) crop demand exceeds the combined supply from soil and rainfall (Scott & Jaggard, 2000). It has been shown for sugar beet in the UK that c. 300 mm water is needed between June and August. The average amount of rainfall in the sugar beet growing area between June and August is 116 mm so, even if the soil is at maximum available water capacity at the start of June (which is unusual), this would give a maximum water availability of 246 mm, which is less than the required amount (Jaggard et al., 2007).

Climate prediction models, such as Atmosphere-Ocean General Circulation Models (AOGCMs), indicate that if the current trend continues there will be an increase in temperature in Western-Europe, including the UK, of 1.5–3°C by 2050 (Coumou & Rahmstorf, 2012; Olesen et al., 2011; Richter & Semenov, 2005). Alongside increases in temperature, it is predicted that the mean precipitation per rainy day will increase resulting in periods of heavy rain alternated with periods of extreme heat and drought (Moriondo et al., 2011; Olesen et al., 2011) leading to more rain in winter and less rain during the crop growing period (Jenkins et al., 2009). These future climate scenarios would have a strong negative impact on crop yield as demand for water would increase while water availability would decrease. Crops are therefore likely to suffer from drought more often and it is important to consider possible adaptations to prevent reductions in yield.

The precise root system architectures of crops and their limitations in relation to water uptake are being increasingly explored. Root plasticity is found to play a great role in enhancing the water availability for plants (Ho et al., 2005; Padilla et al., 2013). When roots detect water, they can adjust their growth so there will be more root proliferation in regions with high water availability and lower root proliferation in soil regions with low water availability (Koevoets et al., 2016). However, this is not always possible and there are many limitations to root growth such as soil compaction/high soil bulk density and low nutrient availability (Carminati et al., 2013; Clark et al., 2003; Hodge, 2004).

Research from the 1980s showed that sugar beet can grow roots over one metre deep but there is little water uptake from this depth (Brown & Biscoe, 1985). More recent studies have shown sugar beet can indeed grow deep roots and, under unrestricted conditions, they can extract water from 1 m depth (Fitters et al., 2017). There are, however, delays between roots being produced at depth and water uptake from the deep layers. It has been shown that the xylem needs time to mature before efficient water uptake takes place (Fitters et al., 2017; Mapfumo et al., 1993).

Current thinking suggests that sugar beet varieties are genetically similar resulting in little or no differences in root traits between varieties (Ober et al., 2004). At the same time, it has been observed that other crops, such as maize and wheat, show great genetic variation in their root distribution under varying water availabilities (Ginkel et al., 1998; Hund et al., 2009). Some key limiting factors to water uptake such as soil impedance have previously been identified but there might be other factors that limit water uptake in sugar beet (Brown & Biscoe, 1985). To verify this, we aimed to answer the following questions: (a) how does the distribution of roots differ between sugar beet varieties when grown in the field? (b) does water availability affect the root distribution? Two years of field experiments were undertaken to gather data to address these questions.

2 | MATERIALS AND METHODS

2.1 | Experimental design

Two field experiments were conducted in 2016 and 2017 at the University of Nottingham Farm, Sutton Bonington Campus (52°50 N, 1°15 W). Both experiments were arranged as split-plot designs with four replicate blocks. Irrigation was implemented on the main plot and variety on the sub-plot. Each plot was 12 rows wide and 7.5 m long with six rows used for destructive measurements while the remainder were grown until harvest. Row spacing was 50 cm, leading to 10 plants m^{-2}. In 2016, the varieties were as follows: Aurora, Haydn and Hornet. These varieties were chosen after a wick and pouch study (Xie et al., 2017) showed that early root depth differed greatly between these three varieties. Sowing date was 7 April and the seed rate for each variety was 100,000 seeds ha^{-1}. In 2017, the same three varieties were grown and two more were added: BTS340 and Darnella which were selected based on their ranking on the UK recommended list. Sowing date was 10 April and the seed rate for each variety was 100,000 seeds ha^{-1}. Irrigation was applied, via trickle tape in between the rows, when wilting occurred: in 2016, irrigation was applied between 124 and 162 days after sowing (DAS), a total of 76 mm was applied. In 2017 irrigation was applied between 70 and 97 DAS, a total of 58 mm was applied. In 2016, the average temperature during the experiment was 14.3°C (Min: 3.4°C, Max: 23.8°C). In 2017, the average temperature was 14.3°C (Min: 4.1°C, Max: 23.6°C). Rainfall distribution differed between the years with mostly spring precipitation in 2016 and summer precipitation in 2017 (Figure 1a,b). In most months, the precipitation was higher than the average monthly precipitation between 1982 and 2010, especially in 2016 when three times the average amount of rainfall was received in June (Figure 2). The soil type for both years was Dunnington Heath Series (FAO class Stagno Gleyic Luvisol), classified as a stony sandy loam (LandIS, Cranfield University, 2018) overlying a clay subsoil at 50 cm. This soil has a water holding capacity of between 100.9 and 119.3 mm up to 1 m depth. The fields were fertilized with 120 kg ha^{-1} of N in both years in accordance with the UK's RB209 standard for sugar beet (Defra, 2010).

2.2 | Field and laboratory

In 2016, fortnightly stomatal conductance (mol m^{-2} s^{-1}) measurements were taken on the youngest fully expanded leaf, from when the fifth leaf had fully expanded. Three random plants per plot were sampled at each measurement date, these three values were then averaged. All measurements were taken between 9.00 and 13.00 hr with an AP4 Porometer (Delta-T Devices; Burwell). Three cores (ø 4.6 cm) were taken from each plot with a tractor-mounted corer to 1 m depth. The cores were taken within the row between sugar beet plants. Each core was then divided into sections: 0–15, 15–30, 30–60 and 60–100 cm depth. Roots from each section were extracted and stored at 4°C. Roots were scanned at 600 dpi on a flatbed scanner (EPSON expression, 11000XL Pro) and analysed with WinRHIZO software (Regent Instruments Inc.) to determine the total root length (cm), and the average root diameter (mm). The root length density (RLD) (cm cm^{-3}) was then calculated (Camposeo & Rubino, 2003). At 179 DAS, the experiment ended and again three cores were taken, and the roots were washed and measured as described above. Due to the soil drying out and the subsequent impact on soil hardness, cores could only be taken to 60 cm depth. Three 12 m rows (approximately 150 beet) were harvested by machine and the sugar beet were sent to the BBRO tare house at Wissington Sugar Beet factory to determine sugar yield.

In 2017, stomatal conductance (mol m^{-2} s^{-1}) was measured as described for 2016. The first destructive measurements were at canopy closure (91 DAS). Three cores were taken, and the roots were extracted and measured as in 2016. At 147 DAS, another three cores were taken, and the roots were measured. At 177 DAS the experiment ended, beet were harvested, and the fresh and dry weights were measured as described for 2016. Three rows were harvested by machine and sent to the BBRO tare house at Wissington Sugar Beet factory to determine sugar yield.

