A sustainable irrigation based on a soil water balance model for the production of *Carpinus betulus* L.

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Abstract

Until recently, it was possible to produce high-quality avenue trees through rain-fed methods. However, due to recent prolonged drought periods during the growing season, the growth and quality of the trees are impacted, leading to a lower economic value. Therefore, the tree nursery sector requires irrigation thresholds and appropriate tools such as plant and soil sensors to schedule irrigation according to crop water needs. In 2022 and 2023, a trial was performed on 3- and 4-year-old hornbeam avenue trees (*Carpinus betulus* L.), in which a rain-fed treatment was compared with a drip-irrigated treatment. Irrigation doses were determined according to a calibrated soil water balance model, based on reference crop evapotranspiration (ET_0), rainfall, and soil hydraulic properties. In 2022, irrigation was mostly applied during the dry months of July and August. Although the effect of irrigation on soil moisture was less straightforward, it had a positive effect on stem water potential. In 2023, the trees were only irrigated during the dry month of June. This had a positive effect on both the soil and the stem water potential. During both years, irrigation had a positive effect on stem growth resulting in a higher economic value.

Keywords: avenue trees, drip irrigation, irrigation scheduling

INTRODUCTION

The ornamental sector is a small, but economically important sector in Belgium with a production value of 579 million euros in 2021, of which the tree nursery sector accounts for one-third (Departement Landbouw en Visserij, 2023; Landbouwwcijfers: Productiewaarde sierteelt; https://landbouwcijfers.vlaanderen.be/landbouw/sierteelt/productiewaarde-sierteelt). In recent years, we have experienced more extreme weather conditions with prolonged drought periods during the growing season due to climate change (Calvin et al., 2023), making rain-fed production of avenue trees nearly impossible. Drought will substantially decrease tree growth in terms of stem diameter (Eilmann and Rigling, 2012), thus reducing their commercial value. To obtain the same or even better growth and plant quality during dry years, irrigation will be needed (Ponder and Kenworthy, 1976; Dickmann et al., 1996). Drip irrigation is a more appropriate irrigation system for low-density tree crops than the traditional sprinkler irrigation because water is applied in the tree row close to the roots, minimizing weed pressure between the tree rows (Bravdo and Proebsting, 1993; Dasberg and Or, 1999). Therefore, growers in our region are more and more switching to this type of irrigation technique. Based on the findings of Jones (2008), it seems that more than half of the irrigation decisions in several countries and horticultural sectors are based on guesswork and intuition, which we also experience in nurseries in Flanders (Belgium). Hence, there is a high demand for appropriate irrigation thresholds and tools to control and predict irrigation. The large number of species grown in tree nurseries, each with variations in water use and soil structure, makes irrigation management diverse and more complex compared to traditional agricultural crops (Lea-Cox et al., 2013). The goal of this study is to determine the effect of a soil water balance model-based irrigation regime on tree growth and quality of 3- and 4-year-old hornbeam (*Carpinus betulus* L.) avenue trees.

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MATERIALS AND METHODS

Plant material, growing conditions, irrigation treatments

One-year-old *Carpinus betulus* L. liners were planted in 2020 in a loamy sand soil (Pcc soil profile) at a tree nursery in West Flanders, Belgium, in four rows of 250-300 trees per row. Weed was controlled mechanically. Fertilization was based on soil analysis and pest management was performed when pest pressure became too high, according to good agricultural practices. In the first two years after planting, trees were mainly dependent on rainfall to fulfill their water needs. In 2022, the grower installed driplines to irrigate the trees during dry periods with groundwater. The driplines had perforations every 50 cm and a discharge of 4.6 L h^{-1}. Two irrigation treatments were installed along the tree rows by removing the dripline at the end of the row leaving ± 30 trees without irrigation, with 12 trees per plot in four replicates for the rain-fed treatment and 26 trees per plot in four replicates for the irrigated treatment in 2022, and 10 trees per plot in four replicates per treatment in 2023. In this way, a model-based irrigated treatment could be compared to a rain-fed treatment. Minimal four trees separated the treatments in each experimental row. The field exhibited a slight slope, with the rain-fed treatment located in the lowest and consequently the slightly wetter part of the field.

