Plant-Soil-Water relations and implications for the management of irrigation and fertilization in 'Conference' pear orchards in a temperate climate

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Dankwoord

Juli 2006 startte ik als projectmedewerker bij de Bodemkundige Dienst van België vzw (BDB). Net na de proclamatie van de Bio-ingenieurs kreeg ik een telefoontje van Frank Elsen die me vertelde dat ik aan de slag mocht op de BDB. Ik werd ingeschakeld in de irrigatieadvisering voor land- en tuinbouwbedrijven of kort 'de Irrigatiesturing'. Simultaan werkte ik mee aan onderzoek rond irrigatie in de perenteelt. Ik wist het toen nog niet maar vanaf dat moment startte eigenlijk mijn doctoraatsonderzoek. Een jaar later vroeg Hilde Vandendriessche of ik geïnteresseerd was om een doctoraatsonderzoek te starten rond irrigatie. Op mijn vraag mocht ik dit onderzoek combineren met 'de Irrigatiesturing'. Ik beken dat ik op dat moment, en ook later nog, getwijfeld heb aan een goede afloop. Slechts dankzij de steun van velen kan ik vandaag trots mijn doctoraatsonderzoek voorstellen.

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Dank aan IWT-Vlaanderen om dit onderzoek mede te financieren. Het onderzoek ging van start tijdens het lopende IWT 050661 *'Basis voor het duurzaam watergebruik bij de irrigatie van de perenteelt'*. De meeste data werden verzameld tijdens dit onderzoek dat afliep in 2010. Dit onderzoek heeft dan ook rechtstreeks geleid tot dit doctoraat. Later ontstond dankzij het IWT-TD 095012 *'Introductie van duurzame irrigatie- en fertigatietoepassing in de perenteelt.'* en dankzij het IWT 090924 *'Remote sensing als instrument voor bodemvochtaansturing in peren- en appelboomgaarden: naar valorisatie van de ruimtelijke variatie'* de mogelijkheid om de projectresultaten, ten behoeve van de praktijk, nog verder te ontwikkelen. Zo ontstond o.a. PWARO een operationele irrigatie- en fertigatiedienstverlening voor de perenteelt en wordt in de toekomst mogelijk ook nieuwe technologie, zoals remote sensing, geïntegreerd in de aansturing van irrigatie en fertigatie op fruitteeltbedrijven.

Een vruchtbaar onderzoek is mijns inziens enkel mogelijk wanneer er naast het werk mensen zijn om plezier mee te maken, en lief en leed mee te delen. Dank aan alle vrienden om mij een leuke tijd te bezorgen naast het werk, op de voetbal, op de mountainbike of in een groot vierkant. Ma, Evelien, bedankt om mij steeds te steunen. Het treft ons zwaar dat onze Pa deze tekst nooit zal lezen. Ik kan alleen maar dankbaar zijn om de vader die hij was en hopen dat zijn waarden doorschemeren in dit onderzoek. Karolien, jouw aanwezigheid en liefde maakt voor mij het leven aangenamer en sinds kort geldt hetzelfde voor onze lieve dochter Norah! Bedankt!

Pieter
Heverlee, 19 november 2015

Abstract

Belgium and the Netherlands are the main production area for ‘Conference’ pear due to its temperate climate which suits ‘Conference’ pear. In 2012 total production in Belgium and the Netherlands accounted for 52% of total ‘Conference’ pear production. Since 2002 there was a sharp increase in ‘Conference’ pear acreage in Belgium and the Netherlands. Encouraged by a higher financial benefit for pear fruit, growers shifted from apple growing to pear growing. Intensive training systems, often combined with root pruning to control tree vigor, increases drought susceptibility of the tree and pushes fruit growers to the installation of irrigation systems. Drip irrigation is often combined with fertigation. Fertigation is a tool to simplify split application of fertilization which has been reported to enhance fertilization efficiency in various fruit crops. Among all nutrients N is most frequently dispensed using fertigation.

Main objective of the PhD was to reveal possible optimization of irrigation and fertigation practices in ‘Conference’ pear. Firstly the need for irrigation in pear trees (*Pyrus communis* L. cv. ‘Conference’) under low evaporative demand conditions was studied in three different orchards. The experiment showed 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 in contradiction to higher thresholds proposed in environments with a higher evaporative demand (Naor, 2001). Just as for arid environments (Marsal et al. 2000, 2002; Naor, 2001; O’Connel and Goodwin, 2007; Ramos et al., 2000), a Ψ_{stem} below -1.5 MPa was related to lower fruit yield in high fruit size classes. 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.

Secondly, in search of methodologies to schedule the irrigation, an approach to use a soil water balance model for irrigation scheduling in fruit orchards was developed. The algorithm permitted to calculate average soil water content in the root zone on a daily basis considering the specific preconditions in fruit orchards being drip irrigation and the interaction between tree root zone and grass strip between the tree rows. Another possibility of irrigation scheduling is the use of continuous plant based measurements. An experiment was set up to detect possible water stress in a pear tree orchard. Thermal dissipation probes were used to detect differences in sap flux density (J_p) between different irrigation treatments. Detection of J_p differences under low evaporative conditions was possible after applying moderate water stress. Next to the soil water balance and continuous plant based measurements soil moisture sensors or Ψ_{soil} sensors can be used to schedule irrigation. The Ψ_{soil} output of the ‘Watermark’ granular matrix sensor was compared to gravimetric moisture measurements and a reasonable correlation was observed between both. Only at high Ψ_{soil} values just after recent wetting events a discrepancy between sensor output and moisture measurement was observed.

To come to optimal installation guidelines for Watermark Ψ_{soil} sensors and other soil moisture sensors better insight in the water extraction pattern of 'Conference' pear tree is a requisite. The water extraction pattern of the 'Conference' pear trees was acquired by a calculation of Ψ_{soil} in three experimental plots with a numerical model. A reasonable accordance between calculated and measured Ψ_{soil} was observed with $R^2 = 0.56$ and RMSE = 13.4 kPa over 1320 observations. Furthermore the sensitivity of the calculation to the selected root distribution was shown.

In search for the optimal N fertigation three different fertigation doses were discussed. Fertigation with 25 to 50 kg N resulted in a 20 % higher fruit yield in two of the three orchards independently from the irrigation regime. N fertigation was related to fruit color in two of the three orchards. Leaf mineral N analysis after the fertigation event related to mineral N content in the fruit and to fruit color. Water stress was also observed to influence TSS however in one of the orchards. The relations between water satus, nitrogen status and fruit quality were elaboraed in a broader survey in 9 commercial orchards.

Overall the conclusions of the PhD contribute to a better understanding of the response of 'Conference' pear to altered irrigation and fertilization doses. This way irrigation and fertigation guidelines could be outlined. Furthermore insights in the calculation of water movement in the pear tree root zone and insights in methodologies for irrigation scheduling allow application of these guidelines in 'Conference' pear orchards.

Korte inhoud

De ‘Conference’ peer wordt hoofdzakelijk in België en Nederland geteeld. In 2012 bedroeg het aandeel in de totale Europese ‘Conference’ productie 52%. Het gematigde klimaat is uitermate geschikt voor deze variëteit. Sinds 2002 steeg het areaal ‘Conference’ aanzienlijk in België en Nederland. Vanwege de hogere rentabiliteit transformeerden fruittelers de appelboomgaarden naar perenboomgaarden. De boomgaarden worden dikwijls geplant in een korte plantafstand en gecombineerd met wortelsnoei, ter controle van de vegetatieve groei. Omdat dit de droogtegevoeligheid van de perenbomen verhoogt, wordt eveneens druppelirrigatie geïnstalleerd. Druppelirrigatie wordt dikwijls gecombineerd met fertigatie. Met behulp van fertigatie kan op een efficiënte manier gefractioneerde bemesting worden toegepast. Van alle minerale voedingstoffen die worden toegediend via fertigatie is stikstof (N) de meest frequente.

De belangrijkste doelstelling van dit doctoraat is het beschrijven van mogelijke optimalisatie van irrigatie en fertigatie in de ‘Conference’ peer. In een eerste experiment werd de irrigatiebehoefte van de peer (*Pyrus communis* L. cv. ‘Conference’) in het gematigde klimaat, met een lage vochtvraag, onderzocht en dit in drie verschillende boomgaarden. Het experiment toonde aan dat een vochtspanning (Ψ_{bodem}) van -60 kPa tijdens de scheutgroei geen negatief effect heeft op de opbrengst in tegenstelling tot observaties in een meer aried klimaat (Naor, 2001). Een drogere bodem, met een vochtspanning lager dan -60 kPa, werd wel gerelateerd aan productieterugval. Conform observaties in meer ariede klimaten (Marsal et al. 2000, 2002; Naor, 2001; O’Connel and Goodwin, 2007; Ramos et al., 2000) werd een stam water potentiaal (Ψ_{stam}) lager dan -1.5 MPa gerelateerd aan een lagere opbrengst in de hoogste diameterklassen. Daarnaast werden lagere Ψ_{bodem} en Ψ_{stam} geobserveerd in gewortelsnoeide bomen vergeleken met niet-gewortelsnoeide bomen hoewel hier geen productieterugval werd vastgesteld.