In 2016, one core (ø 4.6 cm, 1 m depth) in each destructive plot was taken at the time of canopy closure (106 DAS). The core was then divided into 10 cm sections at the following depths: 10–20, 35–45 and 55–65 cm. These sections were then scanned with a Phoenix X-ray CT scanner (GE Measurement & Control Solutions, Wunstorf, Germany). X-ray CT energy was set at 140 kV and 160 µA. The resolution was set to 40 µm and each section took 15 min to scan. After scanning the grey-level X-ray CT images (c. 2,000 per scan) were reconstructed using the datos|x software associated with the scanner and resized to 650 × 650 pixels to exclude non-soil areas and minimize the potential inclusion of artefacts. The images were processed with ImageJ 1.52a software (Schindelin et al., 2012). First, the images were converted to 8-bit after which the *Mean* filter was used and then the *Sharpen* was used to enhance the image quality

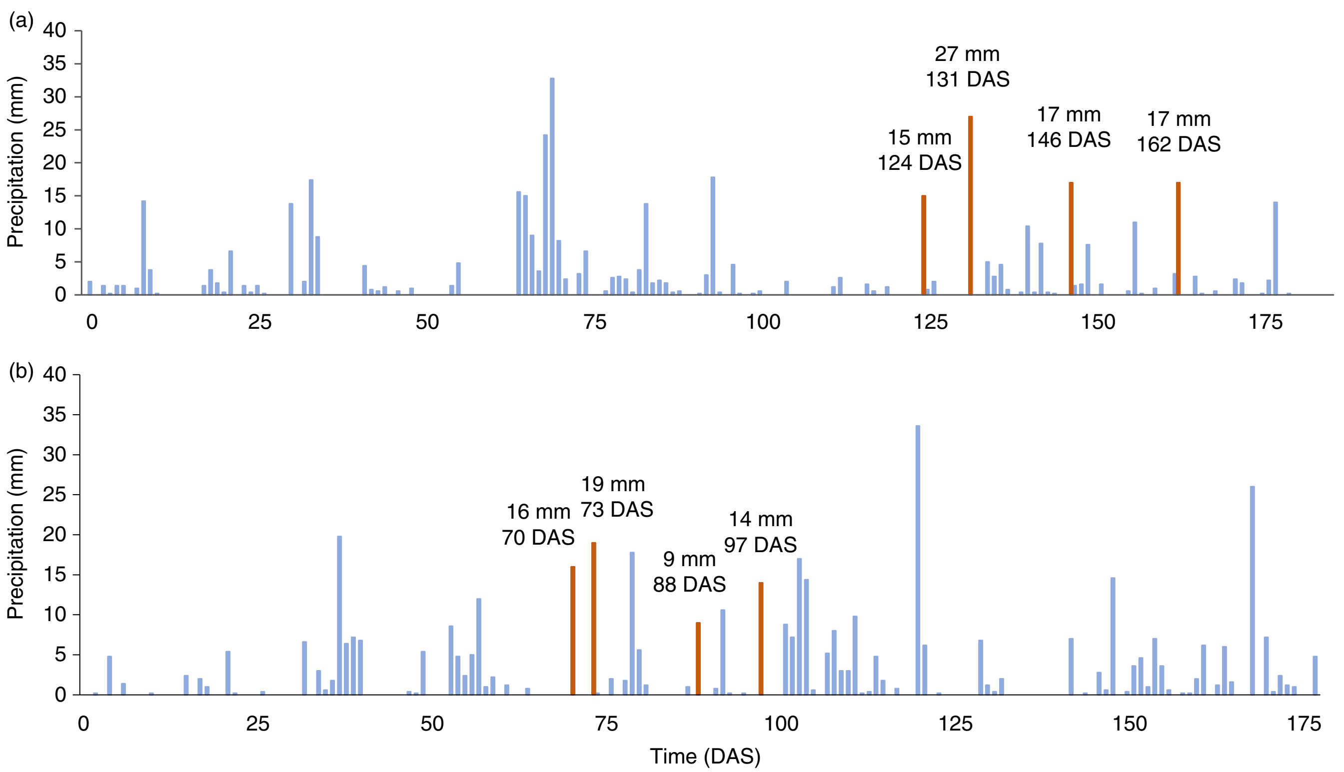

FIGURE 1 (a) Precipitation during the experiment in 2016, the orange bars represent the irrigation at 124, 131, 146 and 162 DAS. (b) Precipitation during the experiment in 2017, the orange bars represent the irrigation at 70, 73, 88 and 97 DAS. Each irrigation includes information on the exact amount of water given

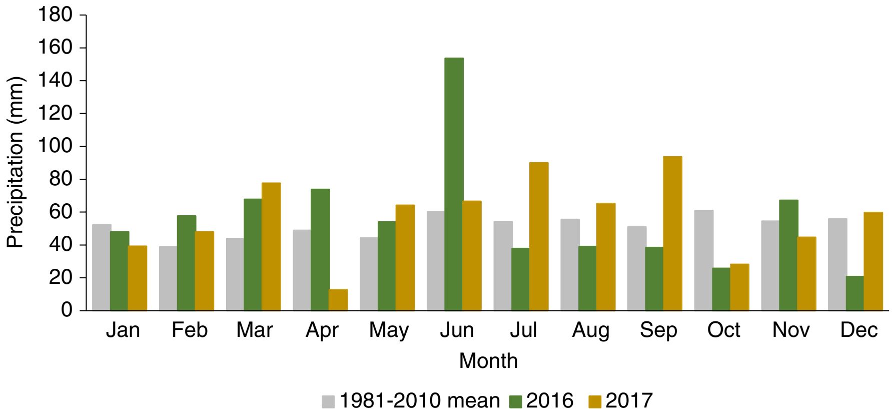

FIGURE 2 Average monthly precipitation (mm) between 1981–2010 and the monthly precipitation for both 2016 and 2017

