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Sensitivity of root pruned 'Conference' pear to water deficit in a temperate climate

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ABSTRACT

The present study examines the need for irrigation in pear trees (*Pyrus Communis*, cv. 'Conference') under low evaporative demand conditions, like in Belgium, in order to maintain a consistent fruit yield and high fruit size. To determine the sensitivity of the pear yield under low evaporative demand conditions three different orchards were monitored. The study shows that a Ψ_{soil} of −60 kPa during shoot growth has no effect on fruit yield but lower Ψ_{soil} values induced a decline in both fruit size and total yield. Just as for arid environments a Ψ_{stem} of −1.5 MPa is related to negative yield responses. In dry conditions lower Ψ_{soil} and Ψ_{stem} values were observed in root pruned trees compared to not root pruned trees in the same irrigation treatment, however without yield decline. In one orchard a biannual bearing tendency was observed after root pruning. Furthermore intensive Ψ_{soil} measurements show a high variation in Ψ_{soil} between orchards, and within an orchard. This underlines the need for irrigation management on a parcel level and the need for new irrigation scheduling techniques which take the spatial variation in the orchard into account.

1. Introduction

Over the past years pear fruit (*Pyrus communis* cv. 'Conference') has become an important part of fruit growing in Belgium and the Netherlands. Belgium is situated in the temperate climate zone with a relatively low average evapotranspiration and a high but variable rainfall from bloom (first half of April) to harvest (first half of September). Since the ban of growth inhibitors based on hormonal applications, for example Paclobutrazol, trees are subjected to different management practises such as root pruning to control the vigour of the tree (Maas, 2007; Vercammen et al., 2005). Root pruning is an effective tool to control the vegetative growth because tree transpiration is reduced (Asín et al., 2007; Rodriguez-Gamir et al., 2010; Schupp et al., 1992). Root pruning reduces the root volume of the tree in the upper soil layer, where the most significant water extraction by the tree occurs (Gong et al., 2006; Green and Clothier, 1999; Green et al., 2003; Ma et al., 2007). As a consequence, it possibly makes the trees more sensitive to water stress.

Market price of fruits having a diameter of >60 mm is twice the price of smaller sized fruits (<55 mm). During summer in Belgium in 30% of the years a rain deficit of at least 10 mm per ten days occurs (Fig. 1a). In those years the price difference between large and small fruits increases significantly. The high market price for large fruit sizes and the higher water stress sensitivity due to root pruning (Marsal et al., 2008; Schupp et al., 1992) has pushed the fruit growers to the implementation of irrigation systems.

In arid and mediterranean environments it has been demonstrated for pear fruit that during fruit maturing, a water deficit is strongly related to a poorer fruit tissue growth but that irrigation can prevent the decline in fruit yield and size (Cui et al., 2008; Marsal et al., 2000, 2002; Naor, 2001). Naor (2001) observed yield decline when Ψ_{soil} dropped below −20 kPa. During the shoot growth, which starts immediately after full bloom and ends one month before harvest, a deficit irrigation scheme can control the vigour of the pear tree (Asín et al., 2007; Cui et al., 2009; Marsal et al., 2000, 2002). However the main focus for the fruit grower is the total yield and fruit size which should not be affected negatively. For jujube pear tree a reduced water supply during shoot growth had no effect on the total yield (Cui et al., 2009). Anconelli and Mannini (2002) even showed that the total yield can increase when the irrigation supply is lowered during shoot growth. In relation to pear fruit size however Marsal et al. (2000, 2002) reported smaller fruit size during deficit irrigation when the stem water potential dropped (Ψ_{stem}) below −1.5 MPa, even during shoot growth. On the other hand excessive irrigation reduced the total number of

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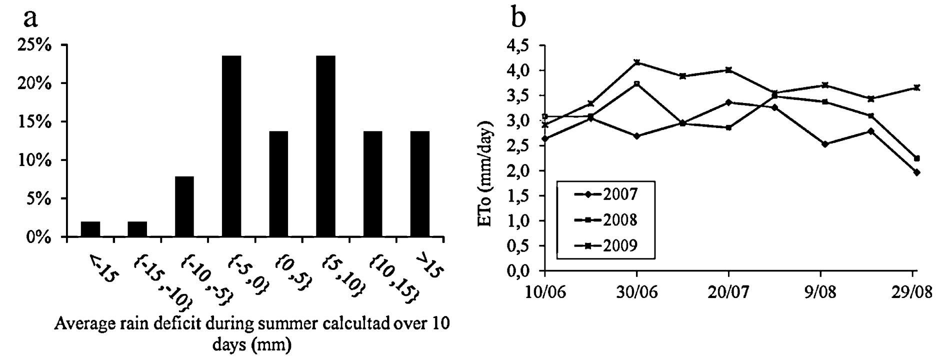

Fig. 1. Distribution of average rain deficit per 10 days during summer in Belgium the last 51 years (a) and average evapotranspiration calculated over 10 days 2007–2009 (b).

fruits and had a negative effect on total yield, which indicates the delicate optimal equilibrium between deficit irrigation and excessive irrigation. An irrigation threshold of a Ψ_{stem} of −1.5 MPa for pear tree in an arid and mediterranean climate has been confirmed by others (Naor, 2001; O'Connell and Goodwin, 2007; Ramos et al., 1994).

Since sap flow, and also water status (Ψ_{stem}), in plants is driven by the difference between Ψ_{air} (evaporative demand) and Ψ_{soil} (Van den Hornert, 1948) the optimal irrigation equilibriums discussed by Anconelli and Mannini (2002), Cui et al. (2008), Marsal et al. (2000, 2002) and Naor (2001) all depend on the local evaporative conditions (Doorenbos and Kassam, 1986). Although more than 30% of the world pear production is situated in the temperate climate zone (WAPA, 2008), the number of irrigation studies on pear tree in a temperate climate is limited. The introduction of root pruning in combination with the market demand for large fruit sizes has only recently increased the interest for irrigation in pear tree in the temperate climate zone. The question which remains is how the pear fruit yield of the trees is affected when deficit irrigation is applied during shoot growth under conditions with low evaporative demand. Also secondly, the relation between deficit irrigation and root pruning for pear has so far only been described by Marsal et al. (2008) in more arid conditions.