Vervolgens werden in het doctoraat methodes onderzocht om de eerder beschreven irrigatierichtlijnen te handhaven. Een bodemwaterbalansmodel werd aangepast om het vochtgehalte in de wortelzone op dagbasis te berekenen rekening houdend met de specifieke randvoorwaarden in een boomgaard; druppelbevloeiing en interactie tussen de wortelzone van de grasstrook en de wortelzone van de perenboom. Naast het aangepaste bodemwaterbalansmodel werd onderzocht in welke mate irrigatieaansturing in het gematigd klimaat mogelijk is met sensoren die de plantstatus monitoren op een continue basis. Er werd een experiment opgezet waarbij een verschil in sap flux dichtheid (J_p) werd geobserveerd in verschillende irrigatiebehandelingen, gebruik makende van temperatuur dissipatie sondes. Naast het aangepaste bodemwaterbalansmodel en de observatie van de plantstatus op continue basis, kunnen ook sensoren die Ψ_{bodem} observeren gebruikt worden voor irrigatieaansturing. Een redelijke correlatie werd geobserveerd tussen Ψ_{bodem} gemeten met

‘Watermark’ sensoren en gravimetrische bodemvochtmetingen, hoewel bij een natte bodem, net na een irrigatie, een discrepantie tussen vochtmeting en Ψ_{bodem} meting werd vastgesteld.

Voordat installatierichtlijnen voor Watermark Ψ_{bodem} sensoren en andere bodemvochtsensoren kunnen worden opgesteld is het noodzakelijk een betere inzicht te verwerven in het wateropnamepatroon van de perenboom. Het wateropnamepatroon werd vastgelegd door Ψ_{bodem} te berekenen in drie proefplots met een numerisch model. Een redelijke overeenkomst werd bekomen tussen de berekende en de gemeten Ψ_{bodem} over 1320 observaties met $R^2 = 0.56$, RMSE = 13.4 kPa. Daarnaast bleek de berekening van Ψ_{bodem} gevoelig aan de geselecteerde wortelverdeling.

Om de optimale N fertigatiedosis vast te leggen werden drie verschillende dosissen bestudeerd. Fertigatie met 25 tot 50 kg N resulteerde in een opbrengstverhoging van 20% in twee van de drie boomgaarden, onafhankelijk van het irrigatieregime. N fertigatie werd gerelateerd aan een meer groene vruchtkleur in twee van de drie boomgaarden. Minerale N inhoud in het blad werd gerelateerd aan minerale N inhoud in de vrucht en eveneens aan de kleur van de vrucht. Water stress bleek eveneens gecorreleerd met de hoeveelheid opgeloste stoffen in de vrucht. De relaties tussen water status, N status en vruchtkwaliteit werden verder onderzocht in 9 praktijkboomgaarden.

Over het algemeen dragen de conclusies van dit doctoraatsonderzoek bij tot een beter inzicht in de respons van de ‘Conference’ peer op irrigatie en fertigatie. Het was mogelijk om irrigatie- en fertigatierichtlijnen op te stellen. Daarnaast werd in het onderzoek een inzicht verworven in de wateropname van de perenboom en in methodes om de irrigatie aan te sturen.

List of abbreviations

A.L.-extract: Ammonium lactate extract
CI: Control Irrigation
DI: Deficit Irrigation
FDR: Frequency Domain Reflectometry
FI: Full Irrigation
NRP: Not Root Pruned
PI: Partial Irrigation
RAW: Readily Available Water
RLD: Root Length Density
RMSE: Root Mean Square Error.
RP: Root Pruned
RWD: Root Weight Density
SSB: Soil Service of Belgium
TAW: Total Available Water
TD: Thermal Dissipation
TDR: Time Domain Reflectometer
VPD: Vapour Pressure Deficit
WRC: Water Retention Characteristics

List of symbols

CR: Capillary Rise (mm d^{-1})

D_i: Soil water content in the root zone at day i (mm)

DP: Deep Percolation (mm)

E: Evaporation (mm d^{-1})

EC: Electrical Conductivity (dS m^{-1})

ET: Evapotranspiration (mm d^{-1})

ET_a: Actual Crop evapotranspiration (mm d^{-1})

ET_c: Crop evapotranspiration under excellent agronomic and soil water conditions (mm d^{-1})

ET_o: Reference evapotranspiration (mm d^{-1})

h: Hydraulic head (m)

I: Irrigation (mm d^{-1})

J_p: Sap Flux Density (m^3 m^{-2} s^{-1})

K: Hydraulic conductivity (m d^{-1})

$K_{c\ end}$: Crop coefficient during the end growing stage

$K_{c\ ini}$: Crop coefficient during the initial growing stage

$K_{c\ mid}$: Crop coefficient during the mid growing stage

K_c: Crop coefficient

K_{cb}: Basal crop coefficient

K_e: Evaporation coefficient

K_{sat}: Saturated Hydraulic Conductivity (m d^{-1})

q: upward constant flux between ground water table and root zone (m d^{-1})

R: Rainfall (mm d^{-1})

RH : Relative Humidity (%)

S: Sink term (d^{-1})

S_e: Effective water content

t: Time (d)

T: Transpiration (mm d^{-1})

T_p: Potential transpiration rate (mm d^{-1})

TSS: Total concentration of solids (°Brix)

u: Wind Speed (m s^{-1})

x: horizontal position

z: Vertical position (m)

$\alpha(h, x, z)$: Dimensionless water stress response function

α: Dimensionless parameter which indicates the surface fraction relevant for the tree root water uptake.

$\beta(x, z)$: Normalized root distribution function

θ: Volumetric water content

θ_r: Residual water content

Ψ_{soil}: Soil water potential (kPa)

Ψ_{stem}: Stem water potential (MPa)

Ψ_{xylem}: Xylem water potential (MPa)

Content

1 Introduction

1.1 Context of the research

1.1.1 Pear production in Europe, Belgium and the Netherlands

Pear (genus *Pyrus*) is one of the oldest temperate tree fruit crops, having been grown since antiquity from Europe to China. Pear production was approximately 25.2 MT worldwide in 2013 (http://faostat3.fao.org/). European pear (*Pyrus Communis*) covers about 10% of worldwide pear production. Average yearly pear production in Europe between 2004 and 2013 was 2.4 MT. Main production countries in Europe are Italy (0.82 MT), Spain (0.47 MT), Belgium (0.26 MT) and The Netherlands (0.25 MT). Main pear varieties in Italy are 'Abate Fetel' (0.29 MT), 'William' (0.18 MT) and 'Conference' Pear (0.11 MT). Main pear varieties in Spain are 'Conference' (0.18 MT) and 'Blanquilla' (0.10 MT). In Belgium and The Netherlands 'Conference' pear is the dominating variety (0.23 MT and 0.20 MT respectively). 'Conference' pear accounts for 34 % of total pear production in Europe (Fig. 1.1). Belgium and the Netherlands are the main production area, representing 53 % of 'Conference' pear production in Europe between 2004 and 2013 (WAPA, prognosfruit 2014). Between 2009 and 2014, 16 % of the total European production was exported outside the European Union (EU) mainly to Russia (60 % of the total export volume) (Schwartau, Prognosfruit 2014). In September 2014 an import embargo was set by Russia for European agricultural products. This led to an oversupply of 'Conference' pears in the autumn of 2014 accompanied with a severe price descent. In 2015 Belgian 'Conference' pear export to Russia was replaced by a 'Conference' pear export to other markets such as Germany and Eastern-European countries. Also new Asian and North-American markets were exploited which led to pricing similar to 2013 and before.