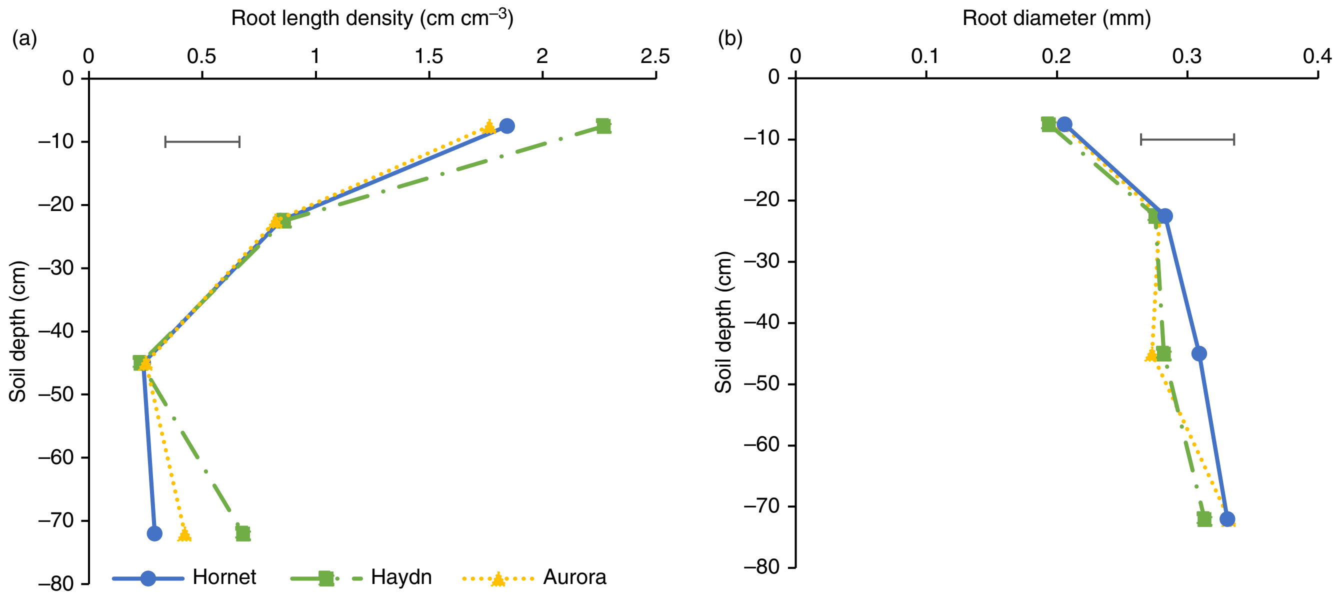

FIGURE 3 (a) Root length density (cm cm^{-3}) at 106 DAS at four different depths . (b) Average root diameter (mm) at 106 DAS at four different depths . Year 2016. The error bar shows the least significant difference (variety*depth)

and assist the segmentation process. After this, the threshold algorithm *IsoData* was used to convert all the images into the binary format (pores in black) for analysis. ImageJ was then used to calculate the number of pores, pore size (based on area and subsequent distribution) and overall porosity. To assess, the distribution of pores based on sizes they were ranked into intervals or size classes. To numerically assess the pore size distribution, we adapted the coefficient of uniformity (Kezdi, 1974). By expressing the ratio of the size of pores at 25% and 75% of the total pore distribution, we could readily observe clear differences between treatments as a larger ratio value relates to a greater number of larger pores.

2.3 | Statistics

Genstat 17th edition (VSN International, 2011) was used to analyse the data. Data were analysed by ANOVA for split-plot designs, with irrigation on the main plot and variety on the sub-plot. Repeated measurement analysis was used to analyse stomatal conductance data. When soil depth was included in the analysis, the design was treated as a split-split plot with irrigation on the main plot, variety on the sub-plot and depth on the sub-sub plot, repeated measurement analysis was used to account for different depths originating from the same core. Four replicates were used in both years and correlations between all variables were calculated and tested for each year separately.

3 | RESULTS

During the first year, at the time of canopy closure, 106 DAS, no irrigation had been applied, and therefore there were no differences in rooting traits between rainfed and irrigated plots. There were, however, varietal and soil depth differences (Figure 3). Haydn had a significantly higher RLD compared with Hornet and Aurora at 0–15 cm and a significantly higher RLD than Hornet at 60–84 cm (Figure 3a. $p < 0.001$, $df = 9$, l.s.d. = 0.327). Overall, there was a higher RLD at 0–15 cm compared with deeper soil layers. The average root diameter showed that the roots in the 0–15 cm section were significantly thinner compared with roots in deeper layers (Figure 3b).

In 2017, no differences were found between the rainfed and irrigated treatments at canopy closure. However, similar to 2016, there were differences between the varieties (Figure 5a). Overall, Aurora had the lowest root length density (RLD) and Haydn and BTS 340 had the highest RLD ($p = 0.002$, $df = 4$, l.s.d. = 0.186). There was a variety*depth interaction where Aurora had a very low RLD in the 30–60 cm section compared to Haydn and BTS 340. Hornet and BTS340 showed an increase in RLD at 15–30 cm compared to 0–15 cm, while Aurora, Darnella and Haydn had a decreased RLD ($p < 0.001$, $df = 10$, l.s.d. = 0.322). BTS 340 had its highest RLD at 30–60 cm and its lowest RLD at 0–15 cm while Aurora and Darnella showed the opposite pattern of having the highest RLD at 0–15 cm and the lowest RLD at 30–60 cm. Considering the average root diameter, there were no significant differences.

At the end of the experiment in 2016, the RLD and average root diameter (Figure 4) had a significant variety*irrigation interaction ($p = 0.011$, $df = 2$, l.s.d. = 0.318). Under irrigated conditions both Haydn and Aurora had a lower RLD than under rainfed conditions. Hornet did not show differences in RLD between irrigated and rainfed conditions. With increasing depth, there was a significant decrease in RLD of all varieties (Figure 4a). Hornet showed the strongest decrease in RLD with depth, the RLD was half that of Aurora in the 30–60 cm section ($p < 0.001$, $df = 6$, l.s.d. = 0.389).

At 170 DAS, the soil had dried out significantly and therefore coring was only possible to 60 cm. The differences previously observed in the average root diameter had disappeared at 170 DAS (Figure 4b).

In 2017, differences became less pronounced over time and the rooting pattern changed. There was an overall increase in RLD at the 0–15 and 30–60 cm at 147 DAS (Figure 5b). There was a significant variety*depth interaction where RLD of BTS340 increased dramatically between 0–15 and 30–60 cm while RLD of the other four varieties was similar at both depths ($p = 0.039$, $df = 10$, l.s.d. = 0.669).

In 2016 the first irrigation was applied at 125 DAS, there was a subsequent significant increase in stomatal conductance at 131 DAS ($p = 0.039$, $df = 1$, l.s.d. = 0.061) as seen in Figure 6a. Throughout the experiment, there were significant varietal differences (Figure 6b) with Hornet having a consistently lower stomatal conductance compared to Haydn and Aurora, which showed similar values ($p = 0.024$, $df = 2$, l.s.d. = 0.075). In 2017, irrigation was first given before canopy closure, at 70 DAS. From this point onward, there were differences in stomatal conductance with the irrigated plots having a higher stomatal conductance than the rainfed plots. No varietal differences were found. After applying a total 328 mm between 70–97 DAS a prolonged period of rainfall started at 101 DAS. By 116 DAS 84 mm of rainfall had fallen and these differences were reduced again (Figure 7). Overall, the irrigated plants had a significantly higher stomatal conductance ($p = 0.045$, $df = 1$, l.s.d. = 0.104).