The first objective of this study is to examine the impact of a low soil water potential (Ψ_{soil}) on the fruit yield and the fruit size and the tree water status quantified by stem water potential (Ψ_{stem}) in a temperate climate. Can the thresholds proposed for irrigation scheduling in arid conditions be maintained in a temperate climate? The second objective is to analyse the impact of root pruning on the fruit yield and the tree water status in a deficit irrigation regime. For this purpose an irrigation experiment and a root pruning experiment were set up.

2. Materials and methods

In Belgium in the pear trees (*Pyrus Communis*, cv. 'Conference') full bloom takes place mid April, followed by a period of intensive cell multiplication until the end of May. June and July are characterised by a period of extensive shoot growth. In August the fruits start to mature with a period of cell elongation, until harvest at the end of August or the beginning of September.

Given the variety in soil profiles and planting regimes in Belgium, three different orchards were selected for this study: an intensively planted orchard on a dry profile on a slope situated in Bierbeek, and two older less intensively planted orchards in Meensel and in Sint-Truiden. In these orchards an irrigation experiment and a root pruning experiment were set up during 2007, 2008 and 2009. In the irrigation experiment a full irrigation regime (FI) was compared to a deficit irrigation regime (DI). In the root pruning experiment a comparison was made between root pruned trees (RP) and not root pruned trees (NRP).

2.1. Experimental sites and plant material

2.1.1. Bierbeek

The first orchard is situated in Bierbeek (50°49′36.35″N, 4°47′40.35″E). The orchard was planted with pear tree cv. 'Conference' on Quince C rootstock. The trees were planted in 2000 with a planting distance of 3.3 m by 1 m. Trees were trained in an intensive V system with four fruiting branches on one central stem. Average tree height was 2.5 m. The orchard was situated on a slope. Soil texture in the upper soil layer was loam; in the deeper soil layer texture was sandy loam. The soil had an organic carbon content of 1% in the upper soil layer (0–30 cm). The water retention curve (WRC) was fitted through 8 measurements on pressure plates. Volumetric water content was 38%, 30% and 12% at −10 kPa, −30 kPa and −1600 kPa, respectively. The bulk density in the upper soil layer (0–30 cm) was 1.4 g m^{-3}and 1.5 g m^{-3} in the deeper soil layer (30–60 cm). Irrigation water had a low salinity risk with a electric conductivity (EC) of 0.76 dS/m at 25 °C.

2.1.2. Meensel

The second orchard is located in Meensel (50°53′40.20″N, 4°55′38.12″E). The orchard was composed of pear tree 'Conference' on a Quince Adams rootstock. The trees were planted in 1996 with a planting distance of 3.5 m by 1.5 m, trained in a free spindle system. The soil texture was sandy loam. A shallow ground water table was present in the soil profile at a depth between 1.5 m and 2 m. The orchard was situated on a small slope and the organic carbon content of the upper soil layer was 1%. Volumetric soil water content was 36%, 29% and 13% at −10 kPa, −30 kPa and −1600 kPa, respectively. The bulk density was 1.4 g m^{-3} in the upper soil layer (0–30 cm) and 1.5 g m^{-3} in the deeper soil layer (30–60 cm). Irrigation water had a low salinity risk with a EC of 0.58 dS/m at 25 °C.

2.1.3. Sint-Truiden

The third orchard is situated in Sint-Truiden (50°45′59.46″N, 5°9′24.68″E) and was planted with Conference trees on a Quince Adams rootstock. The trees were planted in 1996 with a planting distance of 3.5 m by 1.5 m. The average tree height was 3.5 m. The trees were never root pruned and were trained in a free spindle system. The orchard was situated on a loamy textured soil. The organic carbon content in the upper soil layer was 1.1%. The volumetric soil water content was 36%, 25% and 11% at −10 kPa, −30 kPa and −1600 kPa, respectively. The bulk density was 1.4 g m^{-3} for the upper soil layer and 1.5 g m^{-3} for the lower soil layer. The EC of the irrigation water was 0.87 dS/m at 25 °C.

In all orchards management practises such as pruning, disease control, fertilization and mulching were carried out in the same way as in a commercial orchard.

2.2. Irrigation experiment

Belgium is situated in a temperate climate zone with frequent rainfall events and a relatively low evapotranspiration during the growing season. Rainfall was recorded on site; the reference evapotranspiration (ETo) was calculated using the Penman–Montheith equation (Allen et al., 1998) based on data recorded at weather stations at 10 km from Bierbeek, 20 km from Meensel and 30 km from Sint-Truiden. In all orchards a drip irrigation system was installed with drippers every 20 cm with a discharge rate of 2 l/h.

In each orchard, in a block of 0.2 ha with identical trees eight plots were at random selected. A plot consisted of four consecutive trees in the same irrigation regime. Between two plots there were minimal two guard trees. Four plots in the FI treatment received 100% ETo throughout the entire growing season. The four remaining plots in the DI treatment received no irrigation between 01 June and 10 July, the period of intensive vegetative growth. In this period these trees were also equipped with rain repelling screens which diverted the rain to the grass strip between tree rows. The rain repelling screens were installed in June–July to insure a low Ψ_{soil} because in 30% of the years rain deficit is lower than zero during summer (Fig. 1a). In periods without rainfall the screens were removed from the orchard. Outside this period the DI treatment was fully irrigated (100% ETo), identically as FI.

Besides the irrigated plots, Ψ_{soil} was monitored in one rainfed plot in each orchard. The experiment was set up in the orchards of Sint-Truiden and Meensel during 2007, 2008 and 2009. In Bierbeek the experiment was set up in 2007 and 2008.