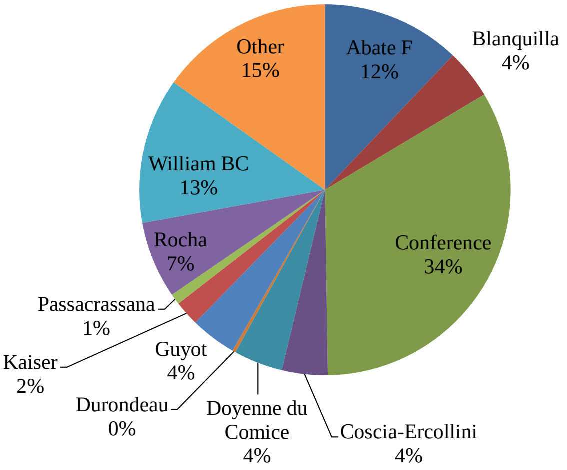


Fig. 1.1 Distribution of European pear (Pyrus Communis), average yield (kT) between 2004-2013. Adapted from WAPA Prognosfruit (2013).

Belgium and the Netherlands are the main production area for ‘Conference’ pear due to its temperate climate which suits ‘Conference’ pear. The ‘Conference’ pear tree is grown on Quince Adams and Quince C rootstock. Quince rootstock is susceptible to frost damage when temperature decreases below -25 °C which hinders ‘Conference’ establishment in continental environments. In warmer mediterranean environments problems of sunburn and malformation of the fruit are reported (Deckers and Schoofs, 2008).

Belgium and the Netherlands are situated in the northern hemisphere. In this region the climate is dominated by the seasonal variation in sunshine and the proximity of the Atlantic Ocean. In pear trees full bloom takes place mid-April, during spring, followed by a period of intensive cell multiplication until the end of May. June and July, the beginning of summer, are characterized by a period of extensive shoot growth. In August fruits increase in size due to cell elongation in the fruit tissue which continues until the harvest at the end of August or the beginning of September. Average potential reference evapotranspiration (ET_o) during the growing season is only slightly higher than average rainfall (Fig. 1.2).

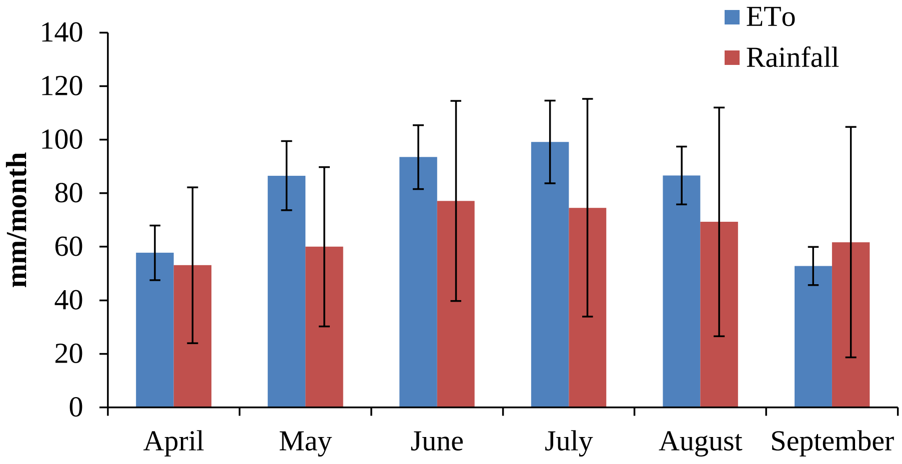


Fig. 1.2 Reference evapotranspiration (ET_o)(Allen et al. *1998) and rainfall during the growing season of ‘Conference’ pear in Belgium averaged for the period 1959-2015, observations obtained in the center of Belgium (Melsbroek). Bars indicate standard deviation.*

Since 2002 there was a sharp increase in ‘Conference’ pear acreage in Belgium and the Netherlands (Fig. 1.3). Encouraged by a higher financial benefit for pear fruit, growers shifted from apple growing to pear growing (Demeyer et al. 2012). In Belgium the majority of the orchards are situated in the central and the eastern part of Belgium (provinces of Vlaams-Brabant and Limburg) while a minor production region is concentrated in the north western part (province of Oost-Vlaanderen). In the Netherlands the orchards are concentrated in the southwest (province of Zeeland) and the center (provinces of Gelderland and Utrecht). The majority of the orchards is situated on moderate to heavy textured soils (loam, silt loam, silt). In 2012 in Belgium ‘Conference’ accounted for 87% of the total pear acreage (http://statbel.fgov.be/), in the Netherlands ‘Conference’ accounted for 75% of the total pear acreage (http://statline.cbs.nl/).

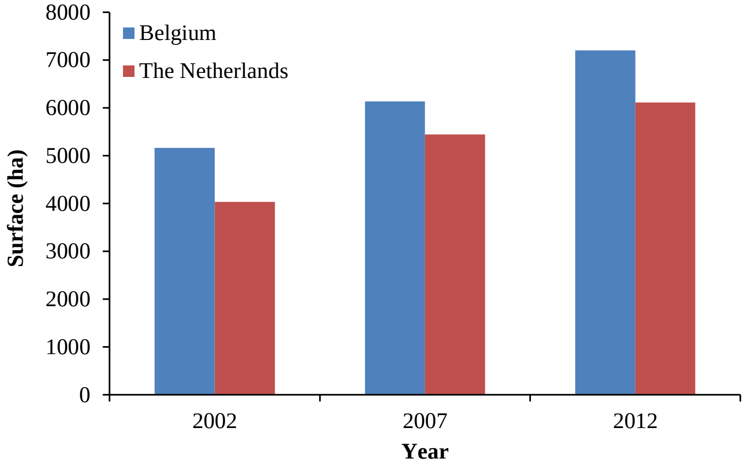


Fig. 1.3 Evolution of ‘Conference’ pear orchards in Belgium and the Netherlands (adapted from *http://statline.cbs.nl/ and http://statbel.fgov.be/)*

1.1.2 Intensive training systems and the introduction of root pruning

The scarcity in arable land in Belgium and the Netherlands pushes fruit growers to intensive training systems. Tree density varies between 1600 and 3300 trees/ha. The planting systems most commonly used are the ‘V-system’ planted on rootstock Quince C, and the ‘free spindle’ system and the ‘Tiense hedge’ planted on rootstock Quince Adams.

Quince C and Quince Adams rootstock have been observed to be less vigorous than other rootstocks used world-wide such as for example OHxF333 and OHF69 used in the USA. On the other hand fruit size was observed to be higher for Quince C and Quince Adams. Quince C was observed to be slightly less vigorous than Quince Adams, yield and fruit size was equal (Iglesias et al., 2004).

In the ‘V-system’, four equally developed branches are chosen and kept as fruiting branches (Fig. 1.4a). These branches can be considered as four central leaders on one stem. Planting distance of the trees is 3.5 x 1.25 m which can be reduced to 3.5 x 1 m for more intensive ‘V systems’. Orchards planted in a ‘V system’ are generally more productive but the planting and labor cost are higher. In the ‘free spindle’ the number of laterals is limited to two branches in the direction of the row (Fig. 1.4b). The planting distance used for the ‘free spindle’ systems is 3.5 x 1.5 m. Labor cost of the free spindle system is lower but also productivity is lower (Deckers and Schoofs, 2001; Vercammen, 2005). Next to the V-system and the free spindle system a number of variations exist which are related to both planting systems. For example in the ‘Tiense hedge’ two branches are attached on a wire along with the row. The two other branches are then placed perpendicular to the row direction. Planting distance in the ‘Tiense hedge’ system is often 3.5 x 1.75 m.

Fig. 1.4 Orchard planted in a V-system in Bierbeek (a) and a free spindle system in Sint-Truiden (b).

The intensive training systems in the pear fruit orchards increase competition for light between the trees. Vegetative growth control in a ‘Conference’ pear orchard is a necessity for a balanced fruit set and regular fruit yield (Deckers and Daemen, 2000). Before 1998 the growth regulator Chloormequat-chloride (CCC) was used to stop vegetative growth and to initiate flower bud formation. However since 1998 CCC is prohibited in Belgium and the Netherlands and root pruning was introduced as a management technique to control tree vigor. Root pruning is carried out with a straight or curved knife at approximately 30 to 40 cm from the trunk. Root pruning can be carried out one sided or two sided. Root pruning is carried out at the end of winter (beginning of March), at least one month before bloom (Vercammen et al., 2005). It 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 can be expected that it makes the trees more sensitive to water stress. Irrigation is a recommended countermeasure to prevent yield decline during dry summers (Maas, 2007). Besides irrigation also adapted fertilization is recommended (Vercammen et al., 2005).

1.1.3 Increasing interest in irrigation

Intensive training systems, often combined with root pruning to control tree vigor, increases drought susceptibility of the tree and pushes fruit growers to the installation of irrigation systems. Moreover financial benefit of higher fruit classes has been substantially higher the past decade (Fig. 1.5).