Root and canopy fresh and dry weights, in 2016, were measured at canopy closure (97 DAS) and at harvest (170 DAS). At 97 DAS, irrigation had not yet been applied and there were no significant differences between the varieties in

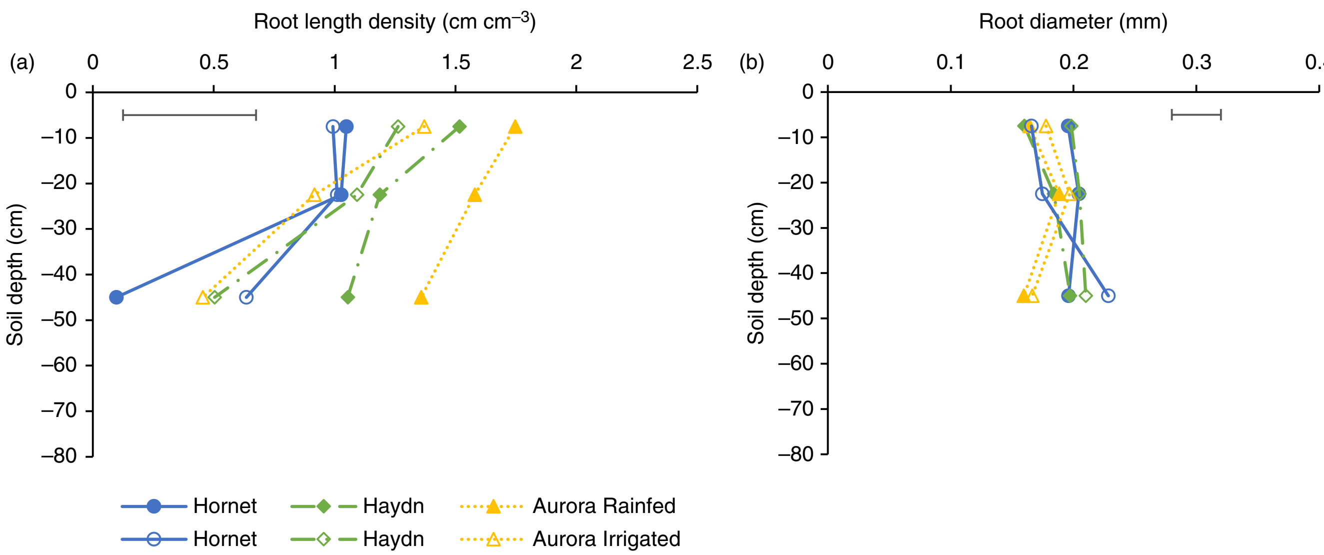

FIGURE 4 (a) Root length density (cm cm^{-3}) at 170 DAS at four different depths. (b) Average root diameter (mm) at 170 DAS at four different depths. Year 2016. The error bar shows the least significant difference (treatment*variety*depth)

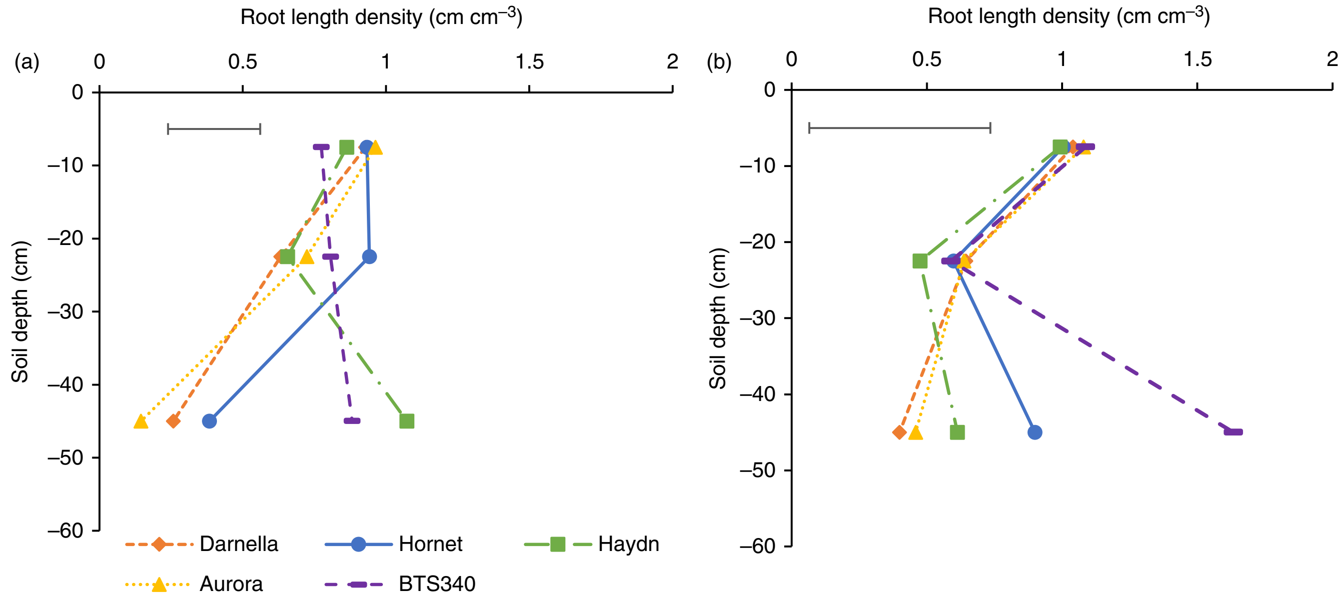

FIGURE 5 (a) Root length density (cm cm^{-3}) at 91 DAS at four different depths at consecutive points. (b) Root length density (cm cm^{-3}) at 147 DAS at four different depths at consecutive points. Year 2017. The error bar shows the least significant difference (variety*depth)

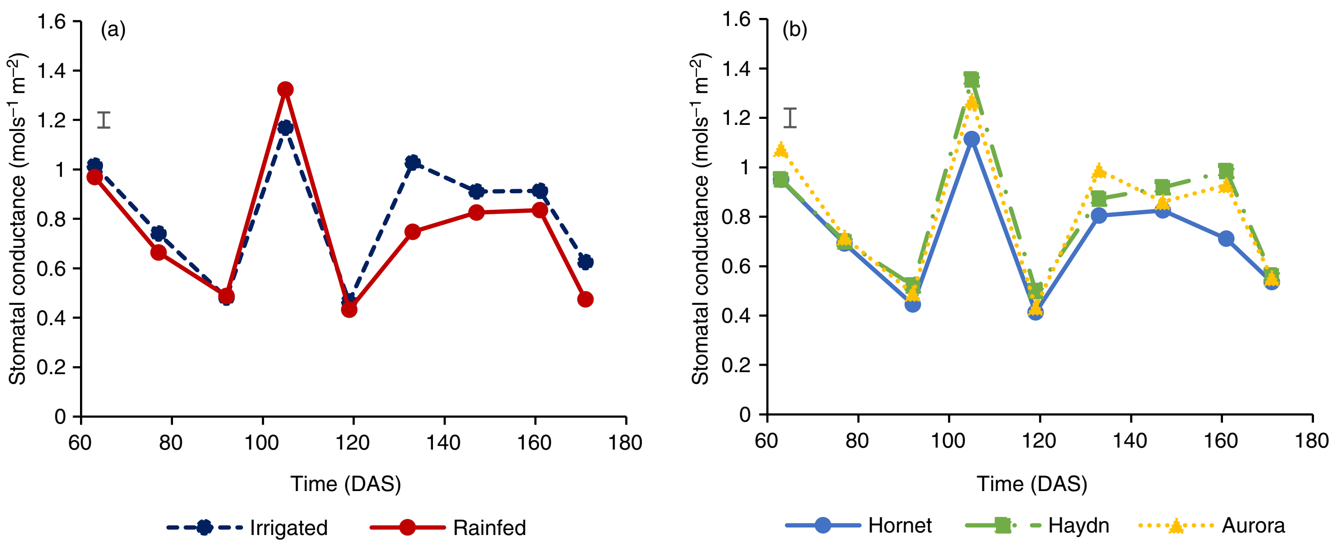

FIGURE 6 Stomatal conductance (mol s^{-1} m^{-2}) over time between (a) different treatments, (b) different varieties. Year 2016. The error bar shows the least significant difference (a) treatment*time, (b) variety*time

either root or canopy fresh and dry weight. At 170 DAS, irrigation had been applied and this resulted in a significantly higher water content in the root of irrigated beet ($p = 0.012$, $df = 1$, l.s.d. = 0.563). However, there were no significant differences in the root dry weights, despite the plant density being uniform across all plots (Table 1). In 2017, leaf fresh and dry weight at 155 DAS showed both significant differences between irrigation treatments as well as varieties. Leaf dry weight was significantly higher in plants that had received irrigation ($p < 0.001$, $df = 1$, l.s.d. = 32.49).