The irrigation dose was determined according to a calibrated soil water balance model (Janssens, 2015). This model predicts the soil water content in the coming days, based on the calculation of reference crop evapotranspiration (ET_0) (Allen and Pereira, 1998), predicted rainfall, and soil hydraulic properties. During the first trial year, in 2022, irrigation was necessary during the dry months of July and August to maintain moisture levels above the intervention threshold, set at a pF value of 2.7 (or a soil water potential of -50 kPa). This threshold is based on previous research in pear orchards (Janssens et al., 2011). During the second wet trial year in 2023, irrigation was only needed during the dry month of June (Table 1).

Table 1. Precipitation and irrigation data for both trial years.

Month	2022		2023	
	Rain (mm)	Irrigation (mm)	Rain (mm)	Irrigation (mm)
April	28.2	0	61.5	0
May	30.1	16.7	35	0
June	115.4	11.1	19.6	95.8
July	6.4	63.9	76.7	33.3
August	17	65.3	92.7	0
September	128.2	12.5	89.7	0
Total	**325.3**	**169.5**	**375.2**	**129.1**

Soil and plant measurements

At the start of the trials, undisturbed soil samples of 100 cm^3 (Kopecky rings) were taken in the field to determine the water retention curve (pF) of the soil. Soil capacitance sensors (Teros-10, METER group, USA) were calibrated for the specific soil type, to improve the accuracy of the measurements, and monitored hourly the soil volumetric moisture content (vol%). In the first year, three sensors per treatment were installed at -15 cm depth spaced ±50 cm from each other. As the trees grew, roots developed deeper in the soil profile, so the sensors were installed deeper at -45 cm depth in 2023. The moisture content was recalculated as soil water potential (kPa) by using the earlier defined pF-curve. This calculation of soil water status as soil water potential eases the comparison of different treatments over the years. Monthly destructive, composite soil samples were taken on several spots in the tree row with a gauge auger in the soil layers 0-30 and 30-60 cm, to calibrate the soil water balance model. Each month, on the same day when soil samples were taken, the midday stem water potential (MPa) was determined with a pressure chamber (PMS Instruments, USA). Leaves were enclosed in bags made of aluminium foil 2 h before sampling, to balance leaf water potential with stem water potential (Garnier and Berger, 1985). Measurements were destructively performed on one leaf per tree and eight trees per treatment. Initially, four trees per treatment were sampled to estimate gas consumption during measurement. To determine the effect of irrigation on growth, the stem diameter at 1 m height, determined by a folding ruler, was monthly measured by a digital caliper.

The commercial quality of a tree is determined by its trunk circumference, based on which they are divided into economic grading ranges established by the tree nurseries ranging from 8 to 10, 10-12 till 18-20, and 20-25 cm for standard trunks. This circumference was calculated based on diameter measurements. All measurements were taken around noon.

Statistical analysis

Statistical analysis was performed using Rstudio (R version 4.3.0). If the data complied with normality and homoscedasticity, they were subjected to a Student's t-test ($p \leq 0.05$). Otherwise, results were analysed by a Mann-Withney-Wilcoxon test ($p \leq 0.05$). All results were expressed as means ± standard errors (SE).