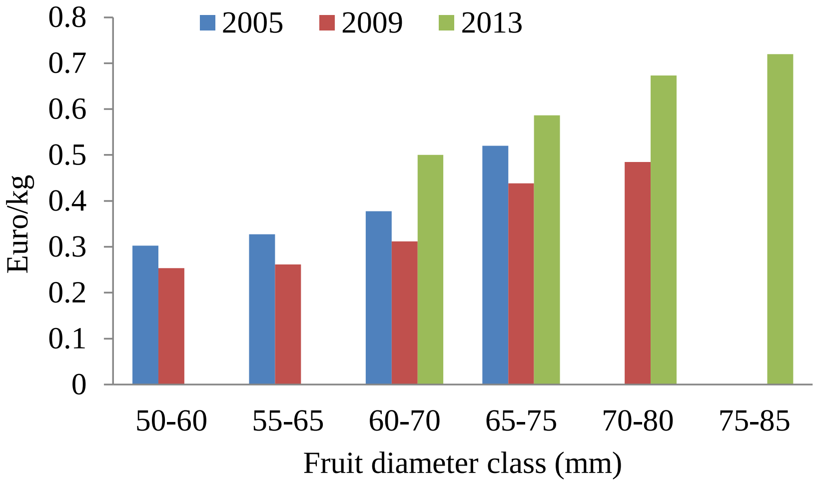


Fig. 1.5 Average market price in September 2005, 2009 and 2013 for 'Conference' pear in Belgium for different fruit size classes (adapted from Boer en Tuinder).

There are no systematic figures that outline the irrigated area and water use in pear orchards in Belgium and the Netherlands. An inquiry in 2009 with 300 fruit growers indicated that 20% of the fruit growers has implemented irrigation in some of their orchards (Tessa De Baets, pcfruit research station, personal communication). In 2013 there were 958 pear fruit growers in Belgium and 1510 pear fruit growers in the Netherlands (http://statline.cbs.nl/ and http://statbel.fgov.be/). Average pear production area per fruit grower was 7.5 ha in Belgium and 4 ha in the Netherlands. Assuming that 20% of the fruit growers applies irrigation on half of the production area, this would imply a total irrigated area of 718 ha in Belgium and 604 ha in the Netherlands. Assuming an average irrigation dose of 100 mm/year in these orchards, which is about the average yearly rain deficit from mid-April until the end of August, this would result in an average yearly water use of 718 000 m^3 in Belgium and 604 000 m^3 in the Netherlands.

Irrigation drippers are used to supply irrigation water in the orchards. The drip line is situated in a weed free strip beneath the tree canopy (Fig. 1.6). The drip line consists of a PE Polyethylene tube with emitters (drippers) every 20 to 50 cm. Dripper discharge varies between 1 to 2 l/h. Drip lines can be managed automatically using electric valves connected to an operating system.

Fig. 1.6 Irrigation drippers in the weed free strip beneath the tree canopy.

Drip irrigation has the advantage that a higher irrigation efficiency is achieved compared to sprinkler irrigation (Bernstein and Francois, 1973; Bowen et al., 2012; Sezen et al., 2011). Water is applied close to plants so that only part of the soil in which the roots grow is wetted. Water is distributed using low pressure (1-2 bar) which implies a lower energy requirement. Labor cost to start up the drip irrigation system is limited. Drip tubes have a lifespan up to 20 years which justifies the installation cost. Water is mostly pumped from aquifers ranging from 10 to 100 m depth depending of the local geology. Water quality is good, with a low salinity, lower than 1 dS/m excluding any salinity risk (Ayers and Westcot, 1988). Also soil salinity is not an issue in fruit orchards in Belgium and the Netherlands.

1.1.4 Drip irrigation permits fertigation

Drip irrigation is often combined with fertigation. Fertigation is the injection of fertilizers through the irrigation system. Fertigation is a tool to simplify split application of fertilization which has been reported to enhance fertilization efficiency in various fruit crops (Sanchez et al., 2003; Yin et al., 2009). Nitrogen (N), potassium (K) phosphorous (P), calcium (Ca) and magnesium (Mg) are the main nutrients applied in fruit orchards. Nitrogen is important in organic compounds found in leaves, fruits, spurs and roots. Nitrogen content in the tree organs influences vegetative growth, flower initiation, fruit set, fruit growth, fruit maturation and flower bud formation (Quast, 1986; Quartieri et al. 2002; Liu et al., 2013; Sanchez, 2002). Potassium is important in plant physiological processes such as photosynthesis, respiration, and maintenance of turgor potential (Bergmann, 1993; Feucht, 1982; Marschner, 1986; Soing et al., 1999). Excessive potassium availability, can however inhibit calcium uptake and calcium is essential for the cell structure (Tromp et al., 1976). Phosphorus is a key compound for the plant DNA and is a key element in the energy production in plants. Phosphorus deficits hinder root growth and tree vigor (Quast 1986). Magnesium is important in the plant photosynthesis. Magnesium deficit is visible by discoloration of the leaves. An excess of Mg concentration in the soil can lead to disturbed Ca uptake (Quast 1986).

In order to interpret the N, P, K and Mg status of the soil, the Soil Service of Belgium (SSB) relies on soil fertility classes for the different soil fertility variables related to the agricultural standards of optimal plant growth. The agricultural standards provide a clear and interpretable reference. The soil fertility classes are based on extensive field research combined with 65 years of experience in the agricultural and horticultural sector. The knowledge gathered from long- and short-term field trials is integrated in response and surplus functions, which are in turn integrated in BEMEX, a fertilizer expert system (Vandendriessche et al., 1996). In the optimal zone (Table 1.1), most plants will show an optimal growth, provided that rational fertilization and liming is applied. The optimal zone is not only an agronomic optimum (optimal plant growth), but is also an environmental optimum since it corresponds to a minimal amount of nutrient leaching (Elsen et al., 2010). The optimal zone for K and Mg differs in function of the soil texture since silt and silt loam soils have a higher cation exchange capacity than sandy soils. Phosphorous (P) is taken up under the form of orthophosphates $H_2PO_4^-$ and HPO_4^{-2} which are anions so for P there is no distinction in soil texture for the soil fertility classes.

Table 1.1 Optimal zone and soil fertility classes used by SSB for evaluating mineral status of the soil of agricultural land. (Maes et al. 2012). Particle distribution of Sand, Silt and Loam are defined as by USDA classification. K, Mg, P measured in ammonium lactate extract (A.L.-extract).

Soil fertility class	mg K/100 g dry soil		mg Mg/100 g dry soil		mg P/100 g dry soil
	Sand	Silt, Loam	Sand	Silt, Loam	All soil textures
very low	<5	<6	<3	<4	<5
Low	5-8	6-10	3-4	4-5	5-8
rather low	9-11	11-13	5-6	6-8	9-11
optimal zone	12-18	14-20	7-10	9-14	12-18
rather high	19-30	21-35	11-15	15-18	19-30
high	31-50	36-60	16-25	19-30	31-50
very high	>50	>60	>25	>30	>50

For K, Mg, and P SSB publishes statistics based soil analysis preformed on the soil layer 0-23 cm (Maes et al. 2012). In the majority of the orchards P, K and Mg content is optimal to high (Table 1.2). This suggest that P, K and Mg concentration in the soil is rarely limiting for optimal crop development. Fertilization recommendations for P, K and Mg by SSB in ‘Conference’ pear are rather low.

Table 1.2 Distribution (%) of nutrient status (P, K, Mg) in all orchards sampled and analyzed by SSB between 01/09/2007 and 31/08/2011 in the soil layer 0-23 cm derived from (Maes et al. 2012). Particle distribution of Sand, Silt and Loam are defined as by USDA classification.

	sandy soils (550 orchards)			loamy soils (1818 orchards)			silt soils (1350 orchards)		
	P	K	Mg	P	K	Mg	P	K	Mg
very low	0.0	0.0	0.0	0.6	0.0	0.1	0.2	0.0	0.0
low	1.3	2.5	0.9	2.4	1.1	0.8	1.9	0.3	0.0
rather low	1.5	3.6	5.1	4.9	3.2	8.1	4.6	1.8	3.9
Optimal	9.6	20.8	31.2	23.7	14.4	43.0	26.6	11.4	32.6
rather high	38.5	48.4	24.5	48.7	48.3	23.0	50.7	48.4	28.9
High	42.4	23.6	27.8	18.1	31.5	21.5	15.0	34.5	29.1
very high	6.7	1.1	10.5	1.6	1.5	3.5	1.0	3.6	5.5

For N no optimal zone is defined. The majority of N is taken up in the mineral form as NO_3^--N. Besides crop uptake, NO_3^--N concentration in the soil is dependent on mineralization, leaching and denitrification. These dynamic processes are controlled by rainfall excess and temperature. N content in an orchard will fluctuate more throughout the years compared to the other soil nutrients. During winter NO_3^--N leaches out of the soil profile after periods of rainfall excess. Therefore N-fertilization is recommended yearly in pear orchards.