In 2016, the change in water content between irrigated and rainfed sugar beet resulted in a difference in the percentage sugar in the beet. The irrigated beet had a significantly lower percentage of sugar ($p < 0.001$, $df = 1$, l.s.d. = 0.324), indicating the sugar in the irrigated beet had been diluted by the extra-water taken up (Table 1). This was confirmed when there were no significant differences found between the treatments when looking at actual sugar yield. Sugar yield did show significant varietal differences with Hornet having a higher sugar yield compared to Aurora ($p = 0.044$, $df = 2$, l.s.d. = 0.954) (Table 1).

Varietal differences were mostly in leaf and root water content. Aurora had a significantly higher leaf water content compared with Darnella ($p = 0.025$, $df = 4$, l.s.d. = 277.9).

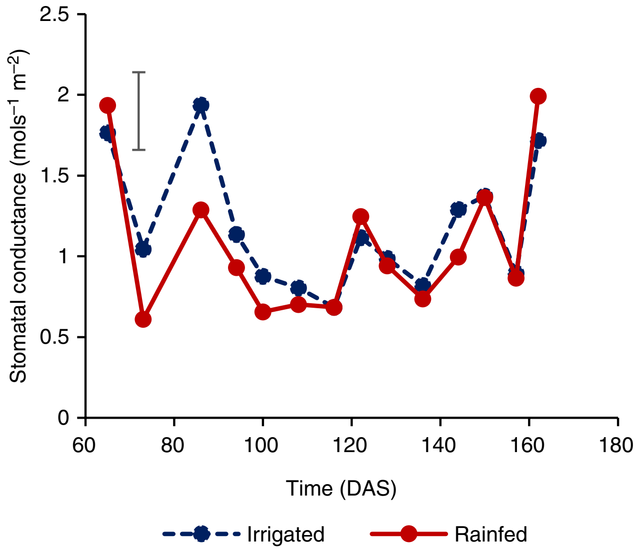

FIGURE 7 Stomatal conductance (mol s^{-1} m^{-2}) over time for irrigated and rainfed beet (averaged across varieties). Year 2017. The error bar shows the least significant difference treatment*time

Darnella had a significantly higher root water content compared with Haydn (p = 0.045, df = 4, l.s.d. = 534.4) (Table 2). Aurora only had a slightly higher water content than Haydn indicating that the trend seen in leaf water content was almost reversed in the root water content. There were no irrigation effects found in sugar content (%) or actual sugar yield (tonnes ha^{-1}). However, varietal differences were found; Hornet had a significantly higher sugar content (%) than Darnella, BTS340 and Aurora (p = 0.007, df = 4, l.s.d. = 0.371) (Table 2). Darnella and BTS340 had a significantly higher sugar yield compared with Hornet, Haydn and Aurora ($p < 0.001$, df = 4, l.s.d. = 0.784; Table 2).

The X-ray CT analysis, in 2016, showed there was a significant decline in the number of pores with increasing depth (p = 0.002, df = 2, l.s.d. = 30.29; Figure 8a). In Figure 8b,c, there is a clear visual difference in samples taken from the top of the soil, 10–20 cm and samples taken deeper (55–65 cm). The pore size distribution did not show any significant differences but there was, however, a trend in the 25:75 ratio when comparing Hornet at 10–20 cm depth (76.5) to Aurora 35–45 cm depth (45.1) and Haydn 55–65 cm depth (29.9) (p = 0.081, df = 6, l.s.d. = 30.8) (Table 3). There was a lot of variation in porosity but deeper layers had a lower porosity; 10–20 cm was 11.4%, 35–45 cm was 6.4% and 55–65 cm was 7.9%.

4 | DISCUSSION

Differences in root traits of plants have often been observed among genotypes of the same species (Hund et al., 2009; Romano et al., 2012). Alongside the genotypic variation, root plasticity can also result in different rooting patterns in response to environmental factors (Ho et al., 2005; Ober et al., 2004; Padilla et al., 2013). Together, genetic and environmental factors determine the root system architecture (Dorlodot et al., 2007). Since current UK sugar beet varieties have all originated from one monogerm plant in around 1948, there is limited genetic variation among the varieties (Bosemark, 2006). We observed differences in rooting patterns between the varieties indicating that even small genetic variations could lead to substantial differences in root morphology. Especially, in 2016, there was a clear difference in rooting patterns between the varieties at 170 DAS, indicating that mild drought stress exaggerated these differences. Under non-drought conditions, differences were less pronounced indicating plant responses become more noticeable when stress levels increase (Chaves et al., 2008).

Previous studies have shown differences in the rooting patterns at depth with deeper soil layers containing fewer roots or roots of thicker diameter (Brown et al., 1987;

TABLE 1 Root dry weight (kg), root water content (%), sugar content (%) and sugar yield (tonnes ha^{-1}) at 170 DAS. Year 2016

	Variety	Root dry weight (kg)	Root water content (%)	Sugar content (%)	Sugar yield (tonnes ha^{-1})
Rainfed	Hornet	0.82	20.8	17.9	14.7
	Haydn	0.84	20.4	17.8	13.6
	Aurora	0.85	20.0	17.3	13.4
Irrigated	Hornet	0.84	20.9	17.2	15.1
	Haydn	0.82	21.7	16.8	14.2
	Aurora	0.75	20.9	16.8	14.0
Grand mean		0.82	20.8	17.3	14.2
l.s.d.		0.126	0.975	0.561	1.349
Variety		p = 0.710	p = 0.185	p = 0.065	p = 0.044
Treatment		p = 0.368	p = 0.012	$p < 0.001$	p = 0.174
Variety*treatment		p = 0.399	p = 0.208	p = 0.371	p = 0.979

Note: The mean, overall l.s.d. and p-values given.

TABLE 2 Root dry weight (kg), root water content (%), sugar content (%) and sugar yield (tonnes ha^{-1}) at 155 DAS. Year 2017

Treatment	Variety	Root dry weight (kg)	Root water content (%)	Sugar content (%)	Sugar yield (tonnes ha^{-1})
Rainfed	Hornet	0.87	75.9	17.2	16.9
	Haydn	0.92	74.8	17.0	17.6
	Aurora	0.90	77.6	16.7	17.4
	Darnella	0.93	78.2	16.6	19.8
	BTS340	0.98	77.3	16.6	18.7
Irrigated	Hornet	0.99	76.7	17.2	17.5
	Haydn	0.90	75.9	16.8	16.4
	Aurora	0.83	77.1	16.7	17.2
	Darnella	1.03	78.1	16.5	19.6
	BTS340	1.10	76.1	16.6	19.4
Grand mean		0.94	76.8	16.8	16.0
l.s.d.		0.204	1.700	0.524	1.109
Variety		$p = 0.144$	$p < 0.001$	$p = 0.007$	$p < 0.001$
Treatment		$p = 0.304$	$p = 0.939$	$p = 0.690$	$p = 0.898$
Variety*treatment		$p = 0.579$	$p = 0.280$	$p = 0.998$	$p = 0.171$

Note: The mean, overall l.s.d. and *p*-values given.