RESULTS AND DISCUSSION

Effect of irrigation on soil and midday stem water potential

In 2022, irrigation was mostly performed in July and August, which were the driest months during the growing season (Table 1). At the start of the measurement campaign, from June to mid-July, the soil water potential of the irrigated treatment was less negative than that measured in the rain-fed treatment. Soil water potential of the latter dropped several times below the defined intervention threshold (Figure 1). The limited irrigation dose and frequency needed seemed to be sufficient according to the sensor measurements during this period. Yet, destructive soil analysis indicated that on June 30, 2022 the rain-fed treatment had a slightly, but significantly less negative soil water potential compared to the irrigated treatment, illustrating the effect of the sampling location and the fixed position of the sensors in the field (Figure 2). Early August, a sharp decrease in soil water potential of the irrigated treatment occurred below the pF threshold value of 2.7 (or -50 kPa). During the same period, the soil water potential of the rain-fed treatment did not decrease but became zero due to a leak in the drip hose from the adjacent tree row, noted on July 25, 2022 and estimated to have lasted for 2-3 days. This strongly influenced the soil moisture content and soil water potential in the rain-fed treatment in the zone around the sensors for a short period during and after the leak was repaired as water needed to infiltrate into the soil (Figure 1). However, the destructive soil analyses taken on July 25, 2022 indicated the expected soil water potential trend during the dry July month, with the rain-fed treatment having a more negative water potential. Soil samples in the rain-fed treatment were taken next to the soil zone influenced by the leak, so the real effect of the treatments was illustrated (Figure 2). End of August, the soil water potential of the irrigated treatment could not fully recover to the reference threshold, and this was also found in the destructive measurements.

There is an increasing interest in continuously monitoring the soil moisture content by soil moisture sensors and in incorporating them into automatic irrigation control systems (Jones, 2008), but the differences we found between the measurements of the soil sensors and the destructive soil analysis showed their drawback. Soil sensors cannot fully cover the variability in the field because of their fixed position compared to the destructive, composite soil samples taken at several spots in the tree row. Sensor measurement always requires sufficient repetitions if the field is not sufficiently homogeneous or if a representative plot in the field cannot be assigned to schedule irrigation (Campbell and Campbell, 1982; Jones, 2008). This might not always be the case in tree nurseries, where different species with different irrigation needs are grown. In 2023, the soil water potential of the rain-fed treatment was always more negative than that of the irrigated treatment. Precipitation seemed to have little effect in July, but from August onwards, the sensors in the rain-fed treatment reacted to rainfall. Soil moisture of the irrigated treatment was close to field capacity at that time, with a soil water potential of about 0 kPa. Although irrigation was only applied in June, the soil water potential of the irrigated plot was less negative and the difference between the treatments remained present (Figure 1). The destructive soil analysis indicated the same pattern, except for the measurement on May 30, 2023 where no significant difference could be observed (Figure 2).