In the FI and the DI plots in Bierbeek in 2007 and in Meensel in 2007, 2008 and 2009 root pruning was carried out with a sloping knife on one side of the Tree 35 cm from the trunk. In Bierbeek in 2008 and in Sint-Truiden in 2007, 2008 and 2009 no root pruning was carried out.

2.3. Root pruning experiment

In the same orchards where the irrigation experiment was conducted a root pruning experiment was set up. In every orchard four root pruned (RP) plots were compared with four not root pruned plots (NRP). Plots were randomly distributed throughout the orchard and consisted of four trees in a row. Between two plots there were minimal two guard trees. Root pruning was carried out with a sloping knife approximately 35 from the trunk. The experiment was set up in Bierbeek in 2007, 2008 and 2009, in Meensel in 2007, 2008 and 2009 and in Sint-Truiden 2007, 2008 and 2009.

Trees in the RP treatment were root pruned in Bierbeek in 2007 and 2009 but not in 2008. In 2008 the recovery of root pruning in 2007 was monitored. In Meensel and in Sint-Truiden trees in the RP treatment were root pruned in 2007, 2008 and 2009. To monitor the effect of a water deficit after root pruning, in all orchards the trees in the root pruning experiment were irrigated similar as the DI trees in the irrigation experiment.

2.4. Measurements

2.4.1. Soil water potential (Ψ_{soil})

In the FI and DI treatment Ψ_{soil} was monitored in three plots. In the RP and NRP treatment Ψ_{soil} was monitored in one plot. Ψ_{soil} was monitored with six Watemark granular matrix sensors per tree (Irrometer Co., USA); 3 sensors at 30 cm, 2 sensors at 60 cm and 1 sensor at 90 cm depth. The sensors were connected to a data logger which recorded Ψ_{soil} every four hours. The standard manufacturer calibration was used to compute Ψ_{soil} from the electrical resistance measured by the sensors. The Watermark registrations were accompanied by gravimetric moisture samples. Samples were taken with a gauge auger of 30 cm in the soil layers 0–30 cm and 30–60 cm. One sample consisted of minimal 8 subsamples taken randomly in the weed free strip beneath the canopy. Gravimetric water content was measured by drying at 105 °C during 24 h. Ψ_{soil} of the samples was calculated with the aid of the water retention characteristics (WRC) and bulk density.

2.4.2. Stem water potential (Ψ_{stem})

In 2008 and in 2009 Ψ_{stem} measurements were performed weekly in periods without rainfall. Ψ_{stem} was measured in each plot where Ψ_{soil} was monitored. Per measurement three leafs were selected from the inner part of the canopy. While still being attached, these leaves were enclosed in plastic bags covered with aluminium foil. After 60 min, the leaves were detached and the Ψ_{stem} was determined immediately using a pressure chamber (Scholander et al., 1965). The Ψ_{stem} was only recorded on sunny days without rainfall. Measurements were performed between 13:00 h and 15:00 h.

2.4.3. Fruit yield and number of flower buds

One day before harvest in the commercial orchard, pears of two trees per plot were harvested. From each plot a yield analysis was performed and the fruit yield was subdivided in the different fruit size classes per 5 mm. For each fruit size class the number of fruits was determined and the average fruit weight was calculated. Flower buds were counted on two trees, shortly before full bloom, in every plot.

Statistical analysis of yield data and the number of flower buds was performed using the Mann–Whitney *U* test with the STATISTICA software (StatSoft, 2009).

3. Results

3.1. Irrigation experiment

The three orchards were situated between 10 km and 30 km from each other. Rainfall differed in the three different sites. This is reflected in the monthly rain deficit calculated from ETo and rainfall (Table 1). Rain deficit in 2009 went up to 20 mm per 10 days which is high for Belgium (Fig. 1a). 2009 was warm and dry especially during June and August. In 2007 and in 2008 rain deficit did not exceed 10 mm, both years are characterised as rather humid. Average ETo per 10 days was between 2.5 and 3.5 mm/day in 2007 and in 2008. In 2009 ETo ranged between 3.5 and 4.5 mm/day (Fig. 1b).

3.1.1. Soil water potential (Ψ_{soil})

In the rainfed plots in Bierbeek, Ψ_{soil} decreased sharply in each year (Fig. 2a) which in Meensel and Sint-Truiden decreased only in 2009 below −100 kPa (Fig. 2b and c).

In Bierbeek in 2007, and in 2008 Ψ_{soil} declined rapidly to −150 kPa in the DI treatment (Fig. 3a and b). In 2008, Ψ_{soil} did not decrease as far as 2007 because irrigation was resumed at the end of July at a higher rate. In the DI treatment the variation of Ψ_{soil} between the plots was high in Bierbeek and increased sharply when Ψ_{soil} decreased below −100 kPa although all plots received the same amount of water. In plots located higher on the slope Ψ_{soil} decreased faster compared to plots lower on the slope (Fig. 3c). When irrigation was resumed at the end of July, the variation between the plots increased further: plots located lower on the slope were faster humidified while plots located higher up the slope remained dry. In Meensel in the DI treatment Ψ_{soil} decreased to below −90 kPa in 2007 and 2009, in 2008 Ψ_{soil} decreased to −60 kPa

Table 1
Average rain deficit (ETo-Rain) calculated over 10 days. Rain (mm) measured on site, ETo (mm) calculated with data recorded at a nearby weather station (Bierbeek 10 km, Meensel 20 km, Sint-Truiden 30 km).