Among all nutrients N is most frequently dispensed using fertigation. Fertigation has the advantage that efficient fertilization is possible in dry periods, during summer. Split N fertilization through the fertigation system should allow optimal fruit size and fruit quality (Duarte et al. 2008, Yin et al. 2009). Phosphorus (P) is rarely dispensed using fertigation because P is mainly fertilized just after winter when the soil moisture content is close to field capacity when irrigation is not yet initiated. Potassium (K) and magnesium (Mg) are occasionally dispensed using fertigation during summer, however fertilization doses are rather low to prevent possible competition with Ca uptake.

1.2 Water movement in the soil-plant-atmosphere continuum: General concepts

1.2.1 Plant water uptake

Water uptake is crucial for plant physiological processes. The uptake of nitrogen and other plant nutrients is for a large part driven by water uptake. Water is required for the photosynthesis, preservation of plant turgor and temperature control of the plant so that the required biochemical processes can proceed. Water uptake in plants is mainly a passive process driven by potential differences between the atmosphere and the soil. Water flows along a gradient of decreasing water potential (Fig. 1.7). The movement of water through plants can be represented by Ohm's law analogy, i.e., current equals driving force (the electrical potential gradient) divided by electrical resistance. Thus, water flow is more clearly understood if it is considered as being driven by a difference in water potential, against a resistance (Blum 2011).

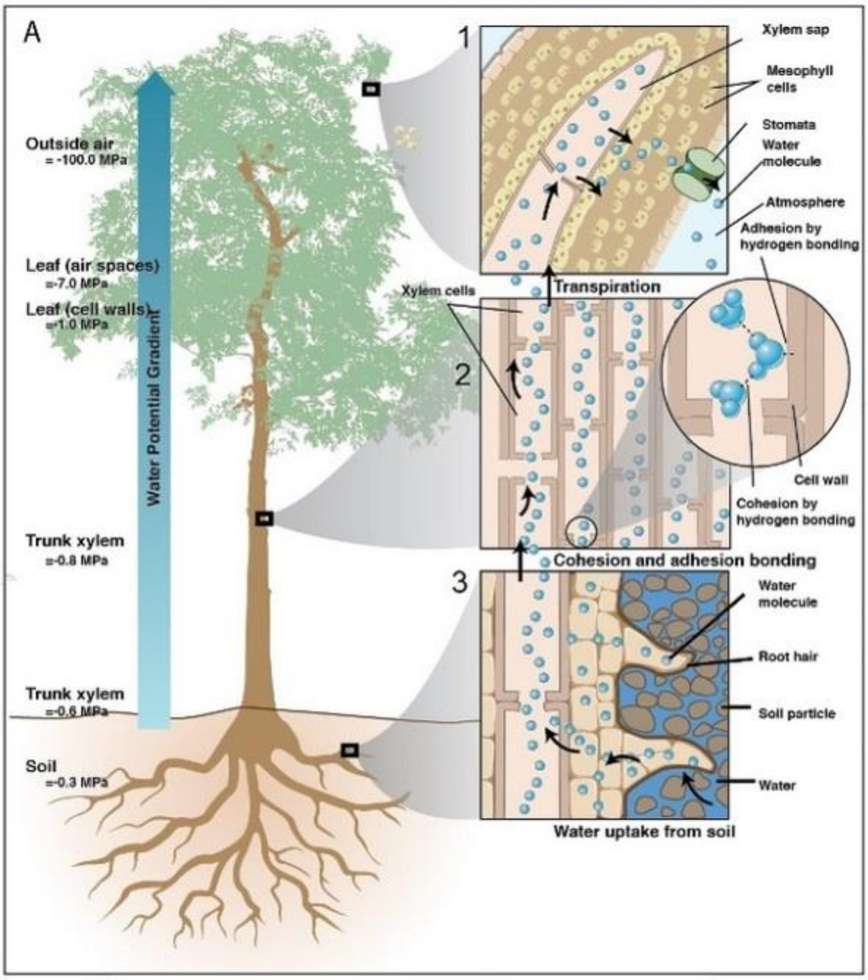


Fig. 1.7 Representation of the water transport pathways along the soil-plant-atmosphere continuum (McElrone et al. 2003).

The vaporization of water from plant tissues to the atmosphere predominately through the plants stomata is called transpiration (T). The vaporization mainly occurs in the leaves. In the water budget of the-soil-plant atmosphere-continuum transpiration is regarded in combination with evaporation (E). Evaporation is the process whereby liquid water is converted to water vapor (vaporization) and removed from the evaporating surface (vapor removal). Water evaporates from a variety of surfaces, such as lakes, rivers, pavements, soils and wet vegetation. Evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes. Apart from the water availability in the topsoil, the evaporation from a cropped soil is mainly determined by the fraction of the solar radiation reaching the soil surface. This fraction decreases over the growing period as the crop develops and the crop canopy shades more and more of the ground area. Evaporation and transpiration are therefore combined as evapotranspiration (ET). Maximal ET or PET (potential evapotranspiration) was first calculated by Penman (1948) who tried to calculate pan evaporation. The estimation of pan evaporation evolved to the calculation of ET for a reference crop (e.g. Makking, 1957; Makking and Van Heemst, 1967) and to the spread of the universal Penman-Monteith equation to calculate ET_o, i.e., the ET of grass as reference crop. Allen et al. (1998) suggested a universal approach to derive ET from various crops (ET_c) from ET_o using crop specific 'K_c' values. The effects of both crop transpiration and soil evaporation are integrated into a single crop dimensionless coefficient 'K_c'.

$$ET_c = K_c\, ET_o \tag{1.1}$$

For describing crop evapotranspiration throughout the season distinction is made between four transpiration stages based on three K_c values, $K_{c\ ini}$, $K_{c\ mid}$ and $K_{c\ end}$ (Fig. 1.8):

1. Initial stage with $K_{c\ ini}$

$$ET_c = K_{c\ ini}\, ET_o \tag{1.2}$$

2. Crop development stage when K_c ranges between $K_{c\ ini}$ and $K_{c\ mid}$. Development stage starts from 10% soil cover and lasts to maximum soil cover. According to Allen et al. (1998) the crop development stage would last 70 days for deciduous orchard. For 'Conference' pear in Belgium and the Netherlands this corresponds to the period between bloom, at the beginning of April, followed by a period of intensive cell division in May up to the shoot growing period which starts in June.

$$ET_c = K_c\, ET_o \quad \text{with:} \tag{1.3}$$

$$K_c = K_{c\ ini} + \left(\frac{K_{c\ mid} - K_{c\ ini}}{\text{Day of maximum soil cover} - \text{Day of bloom}}\right) . \text{Day since bloom} \tag{1.4}$$

3. Mid-season stage with $K_{c\ mid}$ starting from maximum soil cover up to the start leaf senescence. According to Allen et al. (1998) this period would last 90 days. For ‘Conference’ pear in Belgium and the Netherlands this includes partly the period of shoot growth in the month of June and July, the period of fruit tissue cell elongation in the month of August, ending two to three weeks after harvest which is at the end of August or the beginning of September.

$$ET_c = K_{c\ mid}\, ET_o \tag{1.5}$$

4. Late season stage when K_c ranges between $K_{c\ mid}$ and $K_{c\ end}$: from the start of leaf senescence to the end of leaf senescence. According to Allen et al. (1998) this would start by the end of September and end by the end of October.

$$ET_c = K_c\ ET_o \text{ With:} \tag{1.6}$$

$$K_c = K_{c\ mid} - \left(\frac{K_{c\ mid} - K_{c\ end}}{\text{Day of maximum soil cover} - \text{Day of full leaf senescence}}\right).\text{Day since harvest} \tag{1.7}$$