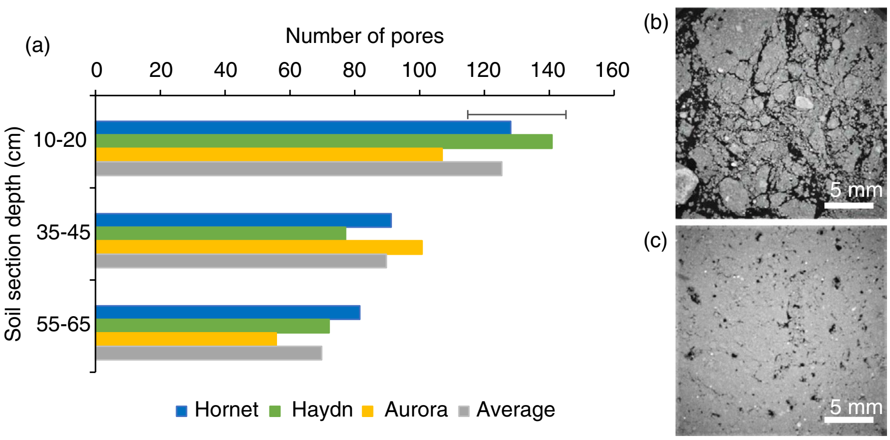

FIGURE 8 (a) Number of pores in different soil sections for the three different varieties and the average number of pores at each depth. The error bar shows the least significant difference (Depth). (b) An X-ray CT image from the 10–20 cm section growing Haydn, pores are shown in black. (c) An X-ray CT image from the 55–65 cm section growing Aurora pores are shown in black

Colombi & Walter, 2016; Fitters et al., 2017; Lipiec et al., 2012). The reduced soil porosity and pore size at depth could explain the differences in rooting patterns at depth. In both years, there were reductions in root length density in most varieties with increasing depth. During the first coring in 2016, the RLD was almost four times as high in the upper 15 cm compared with the 60–84 cm section. This difference was reduced by the time of harvest when the top 15 cm had only twice the RLD found at the 30–60 cm section, which was, at that time, the deepest layer that cores could be extracted from. Kashiwagi et al. (2006) found that, in chickpea, the RLD in deeper soil layers correlated better with yield than the RLD from shallow layers. This suggests that, even though the RLD was substantially higher in the top soil section, this might not have any influence on the final yield. However, in this study, no correlation between RLD at any depth and sugar yield was found. This was most likely due to the limited drought stress in both years. The amount of precipitation in almost all months of both the 2016 and 2017 growing season was higher than the long-term average between 1981 and 2010 (MetOffice, 2018). There were few differences in root diameter but the average root diameter became slightly greater with depth at both coring times, most likely as a result of increased penetration resistance with depth (Lipiec et al., 2012).

In 2017, differences in RLD at different depths were less clear, Darnella, Hornet and Aurora showed a clear decrease in RLD with depth at 91 DAS, but Haydn and BTS340 showed a mild increase in RLD with depth. At 147 DAS, Darnella and Aurora still showed the same pattern, yet Hornet, Haydn and BTS340 now showed a pattern with the lowest RLD at 15–30 cm and a higher RLD at both the 0–15 and 30–60 cm sections. Dardanelli et al. (1997) stated that the root system

TABLE 3 Pore size distribution 25:75 ratio from the X-ray CT scans taken in 2016

Depth	Variety	25:75 ratio	Total porosity (%)
10–20 cm	Hornet	61.36	11.4
	Haydn	38.91	
	Aurora	33.09	
35–45 cm	Hornet	33.51	6.4
	Haydn	46.40	
	Aurora	20.88	
55–65 cm	Hornet	30.13	7.9
	Haydn	12.08	
	Aurora	41.50	
Grand mean		35.32	8.6
l.s.d.		30.8	8.0
Variety*treatment		$p = 0.081$	$p = 0.232$

Note: The mean, overall l.s.d. and *p*-value is given.

architecture is highly variable under slightly different environmental conditions. This indicates the differences found in rooting patterns of varieties used in both 2016 and 2017 can be very different, even though the environmental factors were only slightly different. The average root diameter was very similar at the different depths. This was likely the result of minimal soil physical constraints (Clark et al., 2003). In 2016, the field contained a clay layer at 50 cm depth, whereas in 2017 clay was found deeper around 70–80 cm depth.

The distribution of sugar beet roots differed among varieties and between years, which has not been previously reported. Haydn had a consistent average RLD in both years but Hornet had a low RLD in 2016 and a high RLD in 2017 while Aurora showed the opposite pattern. In both years, the plants were only subjected to mild stress and this might have contributed to non-consistent varietal differences. There is the possibility that one of the varieties is more sensitive to strong compaction (present at 50 cm in 2016), or more sensitive to drought at a later stage during growth. This would explain the difference in performance between the two varieties in the subsequent years. Irrigation only affected root growth when mild drought occurred later in the 2016 season; there was no water stress in 2017.

Increased water availability did not lead to large differences in root traits most likely because water availability was rarely limiting in either year. From February to June 2016, the amount of rainfall was higher than the long-term average, and in June three times the average rainfall was received (MetOffice, 2018). Hence, no irrigation was given until September. In 2017, the amount of rainfall was higher than average from February until September, with the exception of April. Since April had seen four times less rainfall compared to the average of 1981–2010 some irrigation was given in May, where several days of no rainfall were alternated with days with heavier rainfall (MetOffice, 2018). In 2016 at 170 DAS, irrigation resulted in a lower RLD in Aurora and Haydn compared with rainfed plots. It is more common to see a higher RLD as a result of drought since roots are thought to explore the soil more under water limiting conditions (Asch et al., 2005; Comas et al., 2013). However, Camposeo and Rubino (2003) found that higher water availability resulted in higher RLD, mostly at shallow soil depths but lower RLD at deeper depths. Since 2017 had been a relatively wet year there were no RLD differences as a result of additional irrigation.

Despite there being no root responses to the additional irrigation, there were differences in stomatal conductance. As soon as irrigation was given, an increase in stomatal conductance was observed in both years. This corresponds to previous studies that have shown stomatal conductance decreases when water availability is reduced (Miyashita et al., 2005; Steduto et al., 2007). The stomatal conductance never reached values of 0.1 mol m^{-2} s^{-1} or lower, which indicates there was no severe water stress at any stage (Flexas & Medrano, 2002). Even though the yield in the rainfed plants was lower than in the irrigated plants, the difference was not significant. Varietal differences in final yield were observed but no relation to the RLD was found, probably because water was not a limiting factor in yield determination during these two seasons.