Year	Bierbeek			Meensel			Sint-Truiden		
	June	July	August	June	July	August	June	July	August
2007	4	−9	3	10	−2	8	−3	−2	−18
2008	−9	6	−1	6	4	−9	−3	1	3
2009	18	16	23	19	7	18	21	15	26

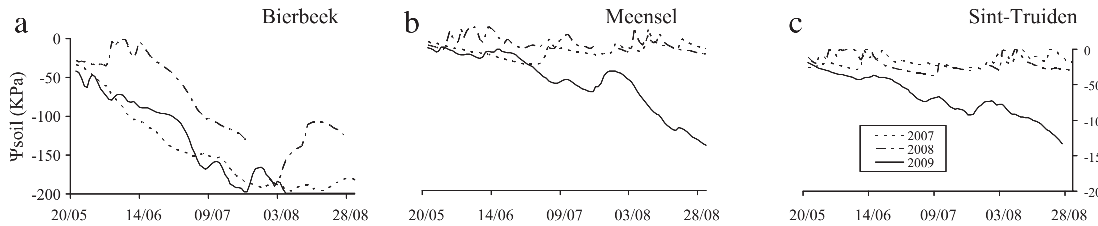

Fig. 2. Ψ_{soil} measured by Watermark sensor in rainfed plots in Bierbeek (a), Meensel (b) and Sint-Truiden (c). Line represents average of three sensors at 30 cm depth.

(Fig. 3d–f). Once irrigation was resumed at the end of July, as in Bierbeek, the variation in Ψ_{soil} between the plots increased sharply. In Sint-Truiden, despite similar irrigation regimes as in Bierbeek no decrease in Ψ_{soil} occurred (Fig. 3g–i) in the DI treatment. Only in 2008, a small differentiation in Ψ_{soil} between the FI and DI treatment was observed. In 2009, Ψ_{soil} dropped slightly compared to 2007 and 2008, in accordance with the higher rain deficit in 2009 (Table 1). In general the variation in Ψ_{soil} between the irrigation plots of the same treatment was lowest in Sint-Truiden.

There was a good correlation between the Ψ_{soil} measured by the Watermark sensor and Ψ_{soil} derived from gravimetric moisture sampling and the WRC (Fig. 4a). Correlation between Watermark and gravimetric sampling became stronger when only data recorded on days without irrigation were considered (Fig. 4b). However the slope through origin became lower. In Sint–Truiden the strongest relationship between the Watermark sensor and gravimetric sampling was found with a R^2 of 0.72 and a slope of 1.06 (data not shown).

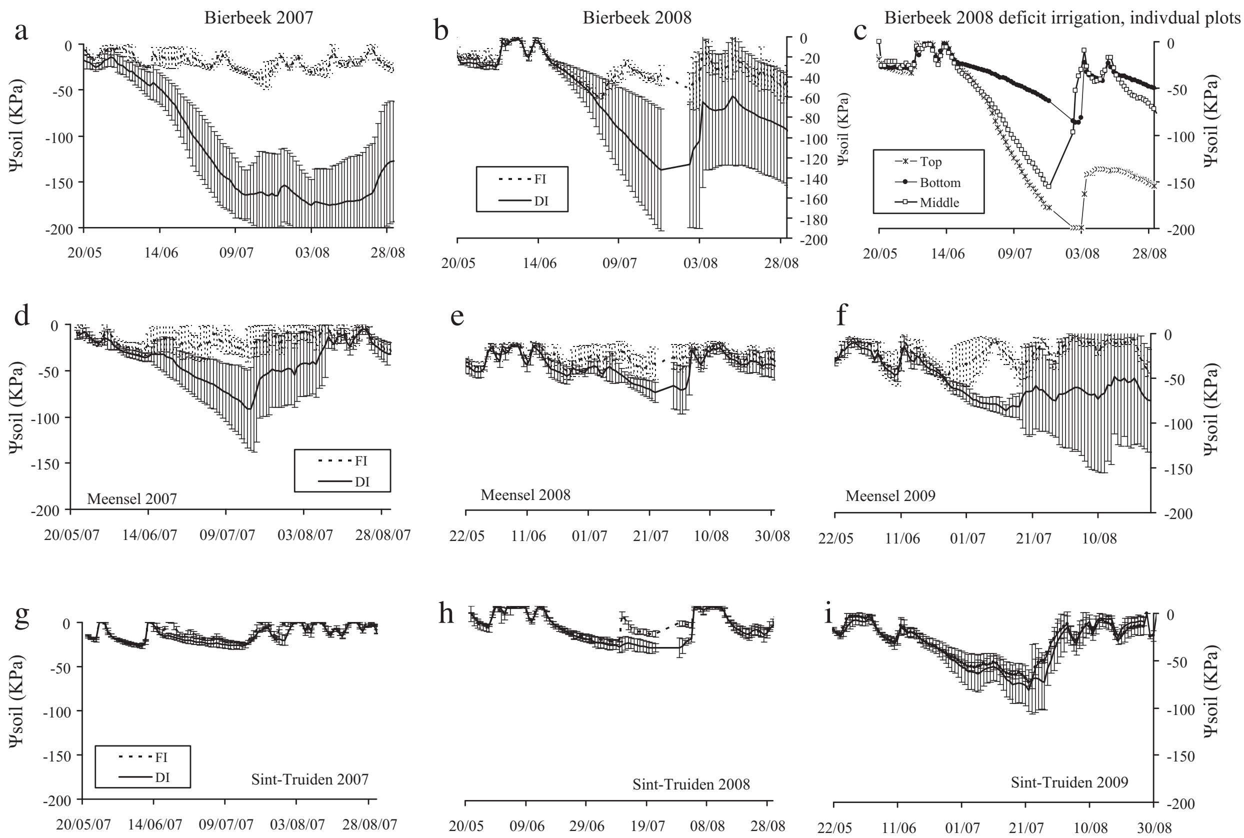

Fig. 3. Ψ_{soil} for the FI treatment and the DI treatment in Bierbeek 2007 (a), Bierbeek 2008 (b) and for the individual plots in the DI treatment in Bierbeek 2008 (c) where location on the slope is indicated in the legend. Ψ_{soil} evolution in FI treatment and DI treatment is shown for Meensel 2007 (d), Meensel 2008 (e), Meensel 2009 (f), Sint-Truiden 2007 (g), Sint-Truiden 2008 (h) and Sint-Truiden 2009 (i). FI was irrigated 100% ETo during the entire growing season. Plots in DI treatment were covered with rain repelling screens during June–July and irrigation was withheld. Line represents Ψ_{soil} monitored with Watermark sensors in three plots per treatment and three sensors at 30 cm per plot. Bars indicate standard deviation between the three plots.