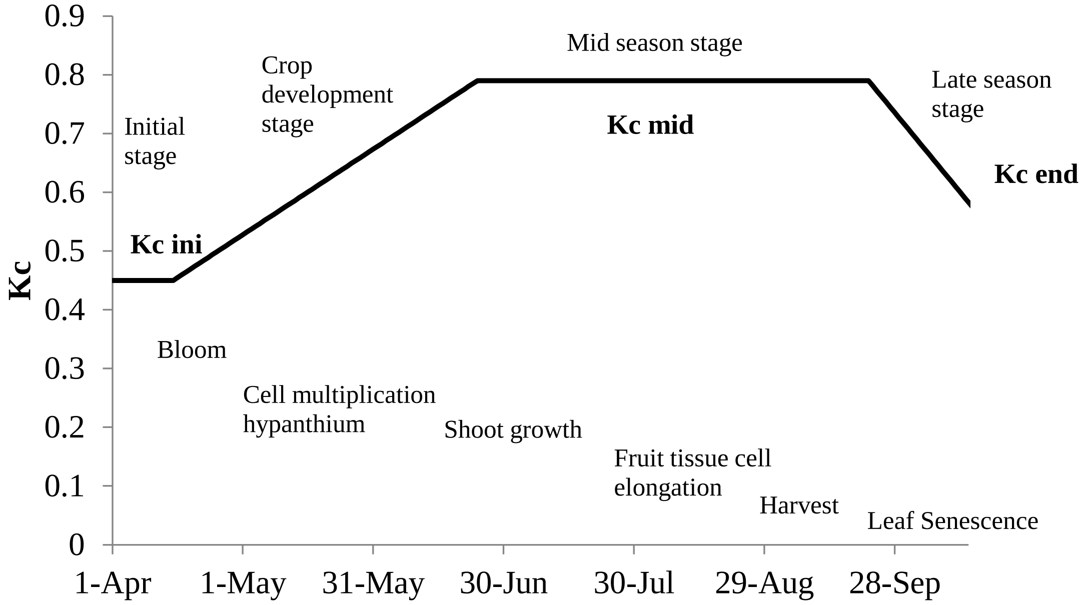


Fig. 1.8 Crop coefficient (K_c) values in function of the growing season of ‘Conference’ pear tree in Belgium and the Netherlands. Adapted from Allen et al. (1998).

For pear tree, lower than 4 m, Allen et. al (1998), Doorenbos and Pruit (1977) and Doorenbos and Kassam (1976) tabulated K_c values (Table 1.3).

Table 1.3 K_c values for pear listed by Allen et al (1998) divided in $K_{c\ ini}$, during initial stage up, $K_{c\ mid}$ during full cover and $K_{c\ end}$ at the end of the growing season.

	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$
No ground cover, killing frost	0.45	0.95	0.7
No ground cover, no frosts	0.60	0.95	0.75
Active ground cover, killing frost	0.50	1.20	0.95
Active ground cover, no frosts	0.80	1.20	0.85

Distinction is made between pear trees above bare soil and trees above ground cover and the occurrence of killing frost. In Belgium and the Netherlands a weed free strip is present beneath the canopy. The weed free strip is 1 m wide. Between tree rows a grass strip 2 to 3 m wide is present, which can be seen as a cover crop. The grass strip has also a significant share in the total water budget in the orchard. However in relation to water management in the orchard with as goal optimal fruit production, the grass strip may be less relevant. Allen et al. (1998) also proposed a dual K_c approach to separate the transpiration component from the evaporation component using a basal crop coefficient K_{cb}.

$$ET_c = (K_{cb} + K_e)\ ET_o \quad (1.8)$$

With K_{cb} the basal crop coefficient and K_e a coefficient related to soil evaporation.

Table 1.4 K_{cb} values for pear listed by Allen et al. (1998).

	$K_{cb\ ini}$	$K_{cb\ mid}$	$K_{cb\ end}$
No ground cover, killing frost	0.35	0.90	0.65
No ground cover, no frosts	0.50	0.90	0.70
Active ground cover, killing frost	0.45	1.15	0.90
Active ground cover, no frosts	0.75	1.15	0.80

The tabulated K_c and K_{cb} values by Allen et al. (1998) refer to a sub-humid climate with an average daytime minimum relative humidity of about 45% and with calm to moderate wind speeds averaging 2 m/s. For other conditions $K_{c\ mid}$ and $K_{c\ end}$ need to be corrected:

$$K_c = K_{c\ table} + [0.04(u_2 - 2) - 0.004\ (RH_{min} - 45)]\left(\frac{h}{3}\right)^{0.3} \quad (1.9)$$

With $K_{c\ table}$: the K_c tabulated in Table 1.4, u: wind speed (m/s), RH_{min} minimal relative humidity (%), h tree height (m). Applying this equation for Belgian conditions (RH_{mid} = 78, RH_{end} = 82 u_{mid} m/s=2.14, u_{end}=2.45 m/s) this would decrease $K_{cb\ mid}$ (no ground cover, killing frost) to 0.79 and $K_{cb\ end}$ to 0.52.

This $K_{cb\ mid}$ is similar to the $K_{c\ mid}$ varying between 0.71 and 0.99 observed between 2002 and 2006 in a 'Conference' orchard planted in 1999, by Girona et al. (2010) in a large lysimeter in Spain (Fig. 1.9). Individual orchard K_c varies between the years and is considered to be dependent form the canopy form and dimensions but according to Girona et al. (2010) also could be the season variation in vapour pressure deficit (VPD). Pears are hypothesized to have slower reacting stomata than grass, which is the reference crop for the calculation of ET_o, so that pear transpiration continuous at a higher rate at a higher VPD.

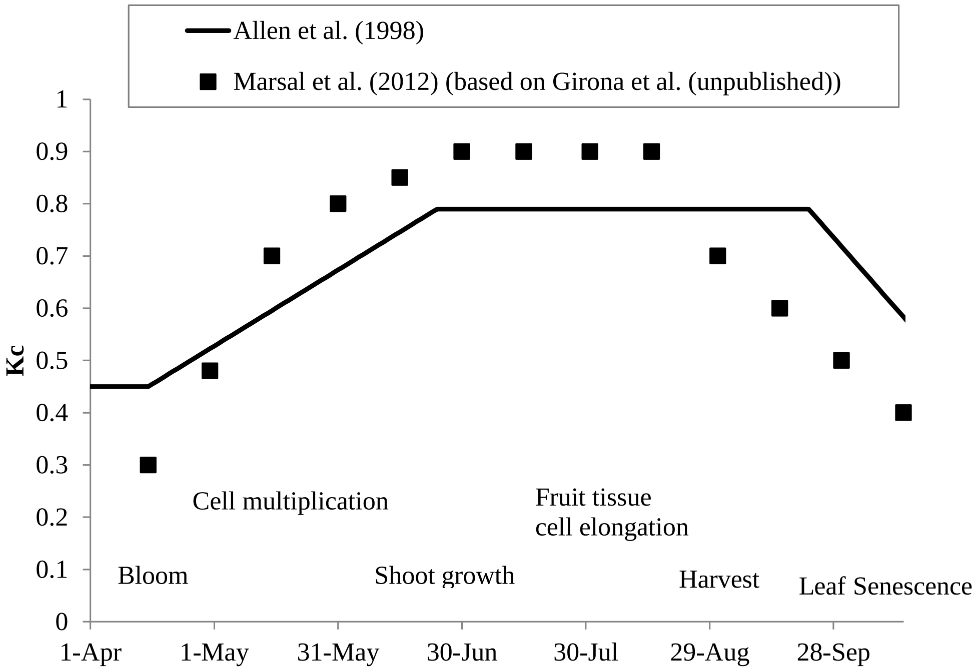


Fig. 1.9 Crop coefficient (K_c) values in function of the growing season of 'Conference' pear tree in Belgium and the Netherlands. Adapted from Allen et al. (1998) and adapted from Marsal et al. (2012) assuming the growing season starts and ends two weeks later than in Spain.

1.2.2 Plant available water in the soil

The amount of plant available water in the soil depends on the dimensions of the root zone, the available water content in the soil and the presence of an upward flux of water coming from a ground water table, or deeper soil layers (capillary rise).

Rogers (1939) already pointed out that root growth of apple is closely related to water content and temperature. Root growth can therefore be considered as site specific. Besides water availability also soil compaction in the deeper soil layers or shallow ground water tables may hinder root development. Root zone depths reported by FAO for apples, cherries, pears vary from 100 to 200 cm (Allen et. al., 1998; Doorenbos and Kassam 1986). Recent studies reported maximal rooting depth of 150 cm (Yao et al. 2011) for pear and 100 cm for apple (Besharat et al,. 2010; Gong et al., 2006). Feyen (1971) observed 80 cm as maximal rooting depth in Belgian apple orchards.