When looking at the root length density and the sugar yield there did not seem to be any correlation. It is, however, possible that no differences were found because of a trade-off effect. Kembel and Cahill (2005) found that when there is more investment in acquisitive roots there are less resources for investment in other parts of the plant. It is common that root proliferation to improve water or nutrient uptake does not necessarily mean that there is a benefit for the whole plant (Walk et al., 2006). When the costs of the improvement are higher than the gain no differences will be found (Ho et al., 2005). In this study, it is possible that the cost of root proliferation to increase water uptake did not benefit the sugar beet storage root and its sugar content. Alternatively, it is possible that there was no trade-off at all by proliferating the lateral roots.

5 | CONCLUSIONS

Overall, it was found that sugar beet yield was not affected by the mild drought stress that occurred. Any differences in yield were attributed to varietal differences that did not correlate with any of the measured rooting traits or stomatal conductance. This was most likely the result of 2 years where water was plentiful and hence other factors limited yield more than water. Given the differences observed in varietal rooting traits, it is possible that some varieties might develop a root system better at mitigating drought under drier conditions and this can be an opportunity to breed a variety with a rooting system that can mitigate drought stress. Further work should explore varietal rooting traits under a range of watering regimes and whether there are any trade-offs between investment in acquisitive roots and sugar yield.

ACKNOWLEDGEMENTS

We acknowledge John Alcock, Matt Tovey, Will Spracklen, Jennifer Bussell, Alistair Wright and Jake Richards for their practical assistance. We acknowledge the technical expertise of Dr Brian Atkinson at the Hounsfield Facility at the University of Nottingham. We also thank the British Beet Research Organisation's trials team for their help with the harvest of our samples. The study was funded by a joint University of Nottingham and British Beet Research Organisation (BBRO) studentship.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Tamara F. J. Fitters https://orcid.org/0000-0002-7695-8552
Debbie L. Sparkes https://orcid.org/0000-0001-5946-2849

REFERENCES

Asch, F., Dingkuhn, M., Sow, A., & Audebert, A. (2005). Drought-induced changes in rooting patterns and assimilate partitioning between root and shoot in upland rice. *Field Crops Research*, *93*, 223–236. https://doi.org/10.1016/j.fcr.2004.10.002

Bosemark, N. O. (2006). Genetics and breeding. In A. P. Draycott (Ed.), *Sugar beet* (1st ed., pp. 50–88). Blackwell Publishing Ltd.

Brown, K., & Biscoe, P. (1985). Fibrous root growth and water use of sugar beet. *Journal of Agricultural Science*, *105*, 679–691. https://doi.org/10.1017/S0021859600059591

Brown, K. F., Messem, A. B., Dunham, R. J., & Biscoe, P. V. (1987). Effect of drought on growth and water use of sugar beet. *Journal of Agricultural Science*, *109*, 421–435. https://doi.org/10.1017/S0021859600081636

Camposeo, S., & Rubino, P. (2003). Effect of irrigation frequency on root water uptake in sugar beet. *Plant and Soil*, *253*, 301–309. https://doi.org/10.1023/A:1024801312711

Carminati, A., Vetterlein, D., Koebernick, N., Blaser, S., Weller, U., & Vogel, H.-J. (2013). Do roots mind the gap? *Plant and Soil*, *367*, 651–661. https://doi.org/10.1007/s11104-012-1496-9

Chaves, M. M., Flexas, J., & Pinheiro, C. (2008). Photosynthesis under drought and salt stress: Regulation mechanisms from whole plant to cell. *Annals of Botany*, *103*, 551–560. https://doi.org/10.1093/aob/mcn125

Christopher, J., Christopher, M., Jennings, R., Jones, S., Fletcher, S., Borrell, A., Manschadi, A. M., Jordan, D., Mace, E., & Hammer, G. (2013). QTL for root angle and number in a population developed from bread wheats (*Triticum aestivum*) with contrasting adaptation to water-limited environments. *Theoretical and Applied Genetics*, *126*(6), 1563–1574. https://doi.org/10.1007/s00122-013-2074-0

Clark, L. J., Whalley, W. R., & Barraclough, P. B. (2003). How do roots penetrate strong soil? *Plant and Soil*, *255*, 93–104. https://doi.org/10.1023/A:1026140122848

Colombi, T., & Walter, A. (2016). Root responses of triticale and soybean to soil compaction in the field are reproducible under controlled conditions. *Functional Plant Biology*, *43*, 114–128. https://doi.org/10.1071/FP15194

Comas, L. H., Becker, S. R., Cruz, V. M. V., Byrne, P. F., Dierig, D. A. (2013). Root traits contributing to plant productivity under drought. *Frontiers in Plant Science*, *4*, 442. https://doi.org/10.3389/fpls.2013.00442

Coumou, D., & Rahmstorf, S. (2012). A decade of weather extremes. *Nature Climate Change*, *2*, 491–496. https://doi.org/10.1038/NCLIMATE1452

Cranfield University (2018). *The Soils Guide*. www.landis.org.uk

Dardanelli, J. L., Bachmeier, O. A., Sereno, R., & Gil, R. (1997). Rooting depth and soil water extraction patterns of different crops in a silty loam haplustoll. *Field Crops Research*, *54*, 29–38. https://doi.org/10.1016/S0378-4290(97)00017-8

Defra (2010). *Fertiliser manual (RB209)* (8th ed.). TSO (The Stationary Office).

Dorlodot, S., Forster, B., Pagès, L., Price, A., Tuberosa, R., & Draye, X. (2007). Root system architecture- opportunities and constraints for genetic improvement of crops. *Trends in Plant Science*, *12*, 474–481. https://doi.org/10.1016/j.tplants.2007.08.012

Draycott, A. P. (2006). Introduction. In A. P Draycott (ed.), *Sugar beet* (1st ed., pp. 1–8). Blackwell Publishing.

Fitters, T. F. J., Bussell, J. S., Mooney, S. J., & Sparkes, D. L. (2017). Assessing water uptake in sugar beet (*Beta vulgaris*) under different watering regimes. *Environmental and Experimental Botany*, *144*, 61–67. https://doi.org/10.1016/j.envexpbot.2017.10.001

Flexas, J., & Medrano, H. (2002). Drought-inhibition of photosynthesis in C3 plants: Stomatal and non-stomatal limitations revisited. *Annals of Botany*, *89*, 183–189. https://doi.org/10.1093/aob/mcf027

Ho, M. D., Rosas, J. C., Brown, K. M., & Lynch, J. P. (2005). Root architectural tradeoffs for water and phosphorus acquisition. *Functional Plant Biology*, *32*, 737–748. https://doi.org/10.1071/FP05043

Hodge, A. (2004). The plastic plant: Root responses to heterogeneous supplies of nutrients. *New Phytologist*, *162*, 9–24. https://doi.org/10.1111/j.1469-8137.2004.01015.x

Hund, A., Ruta, N., & Liedgens, M. (2009). Rooting depth and water use efficiency of tropical maize inbred lines, differing in drought tolerance. *Plant and Soil*, *318*, 311–325. https://doi.org/10.1007/s11104-008-9843-6