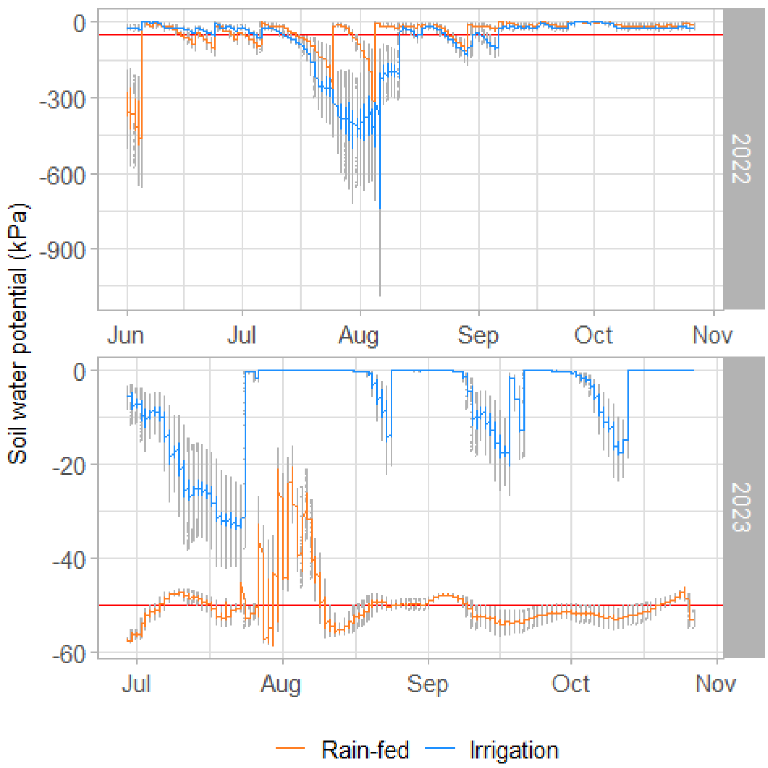

Figure 1. Evolution of the soil water potential (kPa), measured by the Teros-10 soil sensors, during the growing season of 2022 (-15 cm depth) and 2023 (-45 cm depth). The irrigation threshold value (pF=2.7) is indicated by the red line. Mean ± SE (grey bars) (n_rain-fed = 3, n_irrigation = 2).

In addition to monitoring the soil water potential, plant-based methods for irrigation control can be used. For example, the determination of physiological plant parameters that integrate soil and climatic conditions, such as the leaf or stem water potential is a possibility. These parameters could be more suitable than soil parameter thresholds for irrigation, as plant physiology might respond directly to changes in water status in plant tissues rather than to changes in soil water content or potential. Thus, a plant may not yet be in stress or may already be in stress when or before the critical soil threshold has been reached (Garnier and Berger, 1985; Jones, 2004, 2008).

In 2022, irrigation tended to maintain higher, at thus wetter, midday stem water potentials than the rain-fed trees from July onwards. The difference in midday stem water potentials between the two treatments was greatest during July, with a value of -0.8 MPa measured in the irrigated treatment compared to -1.4 MPa measured in the rain-fed treatment. This difference was also seen in the soil water potentials (Figure 2). In 2023, the differences in stem water potential between the treatments were smaller and not statistically significant. From May to June, stem water potentials of both treatments decreased from -0.75 MPa to -1.2 MPa. In July and August, the stem water potential of the treatments was around -1 MPa. In late September 2023, during another dry period, the stem water potentials differed between the treatments, but the rain-fed treatment had a less negative value. Neither treatment showed stress as stem water potential values were about -1 MPa (Figure 2).

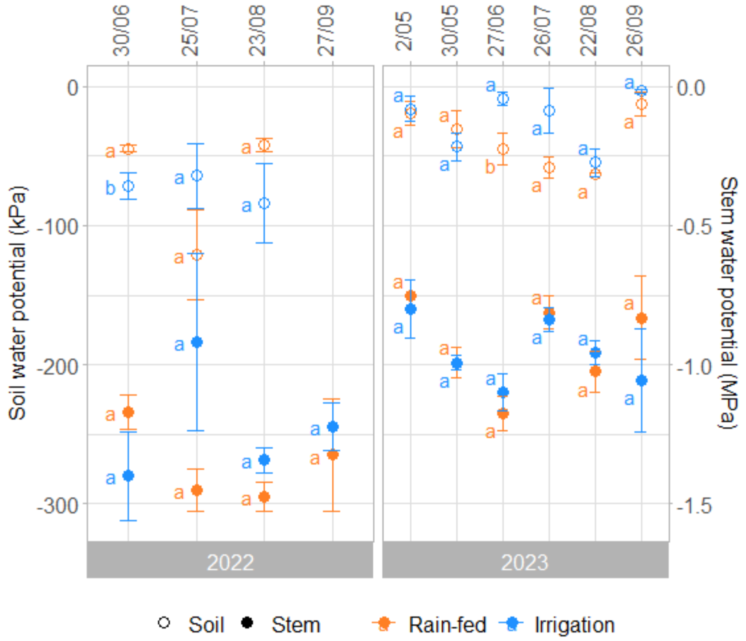

Figure 2. Effect of model-based irrigation (in blue) on soil water potential (kPa) (left axis) and midday stem water potential (MPa) (right axis) of hornbeam compared to the rain-fed treatment (in orange) in both trial years. Different letters (a and b) between the treatments per measurement day and per level (soil or plant) indicate a significant difference at p≤0.05 (mean ± SE, n_plant = 8, n_soil=4).