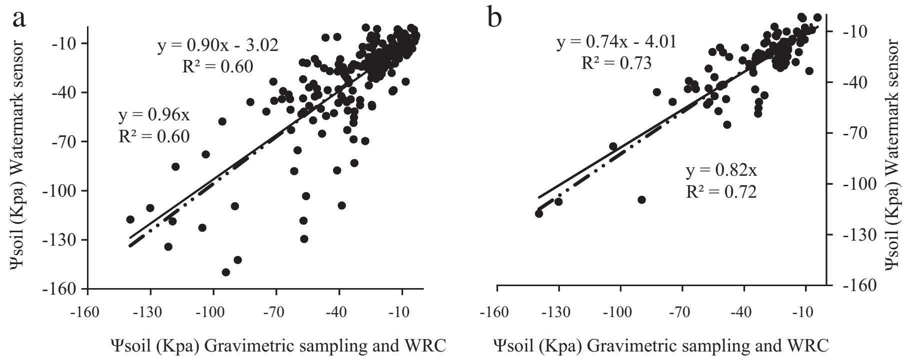

Fig. 4. Relation between Ψ_{soil} measured by Watermark sensor and Ψ_{soil} derived from gravimetric sampling, bulk density and Water Retention Curve (WRC) during 2007–2009 in three orchards at 0–60 cm. (a) all measurements (b) measurements on days without irrigation.

3.1.2. *Stem water potential (Ψ_{stem})*

Ψ_{stem} measurements during the experiment differed only in Bierbeek in 2008 (Fig. 5a) and in Meensel in 2009 (Fig. 5b) which is in accordance with the Ψ_{soil} registrations (Fig. 3). In Meensel in 2009 Ψ_{stem} reached −1.5 MPa while in Bierbeek in 2008 Ψ_{stem} dropped to −2 MPa. In Sint-Truiden in 2008 and in 2009, in Bierbeek in 2008 and in Meensel in 2008 there was no differentiation in Ψ_{stem} between both treatments (data not shown) and no depressed Ψ_{stem} values were observed, in accordance with Ψ_{soil} observations (Fig. 3).

3.1.3. *Fruit yield and number of flower buds*

Total fruit yield and fruit yield in the size class >60 mm was affected negatively in the DI treatment in Bierbeek 2007 (Table 2) which confirmed measurements of Ψ_{soil}. In 2008 in Bierbeek the number of flower buds was higher in the DI regime. Total fruit yield and yield in the different size classes was in 2008 not significantly different although yield in the high fruit size classes slightly decreased. Thinning was performed as in a commercial orchard. Therefore despite the higher amount of flower buds, there were no differences in the total number of fruits. In the FI treatment in Meensel in 2007 and 2009 fruit yield was higher in the high size classes but due to variation between the plots there was no significance. In Meensel in 2008 and in Sint-Truiden in 2007, 2008 and 2009, fruit yield and fruit size were not different between the DI and the FI treatment.

Only in Bierbeek in 2007, the fruit yield in the size class >60 mm was negatively related with Ψ_{soil} (Fig. 6a). In other years at other locations no relation between Ψ_{soil} and yield was observed. In Meensel in 2009 Ψ_{stem} was negatively correlated with fruit yield in the size class >65 mm (Fig. 6b). In Sint-Truiden there was no correlation between Ψ_{soil}, Ψ_{stem} measurements and yield because differentiation in Ψ_{soil} and Ψ_{stem} between the irrigation treatments is lower. In all orchards Ψ_{stem} was linearly related to Ψ_{soil} and ETo (Table 3). A low Ψ_{soil} on a day with high ETo is correlated with low Ψ_{stem}. Correlation was strongest in Bierbeek 2008 and Meensel 2009.

Overall there was large variation in Ψ_{soil} evolution between the different irrigation plots within an orchard and between the orchards during the three years of the experiment. A depressed Ψ_{soil} (<−90 kPa) had a negative impact on the fruit yield and the fruit size. A moderately depressed Ψ_{soil} of −60 kPa did not influence the fruit yield or size. Low Ψ_{stem} observations were related to fruit size decline.

3.2. *Root pruning*

3.2.1. *Soil water potential (Ψ_{soil}) and stem water potential (Ψ_{stem})*

In Bierbeek Ψ_{soil} decreased sharply to −600 kPa after root pruning which is lower then the recordings of the watermark sensors which are limited to −200 kPa (Fig. 7a and b). The difference in Ψ_{soil} was reflected in the Ψ_{stem} measurements which decreased to −2 MPa and lower (Fig. 7c and d). In Meensel root pruning had no clear effect on the evolution in Ψ_{soil} in 2008. In 2009 Ψ_{soil} was slightly lower (Fig. 7e and f) up to −100 kPa. The influence of root pruning on Ψ_{stem} was more pronounced especially in 2009 (Fig. 7 g and h). In Sint-Truiden, the difference in Ψ_{stem} between the RP and NRP treatment was most pronounced in 2009 when Ψ_{soil} decreased to −100 kPa (Fig. 7k and l). In 2008 there was no clear differentiation.

3.2.2. *Fruit yield and number of flower buds*

In Bierbeek and in Meensel, root pruning had no effect on flower bud, fruit yield and fruit size (Table 4). In Sint-Truiden the trees show biannual bearing tendency. In 2008 the total yield was significantly lower in the RP treatment. Although it was not significant, in 2009 total yield and amount of flower buds increased in relation to the NRP treatment. Fruit size was not affected by root pruning.