The fraction crop-available water in the soil can be derived from the hydraulic properties of the soil; in essence field capacity and wilting point. Field capacity is the amount of water that a well-drained soil should hold against gravitational forces, or the amount of water remaining when downward drainage has markedly decreased. As water uptake progresses, the remaining water is held to the soil particles with greater force, lowering its potential energy and making it more difficult for the plant to extract it. Eventually, a point is reached where the crop can no longer extract the remaining water. The water uptake becomes zero when wilting point is reached. Wilting point is the water content resulting in permanent wilting (Allen et al. 1998). The relationship between the potential energy in the soil and the corresponding water content can be presented through a water retention curve initially suggested by Buckingham (1907) for six different soil textures. Wilting point is mostly assumed at water content at pressure head -16000 cm or pF 4.2 (Richards, 1931; Veihmeyer and Henderson, 1928). Field capacity is generally suggested at pF 2.5, however lower values (pF 1.7- pF 2) have been suggested by various authors worldwide (Nemes et al., 2010). After 25 years of soil water balance modeling on Belgian parcels planted with various crops Frank Elsen (Frank Elsen, SSB, personal communication) concluded that pF 1.8 to pF 2 is a better assumption for field capacity in the upper soil layer (0-30 cm). In Belgium and the Netherlands pear tree is grown mainly on loam, silt loam or silt. Typical Total Available Water (TAW) [mm] content between pF 2 and pF 4.2 ranges about 25% of the root zone depth however important site specific variations may occur (Fig. 1.10).

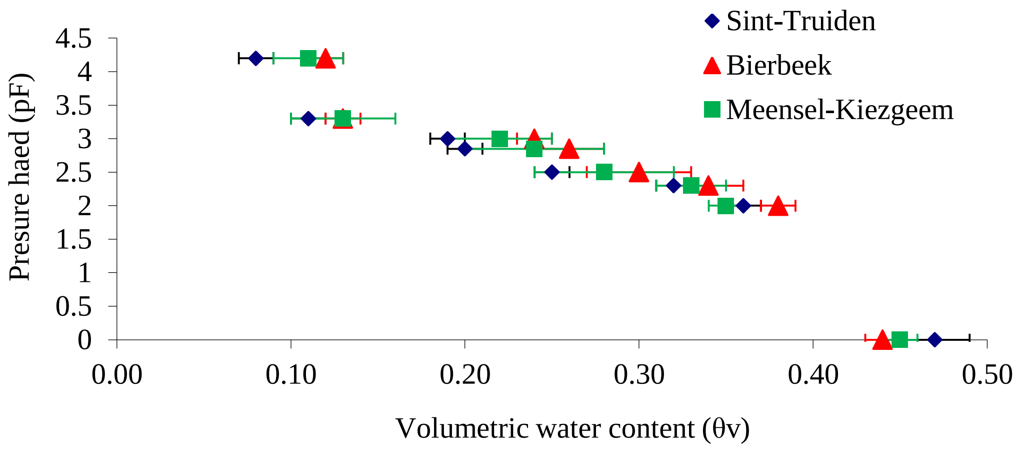


Fig. 1.10 Typical water retention characteristics observed in the soil layer 0-30 cm in fruit orchards in Sint-Truiden, Bierbeek and Meensel. Graph show average of eight different locations in the orchards, bars indicate standard deviation. Experimental observation described in chapter 2, 3, 4, 5 and 6 were assembled in the same orchards.

When root zone depth is assumed 1000 mm and TAW is 25%, the pear tree has 250 mm available for water consumption before wilting. The tree may however also benefit from the presence of an upward flux of water coming from a ground water table, or deeper soil layers. This water movement in the unsaturated zone can be considered as steady state flow mathematically described with Darcy's law (Richards, 1931):

$$q = -K(h) \left(\frac{\partial h}{\partial z}\right) \tag{1.10}$$

With q the upward constant flux between ground water table and root zone (m d^{-1}), h (m) is hydraulic head, t is the time, z is the vertical position, K (m d^{-1}) is the hydraulic conductivity. An estimation of the theoretical upward flux can be calculated using UPFLOW (Raes and Deproost, 2003), which is a software program which calculates the upward flux using an approach proposed by De Laat (1980). Calculation of the capillary rise with UPFLOW using the water retention curves depicted in Fig. 1.10 and assuming a saturated hydraulic conductivity of 0.06 m/day, indicates that capillary rise can contribute 1 mm/day to the root zone when a shallow ground water table is present 1.6 m below soil surface. In Belgium in nearly all soil profiles where pear trees are grown, well drained silt and loamy textured soils, spots of rust are found to soil depths closer than 1.6 m to the soil surface (Bayens 1958; Bayens and Scheys, 1958; Snacken 1964). This indicates the occasional presence of water stagnation and thus capillary rise.

1.2.3 Plant water stress

In absence conditions water uptake of the plant occurs at the maximal rate (ET_c). With continuing plant water uptake, in the absence of irrigation or rainfall, soil water potential (Ψ_{soil}) decreases. By decreasing Ψ_{soil}, the water potential in the plant xylem (Ψ_{xylem}) decreases to a lower value to permit water flow from soil to plant. Due to osmotic adjustment cell turgor remains constant despite decreasing Ψ_{xylem}. At a certain critical potential (Ψ_{crit}) in soil and xylem, osmotic adjustment is no longer sufficient to maintain cell turgor which starts to decrease. Under a high evaporative demand ($ET_{o\ high}$) Ψ_{crit} in the soil is higher compared to low evaporative demand ($ET_{o\ low}$) (Fig. 1.11) (Doorenbos and Kassam, 1986).

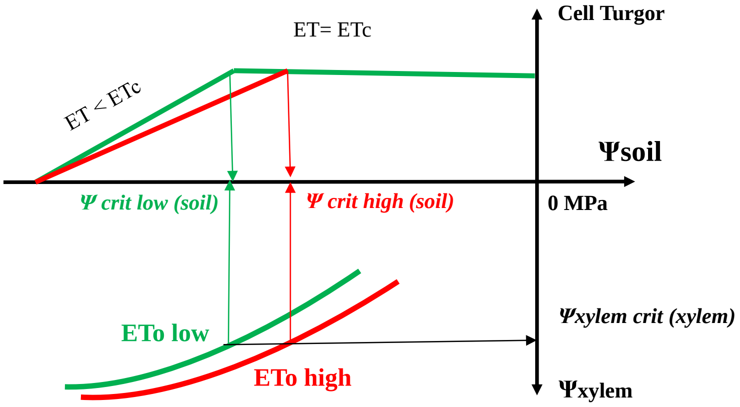


Fig. 1.11 Synthesis of potential in the pear tree under varying atmospheric conditions. (Adapted from Elsen, 2014) with Ψ_{crit}: the critical potential in soil and xylem where cell turgor declines. In the soil Ψ_{crit} differs in relation to the evaporative conditions ($ET_{o\ high}$ or $ET_{o\ low}$).

In a first stage cell expansion and cell-wall synthesis in fast growing tissues are affected after water deficits. In a second stage stomatal conductance is affected which influences photosynthesis and plant transpiration (Hsiao, 1973; Sadras and Milroy, 1996). After stomatal closure plant transpiration is affected ($ET < ET_c$) (Hsiao, 1973) which can be related to yield decline (Allen et al., 1998). The soil water available between field capacity and Ψ_{crit} in the soil is considered as the Readily Available Water content (RAW). To prevent Ψ_{soil} decrease below Ψ_{crit} in a water limiting environment water can be supplied using irrigation, this way actual evapotranspiratoin (ET_a) can be maintained close to maximal evapotranspiration (ET_c). However at certain growth stages in various crops an ET_a/ET_c decrease may not have immediate consequences for the crop yield. In those cases deficit irrigation schemes can be applied. This implies that irrigation is applied at a lower rate, in relation to ET_c, during certain growing stages of the crop. Benefits are lower water consumption, less leaching of soil nutrients and in some cases even a more optimal yield (Geerts and Raes, 2009).

1.3 Objectives of the research

Main objective of the PhD is to reveal possible optimization of irrigation and fertilization practices in ‘Conference’ pear. Five specific research questions are addressed:

1. How sensitive is ‘Conference’ pear to a water deficit in a temperate climate and how does root pruning affects water stress sensibility?
2. How can irrigation be scheduled in ‘Conference’ pear?
3. Is it possible to calculate the water extraction pattern of the ‘Conference’ pear tree?
4. What is the optimal N fertigation dose for ‘Conference’ pear?
5. How does ‘Conference’ pear fruit quality relate to varying water and nitrogen status?

The first three research questions relate to possible optimization of irrigation practices, the last two research questions relate to possible optimization of fertilization practices. However, also the interaction between both is studied.

1.3.1 How sensitive is ‘Conference’ pear to a water deficit in a temperate climate?

In arid and mediterranean environments it has been demonstrated for pear fruit that during fruit tissue elongation, 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, Marsal et al., 2002; Naor, 2001). 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 thresholds all depend on the local evaporative conditions (Doorenbos and Kassam, 1986). 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.