Jaggard, K. W., Qi, A., & Semenov, M. A. (2007). The impact of climate change on sugarbeet yield in the UK: 1976–2004. *Journal of Agricultural Science*, *145*, 367–375. https://doi.org/10.1017/S0021859607006922

Jaggard, K. W., Qi, A., & Ober, E. S. (2009). Capture and use of solar radiation, water, and nitrogen by sugar beet (*Beta vulgaris* L.). *Journal*

of Experimental Botany, 60, 1919–1925. https://doi.org/10.1093/jxb/erp110
Jenkins, G. J., Murphy, J. M., Sexton, D. M. H., Lowe, J. A., Jones, P., & Kilsby, C. G. (2009). *UK Climate Projections: Briefing report*. Met Off. Hadley Cent.:59. doi:ISBN 978-1-906360-04-7.
Kashiwagi, J., Krishnamurthy, L., Crouch, J. H., & Serraj, R. (2006). Variability of root length density and its contributions to seed yield in chickpea (*Cicer arietinum* L.) under terminal drought stress. *Field Crops Research*, *95*, 171–181. https://doi.org/10.1016/j.fcr.2005.02.012
Kembel, S. W., & Cahill, J. F. Jr (2005). Plant phenotypic plasticity belowground: A phylogenetic perspective on root foraging trade-offs. *The American Naturalist*, *166*(2), 216–230. https://doi.org/10.1086/431287
Kezdi, A. (1974). *Handbook of soil mechanics. Vol. 1: Soil physics* (p. 34). Elsevier Scientific Publishing.
Koevoets, I., Venema, J. H., Elzenga, J. T., & Testerink, C. (2016). Roots withstanding their environment: Exploiting root system architecture responses to abiotic stress to improve crop tolerance. *Frontiers in Plant Science*, *7*, 1335. https://doi.org/10.3389/fpls.2016.01335
Lipiec, J., Horn, R., Pietrusiewicz, J., & Siczek, A. (2012). Effects of soil compaction on root elongation and anatomy of different cereal plant species. *Soil and Tillage Research*, *121*, 74–81. https://doi.org/10.1016/j.still.2012.01.013
Mapfumo, E., Aspinall, D., Hancock, T., & Sedgley, M. (1993). Xylem development in relation to water uptake by roots of grapevine (*Vitis vinifera* L.). *New Phytologist*, *125*(1), 93–99.
MetOffice (2018). *Sutton Bonington Rainfall data 1981–2010*. https://www.metoffice.gov.uk/public/weather/climate/gcrhe9cy8#?region=midlands
Miyashita, K., Tanakamaru, S., Maitani, T., & Kimura, K. (2005). Recovery responses of photosynthesis, transpiration, and stomatal conductance in kidney bean following drought stress. *Environmental and Experimental Botany*, *53*, 205–214. https://doi.org/10.1016/j.envexpbot.2004.03.015
Moriondo, M., Giannakopoulos, C., & Bindi, M. (2011). Climate change impact assessment: The role of climate extremes in crop yiels simulation. *Climatic Change*, *104*, 679–701. https://doi.org/10.1007/s10584-010-9871-0
Ober, E. S., Clark, C. J. A., Bloa, M. L., Royal, A., Jaggard, K. W., & Pidgeon, J. D. (2004). Assessing the genetic resources to improve drought tolerance in sugar beet: Agronomic traits of diverse genotypes under droughted and irrigated conditions. *Field Crops Research*, *90*, 213–234. https://doi.org/10.1016/j.fcr.2004.03.004
Olesen, J. E., Trnka, M., Kersebaum, K. C., Skjelvag, A. O., Seguin, B., Peltonen-Sainio, P., Rossi, F., Kozyra, J., & Micale, F. (2011). Impacts and adaptation of European crop production systems to climate change. *European Journal of Agronomy*, *34*, 96–112. https://doi.org/10.1016/j.eja.2010.11.003
Padilla, F. M., Aarts, B. H. J., Roijendijk, Y. O. A., de Caluwe, H., Mommer, L., Visser, E. J. W., & de Kroon, H. (2013). Root plasticity maintains growth of temperate grassland species under pulsed water supply. *Plant and Soil*, *369*, 377–386. https://doi.org/10.1007/s11104-012-1584-x
Richter, G. M., & Semenov, M. A. (2005). Modelling impacts of climate change on wheat yields in England and wales: Assessing. Drought risks. *Agricultural Systems*, *84*, 77–97. https://doi.org/10.1098/rsif.2008.0285
Romano, A., Sorgonà, A., Lupini, A., Araniti, F., Stevanato, P., Cacco, G., & Abenavoli, M. R. (2012). Morpho-physiological responses of sugar beet (*Beta vulgaris* L.) genotypes to drought stress. *Acta Physiologiae Plantarum*, *35*, 853–865. https://doi.org/10.1007/s11738-012-1129-1
Schindelin, J., Arganda-Carreras, I., Frise, E., Kaynig, V., Longair, M., Pietzsch, T., Preibisch, S., Rueden, C., Saalfeld, S., Schmid, B., Tinevez, J.-Y., White, D. J., Hartenstein, V., Eliceiri, K., Tomancak, P., & Cardona, A. (2012). Fiji: An open-source platform for biological-image analysis. *Nature Methods*, *9*, 676–682. https://doi.org/10.1038/nmeth.2019
Scott, R. K., & Jaggard, K. W. (2000). Impact of weather, agronomy and breeding on yields of sugarbeet grown in the UK since 1970. *Journal of Agricultural Science*, *134*, 341–352.
Steduto, P., Hsiao, T. C., & Fereres, E. (2007). On the conservative behavior of biomass water productivity. *Irrigation Science*, *25*, 189–207. https://doi.org/10.1007/s00271-007-0064-1
Supit, I., van Diepen, C. A., de Wit, A. J. W., Kabat, P., Baruth, B., & Ludwig, F. (2010). Recent changes in the climatic yield potential of various crops in Europe. *Agricultural Systems*, *103*, 683–694. https://doi.org/10.1016/j.agsy.2010.08.009
van Ginkel, M., Calhoun, D. S., Gebeyehu, G., Miranda, A., Tian-you, C., Lara, R. P., Trethowan, R. M., Sayre, K., Crossa, J., & Rajaram, S. (1998). Plant traits related to yield of wheat in early, late, or continuous drought conditions. *Euphytica*, *100*, 109–121. https://doi.org/10.1023/A:1018364208370
VSN International (2011). *GenStat for windows 17th edition*.
Walk, T. C., Jaramillo, R., & Lynch, J. P. (2006). Architectural tradeoffs between adventitious and basal roots for phosphorus acquisition. *Plant and Soil*, *279*, 347–366. https://doi.org/10.1007/s11104-005-0389-6
Xie, Q., Fernando, K. M. C., Mayes, S., & Sparkes, D. L. (2017). Identifying seedling root architectural traits associated with yield and yield components in wheat. *Annals of Botany*, *119*(7), 1115–1129. https://doi.org/10.1093/aob/mcx001

How to cite this article: Fitters TFJ, Mooney SJ, Sparkes DL. Impact of water availability on root growth of sugar beet varieties. *Soil Use Manage*. 2020;00:1–11. https://doi.org/10.1111/sum.12664