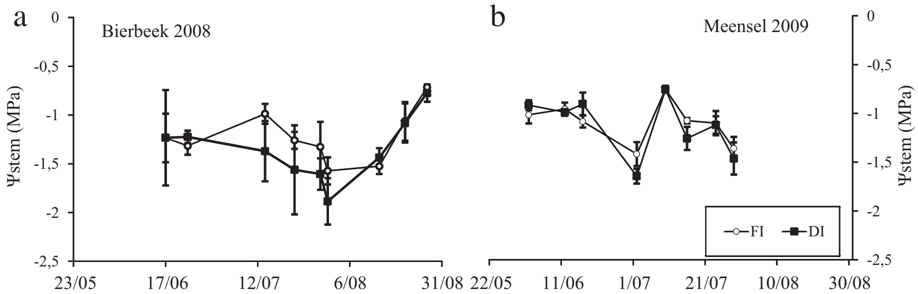

Fig. 5. Evolution of Ψ_{stem} in Bierbeek 2008 (a) and Meensel 2009 (b) in the irrigation experiment. Each dot represents average of three plots on three measurements per tree. Bars indicate standard deviation between the three plots.

Table 2
Average fruit yield, fruit size and number of flower buds counted just before full bloom two different irrigation regimes for 'Conference' pear tree. Full irrigation (FI) received 100% ETo during the entire growing season. In the deficit irrigation (DI) treatment irrigation was withheld during shoot growth (1/6-10/7) and rain repelling screens were installed. Outside this period DI was irrigated like FI.

		# Flower buds/tree	Yield (kg/tree)	Crop level (#fruits/tree)	Yield in size class (kg/tree)		
					<55 mm	>60 mm	>65 mm
Bierbeek							
2007	FI	88	26	152	1	21 a	13
	DI	96	22	131	1	18 b	9
2008	FI	85 a	27	145	1	21	12
	DI	111 b	27	146	1	19	8
Meensel							
2007	FI	144	34	229	5	20	7
	DI	152	33	233	4	15	4
2008	FI	112	25	151	4	16	9
	DI	122	26	159	5	16	8
2009	FI	21*	26	162	2	18	8
	DI	19*	23	162	4	12	5
Sint-Truiden							
2007	FI	132	23	150	2	17	9
	DI	118	24	154	2	18	9
2008	FI	59	16	90	2	11	6
	DI	59	15	86	2	11	6
2009	FI	30	11	63	1	9	6
	DI	34	12	75	1	10	7

a and b indicate a significant difference according to the Mann–Withney U test at $P < 0.05$.
* Flower buds/shoot instead of flower buds/tree.

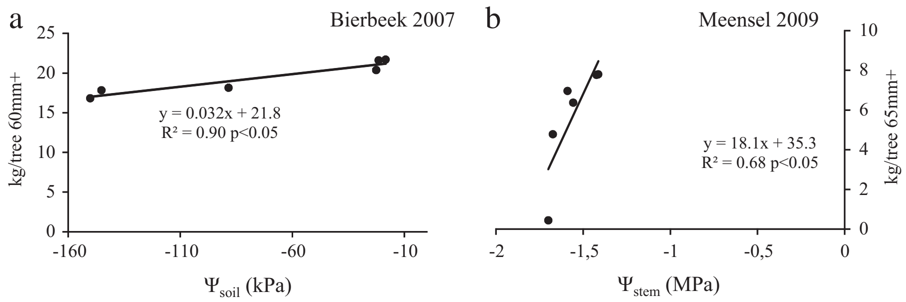

Fig. 6. Relation between Ψ_{soil} and yield in size class 60 mm+ for Bierbeek in 2007 (a). Relation between Ψ_{stem} and yield in size class 65 mm+ for Meensel 2009 (b).

In general lower Ψ_{soil} and Ψ_{stem} values were observed when trees were root pruned, however no negative effects on fruit yield could be dedicated to them. In one orchard (Sint-Truiden) trees show biannual bearing tendency after root pruning.

4. Discussion

4.1. Irrigation

The first objective of the present study was to describe the sensitivity of pear tree to water stress in a temperate climate and to compare it to previous work under more arid conditions. Based on our results we conclude that irrigation was relevant during shoot growth to prevent decline in fruit size when Ψ_{soil} decreases to −100 kPa. However in none of the orchards yield decline, or decline in fruit size was observed when Ψ_{soil} reached −60 kPa which is lower then Ψ_{soil} thresholds described in more arid conditions. The thresholds of Ψ_{stem} for irrigation scheduling described in arid conditions can however be maintained in a temperate climate.

In a semi arid climate, yield decline and decline in fruit size was observed when Ψ_{soil} exceeded −20 kPa (Naor, 2001). In 2008, in Meensel and in Sint-Truiden, in moderate evaporative conditions (2.5–3.5 mm/day), no yield decline or decline in fruit size was observed when Ψ_{soil} dropped to −60 kPa. This illustrates that thresholds designed for irrigation scheduling, often expressed in terms of soil water depletion fraction, are depending on the evaporative demand in accordance with Doorenbos and Kassam (1986).

When Ψ_{soil} reached less than −150 kPa, a decline in fruit size was observed in Bierbeek 2007. In Bierbeek 2007 the depressed Ψ_{soil} in the deficit treatment led to an increase in amount of flower

Table 3
Linear regression between Ψ_{stem}, ETo and Ψ_{soil} ($\Psi_{stem} = a\text{ETo} + b\Psi_{soil} + c$). Ψ_{stem} observation is average of three measurements per tree. Ψ_{soil} is measured by three Watermark sensors at 30 cm. ETo is calculated by Penmann–Montheith (Allen et al., 1998) on a nearby weather station (Bierbeek 10 km, Meensel 20 km, Sint-Truiden 30 km).

Location	Year	R^2	a	b	c	n
Bierbeek	2008	0.49**	−0.27**	0.003**	−0.18	54
Meensel	2008	0.30**	−0.14**	0.002*	−0.36**	54
	2009	0.57**	−0.24**	0.003**	−0.015	60
Sint-Truiden	2008	0.30**	−0.14**	0.0003	−0.52**	48
	2009	0.30**	−0.25**	0.004	0.14	54

* Significance at $P < 0.05$.
** Significance at $P < 0.001$.