Most previous research on irrigation scheduling using stem water potential focused on fruit orchards such as peach (Garnier and Berger, 1985), apple (Naor, 1998; Naor and Cohen, 2003; De Swaef et al., 2009), grapevine (Naor, 1998; Williams and Araujo, 2002), nectarine (Naor, 1998), pear (Janssens et al., 2011), almond (Shackel et al., 1997), and prune (McCutchan and Shackel, 1992). The midday stem water potentials of these trees grown under well-irrigated conditions varied between -0.5 and -1.0 MPa. Irrigation research on open-field tree nurseries is rather limited. Nevertheless, the values in other cultivation systems under well-irrigated conditions are similar to those of fruit orchards, such as on *Amelanchier* grown via the pot-in-pot system. Continuous measurement of the plant water potential of these trees indicated that under well-irrigated conditions, the potential remained around -1 MPa; under reduced irrigation, the plant water potential reached values of about -2 MPa (Stoochnoff et al., 2018). This range of -0.5 to -1.0 MPa corresponds to the model-based irrigated hornbeam trees in this experiment of 2023. In 2022, the values of the irrigated hornbeam trees decreased below -1 MPa, mainly at the moment irrigation was not yet or no longer applied. During the dry July and August months of 2022, the stem water potential of the rain-fed treatment did not drop below -1.5 MPa, which is relatively wet compared to the abovementioned studies. The establishment of two years (in 2022) or three years (in 2023) after transplanting the one-year-old trees, allowed them to develop their root system into deeper soil layers, thus exploiting a larger volume of soil for water.

Effect of irrigation on plant growth

At the start of the growing season in 2022, when trees were already established in the field for two years, the trees in the rain-fed treatment had an initially larger stem diameter, probably due to their location in the field. In 2022, the 30±3% increase in stem diameter of irrigated trees at the end of September was significantly higher compared to only 17±2% for the rain-fed trees (Figure 3A). Rain-fed trees stopped growing from August onwards. In 2023, the trees were only irrigated during the dry month of June; after that, irrigation was no longer advised by the model. Starting in June 2023, the irrigated trees grew significantly faster, resulting in a 38±4% increase in stem diameter compared to a 28±2% increase in the rain-fed trees at the end of the season. Irrigation improved stem growth at the start of the season of 2023 and seemed to have an effect even after irrigation stopped (Figure 3A). When sold, trees are sorted in commercial grading ranges based on their stem circumference. Irrigation had a positive, non-significant effect on the grading of the 4-year-old trees across the ranges at the end of the growing season, with more trees in the higher ranges (Figure 3B). The irrigated trees could on average be sorted in the 12-14 cm commercial grading range compared to the rain-fed trees, which were on average sorted in the range of 10-12 cm.