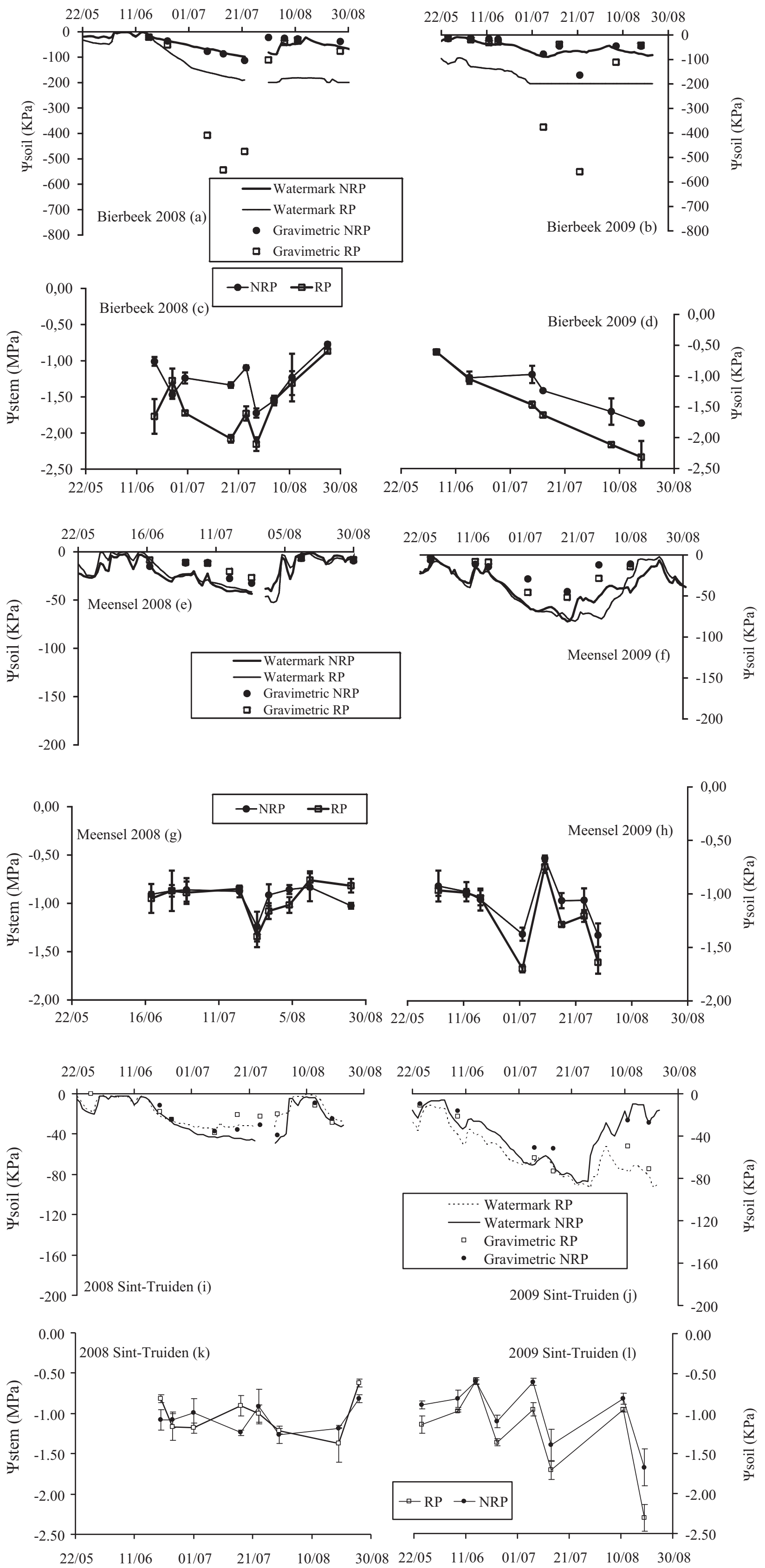

Fig. 7. Ψ_{stem} and Ψ_{soil} for a tree in RP treatment and a tree in NRP treatment located less then 10 m from each other in Bierbeek (a)–(d), Meensel (e)–(h) and Sint-Truiden (i)–(l). Ψ_{soil} measured with Watermark sensor, six sensors per tree, and derived from gravimetric sampling, bulk density and WRC. Ψ_{stem} measured on three leaves per tree, bars indicate standard deviation.

Table 4
Average fruit yield, fruit size and number of flower buds/tree in root pruned trees (RP) compared to not root pruned trees (NRP).

		# Flower buds	Yield (kg/tree)	Crop level (#fruits/tree)	Yield in size class (kg/tree)		
					<55 mm	>60 mm	>65 mm
Bierbeek							
2007	RP	96	22	131	1	18	9
	NRP	106	24	155	2	18	9
2008	RP**	111	28	151	1	19	8
	NRP	86	27	145	2	20	9
2009	RP	106	22	152	4	11	3
	NRP	117	21	144	3	12	4
Meensel							
2007	RP	152	33	233	4	15	4
	NRP	149	37	268	6	19	5
2008	RP	122	26	159	5	16	8
	NRP	100	22	133	4	15	9
2009	RP	19*	23	162	4	12	5
	NRP	15*	19	124	2	11	5
Sint-Truiden							
2007	RP	119	23	146	2	18	9
	NRP	118	24	154	2	17	9
2008	RP	66	9 a	45 a	1	8	5
	NRP	59	15 b	86 b	2	11	6
2009	RP	53	20	138	3	12	6
	NRP	34	12	75	1	10	7

a and b indicate a significant difference according to the Mann–Withney *U* test at $P < 0.05$ respectively.
* flower buds/shoot instead of flower buds/tree.
** In 2008 in Bierbeek trees were not root pruned in the RP treatment to evaluate the recovery of root pruning in 2007.

buds in 2008, which is probably the main reason why total yield is not lower in the deficit treatment despite a depressed Ψ_{soil}. Water stress seems to increase the amount of flower buds in pear tree but due to higher fruit load and lower water consumption, fruit size can be negatively affected (Marsal et al., 2002). In the rain fed plots, Ψ_{soil} decreased in all orchards to −150 kPa in 2009. In 15% of the years, during the last 50 years, rain deficit during summer was higher. In those conditions, irrigation in pear tree is necessary to obtain an optimal fruit yield and size. However there is large variation between the orchards, for example in Bierbeek irrigation was necessary every year. Even between the different plots within each orchard there was a large variation in Ψ_{soil} evolution. In Bierbeek and in Meensel, in the same irrigation treatment, there were differences of more than 50 kPa. This emphasizes the need for sufficient measurements in an orchard for irrigation scheduling. Irrigation scheduling solely based on evapotranspiration or rain deficit is not possible or should be done with crop models which are calibrated for the present conditions. It also underlines the importance of upcoming remote sensing techniques (Dzikiti et al., 2010; Suarez et al., 2010) where information on spatial variation in the orchard can be acquired.

The Watermark sensor showed good correlation with Ψ_{soil} determined through gravimetric sampling in combination with the WRC. Correlation improved when only days without irrigation were regarded which is probably related to the more heterogeneous water distribution in the soil after drip irrigation (Green and Clothier, 1999; Green et al., 2003). These observations support the conclusions by Leib et al. (2003) and Thompson et al. (2006) that the sensor is accurate enough for irrigation scheduling when multiple sensors are used.

A linear relationship between fruit size and Ψ_{soil} could only be found in Bierbeek in 2007. In Meensel 2009 a similar correlation was found between Ψ_{stem} and fruit size however no such relation was found between Ψ_{soil} and fruit size. Probably because a lower Ψ_{stem} value is better related to the decline in fruit size compared to Ψ_{soil} (Intrigliolo and Castel, 2006; Naor et al., 2006).

The negative linear relationship between Ψ_{stem} and fruit size in Meensel in 2009 and the lower Ψ_{stem} observations in Bierbeek in 2008 and in Meensel 2009 suggest that for pear tree the threshold of −1.5 MPa communicated by various authors in arid or semi-arid conditions (Marsal et al., 2000; Naor, 2001; O'Connell and Goodwin, 2007; Ramos et al., 1994) can be maintained in a temperate climate.

The relationship between Ψ_{stem}, Ψ_{soil} and ETo was described with a multiple linear regression with moderate correlation, showing the dependency of Ψ_{stem} on Ψ_{air} and Ψ_{soil} as stated in the cohesion–tension theory by Van den Hornert (1948). For all orchards Ψ_{stem} decreased with higher ETo values and decreased with lower Ψ_{soil} values. The correlation was strongest in Bierbeek, probably because the measurements were preformed in drier conditions where the Watermark sensor seems to be a better estimator for Ψ_{stem} (Intrigliolo and Castel, 2004).

4.2. Root pruning

The second objective of the study was to analyse the impact of root pruning on fruit yield and tree water status. Lower Ψ_{soil} and Ψ_{stem} values were observed for root pruned trees in dry conditions but it did not result in fruit yield decline. Only in one orchard (in Sint-Truiden) differentiation in fruit yield was observed.

Despite lower transpiration rates, lower stem water potential and leaf water potential readings frequently reported after root pruning (Marsal et al., 2008; Rodriguez-Gamir et al., 2010; Schupp et al., 1992), yield decline is not often observed on root pruned trees for apple (Schupp et al., 1992) and for pear (Asín et al., 2007). Yield analysis and Ψ_{stem} measurements in Bierbeek and Meensel support these observations. In dry conditions (in Bierbeek in 2007, 2008 and 2009, in Meensel in 2009 and in Sint-Truiden in 2009) there was clear differentiation in Ψ_{stem} and Ψ_{soil} but no differentiation in fruit size or yield. Root pruning decreases the soil volume from which the roots can extract water. This could lead to faster water depletion in dry conditions.

In Sint-Truiden in 2008 there was a yield decline in the root pruned treatment due to a lower fruit count, but in 2009 average yield was again higher in the root pruned treatment, although not significant due to large variation between the root pruned plots. Because in Sint-Truiden in 2008 no low Ψ_{soil} and Ψ_{stem} values where observed the differences cannot be addressed to water stress or increased root zone depletion. The total amount of fruits harvested and the number of flower buds indicate that root pruning induced a biannual bearing tendency in this orchard. Root regeneration following root pruning can influence the amount of cytokines in the xylem with consequences to fruit set (Webster et al., 2003). Also Mcartney and Belton (1992) and Asín et al. (2007) observed that return bloom was influenced by root pruning for respectively apple and pear. Remarkably the effect was only clearly visible in Sint-Truiden. Possibly other management techniques such as fruit thinning and pruning prohibit similar effects in Meensel and in Bierbeek.

5. Conclusion

Observations made in the present study indicate that irrigation is necessary in a temperate climate in order to consistently achieve maximal fruit size and yield. Fruit size was negatively influenced when Ψ_{soil} dropped to −100 kPa. A Ψ_{soil} of −60 kPa during shoot growth had no negative effect on fruit yield showing that the threshold for Ψ_{soil} is lower in less evaporative conditions compared to more arid conditions. The same observations show high variation in Ψ_{soil} between the orchards and between the different plots in an orchard which emphasizes the importance for irrigation scheduling on parcel level and the need for new techniques which reveal the spatial variation in the field. In contrast with the thresholds proposed for Ψ_{soil}, the thresholds proposed for Ψ_{stem} in more evaporative conditions can be maintained in a temperate climate.

Root pruning induced lower Ψ_{soil} and Ψ_{stem} values but the difference was not large enough to induce differences in yield or fruit size. However in one of the three orchards root pruning seemed to interfere in the flower bud formation and induced a biannual bearing tendency. More research is necessary to identify why this tendency was only observed in one orchard.

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