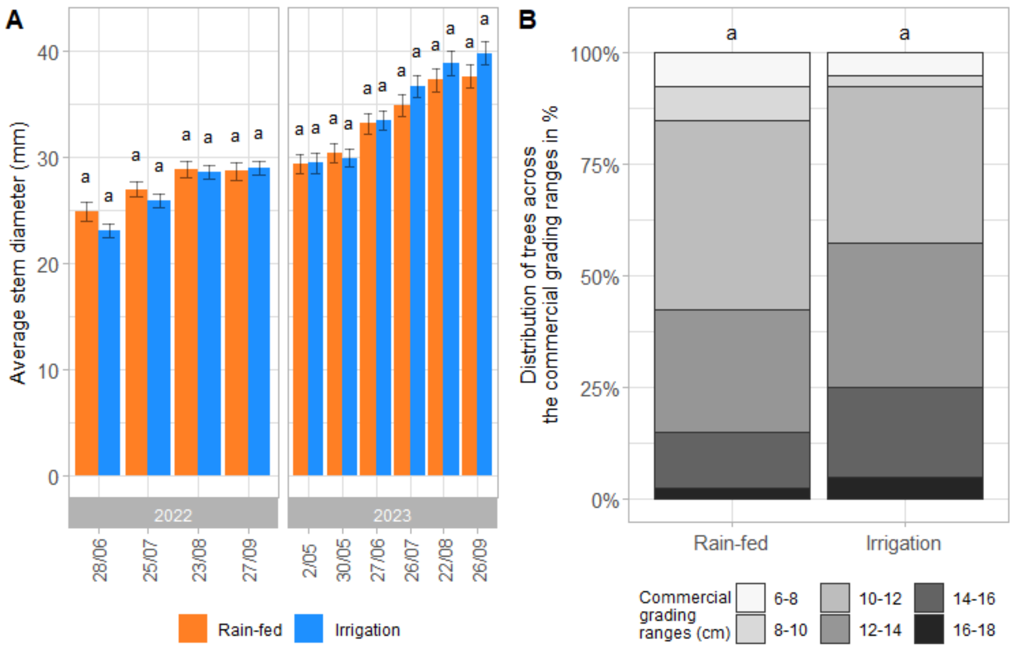

Figure 3. A) Effect of soil water balance model-based irrigation on tree growth of hornbeam in terms of stem diameter compared to a rain-fed treatment. Different letters (a and b) between the treatments per measurement day indicate a significant difference at p≤0.05. Mean ± SE (2022: n_irrigation = 104 and n_rain-fed = 48; 2023: *n*=40); B) Effect of soil water balance model-based irrigation on the distribution of 4-year-old hornbeam across the commercial grading ranges (cm) in percentages at the end of the growing season.

In this study, irrigation had a positive effect on the growth of hornbeam and seemed to extend its growing period. In previous research, a positive effect of irrigation on growth was not always observed, partly depending on the drought sensitivity of the species. In the study of Dickmann et al. (1996), three years of drip irrigation induced a significant growth response on one of the one-year-old *Populus* cultivars on the plantation. Eakes et al. (1985) evaluated drip irrigation in one-year-old liners of five different tree species grown in silt loam soil. Results for the species varied according to irrigation rates. Irrigation significantly increased the stem diameter (+15% for 100% irrigation) and length (+9% for 100% irrigation) of flowering dogwood (*Cornus florida*) and stem diameter of river birch (*Betula nigra*) (+9% for 100% irrigation) compared to the rain-fed treatment after two growing seasons. The other species tested showed only a limited response to drip irrigation. Ponder and Kenworthy (1976) found that drip-irrigated trees showed a greater trunk diameter than non-irrigated trees grown in loamy soil. Except for 3-years-old honey locust (*Gleditsia triacanthos* L.), trunk diameter even doubled in the case of 4-years-old sugar maple (*Acer saccharum* Marsh.) and white ash (*Fraxinus americana* L. 'Autumn purple'). Drip irrigation was also tested on container-grown tree nursery crops, where it often had no significant effect on stem diameter growth, also depending on the species (e.g., oak (Costello et al., 2005), maple, redbud, hawthorn (Fox and Montague, 2009), serviceberry (Stoochnoff et al., 2018)).

CONCLUSIONS

In this study, drip irrigation had a positive effect on the growth of 3- and 4-year-old hornbeams in terms of stem diameter. Although the difference in stem diameter between the treatments was not significant at the end of 2023, there was an economic benefit of drip irrigation as the irrigated trees could on average be sorted in a higher commercial grading range. The midday stem water potential was less negative under irrigation, but the midday stem water potential of the rain-fed trees also did not decrease below -1.5 MPa. There was a higher variation in the soil moisture observations compared to the measurements of plant water potential. Irrigation probably has a larger and more significant effect on the growth and water potential of the trees when it is also applied during the first and second growing year when trees are less deeply rooted in the soil, especially since we saw an effect when the trees were already older. This would be an interesting starting point for future research.

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