Secondly the effect of root pruning on the water stress sensibility of the tree needs to be further addressed. Root pruning is an effective tool to control the vegetative growth because tree transpiration is reduced (Asin et al., 2007; Rodriguez-Gamir et al., 2010; Schupp et al., 1992). 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 part of the PhD 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 analyze the impact of root pruning on the fruit yield and the tree water status in a deficit irrigation regime.

1.3.2 Methodologies for irrigation scheduling in ‘Conference’ pear orchards in a temperate climate

When optimal irrigation thresholds can be obtained for ‘Conference’ pear the question rises how they can be applied efficiently in a temperate climate with unpredictable rainfall. Three different approaches are available for fruit growers.

- Soil sensors which observe soil moisture or soil water potential.
- Calculation of the soil water content with a soil water balance
- Implementation of continuous plant based measurements.

The soil sensor the most widespread among fruit growers in Belgium is the Watermark sensor (Irrometer Co., USA). This sensor is an electrical resistance sensor with two electrodes embedded in a granular matrix. The granular matrix is a gypsum tablet embedded in polyvinyl chloride plastic fill. The watermark soil water potential sensor will be used continuously throughout the PhD, however laboratory testing to indicate its accuracy is not a specific goal of the PhD since it has been done by others (Jabro et al., 2009; Leib et al., 2003; Thompson et al., 2006).

Specific objectives to be addressed in this part of the PhD are how can a soil water balance be used for irrigation scheduling in pear orchards? A soil water balance model in combination with forecast of reference evapotranspiration (ET_o) can be a very efficient way to predict the moisture content. In the tree root zone it is not easy to calculate the soil water content because there is an interaction between tree root zone and the grass strips between the trees. In essence in the orchard a more heterogeneous water distribution in the root zone will occur as compared to field crops.

Secondly the possibilities of continuous plant based measurements will be investigated for ‘Conference’ pear in the temperate conditions. Continuous plant measurements can be based on stem diameter fluctuations (e.g. Goldhamer and Fereres, 2001; Intrigliolo and Castel, 2004), on sap flow (e.g. Caspari et al., 1993; Fernandez et al., 2008) or combinations to estimate Ψ_{stem} (Steppe et al., 2008). Continuous plant based measurements have been proposed since they are more connected to metabolic and physiological processes than soil based measurements (Jones, 2007). In the previous studies (e.g. Caspari et al., 1993; Fernandez et al., 2008), the continuous plant based measurements were conducted in arid and semi-arid areas or greenhouses where a large difference in Ψ_{soil} between the control and the water stressed treatment was installed. Few experiments have been set up in temperate climates under field conditions. The question remains whether plant based measurements can be successful in a temperate climate under low evaporative conditions with a small difference in Ψ_{soil} between control and water stressed treatment. A better understanding of the possibilities of continuous plant based measurements in a temperate climate could result in improved irrigation practices in pear production, of which 30% is situated in the temperate climate zone (WAPA, 2010).

1.3.3 Model calculation of soil water potential in an irrigated ‘Conference’ pear orchard

Knowledge of soil water dynamics in the root zone of pear orchards permits improvements in irrigation scheduling (Green et al. 2006). In this case specific attention is addressed to the dynamics of Ψ_{soil} in the root zone since irrigation guidelines for fruit growers are often expressed in Ψ_{soil}. A model calculation of the root zone dynamics can be executed with HYDRUS (Simunek et al., 2006). Input parameters needed for the model simulation are soil hydraulic properties, rainfall, irrigation rate, evaporation, transpiration of the tree and root distribution of the tree. Root distribution of the tree is probably one of the parameters the most difficult to obtain. In this case root distribution may be crucial since it can be expected to play a major role in the water extraction pattern of the tree. First objective of this part of the PhD will be to evaluate to what extent Ψ_{soil} observations obtained with Watermark sensors in irrigated pear orchards can be related to calculations of Ψ_{soil} distribution. Secondly the sensitivity of the HYDRUS calculation to the implemented root distribution will be investigated.

1.3.4 What is the optimal N fertigation dose for ‘Conference’ pear?

As described above N, K, Mg and P are the main nutrients which are fertilized in ‘Conference’ pear orchards. Distinction is to be made between K, Mg, P of which the concentration in the soil remains more stable compared to the concentration of N which is susceptible to mineralization, denitrification and leaching. Among all nutrients N is most frequently dispensed using fertigation. Since fertigation allows a more precise allocation of fertilizers to the root zone (Yin et al., 2009), fertilization guidelines derived for broadband fertilization should be reconsidered and specific fertigation guidelines are to be derived. Next to maximal fruit yield, the N fertigation guidelines should also consider optimal fruit quality.

1.3.5 How does ‘Conference’ pear fruit quality relate to varying water and nitrogen status in soil, leaf and fruit?

Maximal fruit yield is of primary importance for fruit growers, however to maintain consumers trust in ‘Conference’ pear a uniform good fruit quality is desirable. Consumers are prepared to pay more when a good taste quality of the fruit is guaranteed (Pinto et al., 2008). Furthermore fruit appreciation by consumers is related to fruit firmness and fruit color (Kappel et al., 1995). Irrigation and fertilization has been reported to affect fruit quality (Cui et al., 2008; Liu et al., 2013; Marsal et al., 2000; Sanchez et al. 2002). Objective of this part of the PhD was to see whether parameters, related to water and nitrogen status in the soil can be related to fruit quality parameters observed in 9 different orchards.

1.4 Thesis outline

The thesis is a compilation of two international peer-reviewed journal publications and four international peer-reviewed conference papers. In these papers the research questions formulated above are addressed:

1. How sensitive is ‘Conference’ pear to a water deficit in a temperate climate?

   This research question is discussed in **chapter 2,** ‘Sensitivity of Root Pruned ‘Conference’ Pear to Water Deficit in a Temperate Climate’. Outcome of the research should be specific irrigation thresholds for ‘Conference’ pear tree in a temperate climate. In this chapter also the impact of root pruning on the water stress sensibility of the trees is discussed.

2. How can irrigation in ‘Conference’ pear be scheduled?

   In **chapter 3** ‘Adapted soil water balance model for irrigation scheduling in pear orchards ‘cv. Conference’’ an approach is presented to schedule irrigation using an adapted soil water balance, in **chapter 4** ‘Water stress detection in a ‘Conference’ pear orchard in a temperate climate using sap flow monitoring’ continuous plant based measurements are evaluated for irrigation scheduling.

3. Is it possible to calculate the water extraction pattern of the ‘Conference’ pear tree?

   In **chapter 5** ‘Numerical calculation of soil water potential in an irrigated ‘Conference’ pear orchard’ an effort is made to reveal the variation in Ψ_{soil} in the root zone of a drip irrigated pear orchard. Furthermore the sensitivity of the root distribution to the numerical calculation is studied.

4. What is the optimal N fertigation dose for ‘conference’ pear?

   In **chapter 6** ‘In search of the optimal N fertigation dose for ‘Conference’ pear tree’ the fruit response to N fertigation is studied.

5. How does ‘Conference’ pear fruit quality relate to varying water and nutrient status in soil, leaf and fruit?

   The relation between pear fruit quality and nitrogen and water status of the ‘Conference’ pear tree is studied in **chapter 7 ‘**Relations between water and nitrogen status of ‘Conference’ pear tree and fruit quality parameters’

In all chapters throughout the PhD data collection and research work is conducted in ‘Conference’ pear orchards which are commercially exploited. The first experiments started in 2007 in three orchards situated in Sint-Truiden, Meensel and Bierbeek. These orchards were considered to be representative for fruit orchards in Vlaams-Brabant and Limburg, where most fruit orchards are situated in Belgium.

Table 1.5 Characteristics of the three experimental orchards described in chapter 2, 3, 4, 5 and 6.

Orchard	Bierbeek	Meensel	Sint-Truiden
Coordinates	50°49'36.35"N, 4°47'40.35"E	50°53'40.20"N, 4°55'38.12"E	50°45'59.46"N, 5° 9'24.68"E
Rootstock	Quince C	Quince Adams	Quince Adams
Planting year	2000	1996	1996
Planting Distance	3.3 m x1 m	3.5 m x 1.5 m	3.5 m x 1.25 m
Training system	Intensive V system	Free spindle	Free spindle
Soil type according to Belgian soil classification	Lbp (Sandy Loam, dry, no specific soil profile formation)	Lhc (Sandy loam, humid, clay accumulation in the subsoil)	Abp (Loam, dry, no specific soil profile formation)
Total available water content upper soil layer (0-30 cm) (%)	26 ± 1	24 ± 1	28 ± 1
Average tree height	3.5 m	3.5 m	3.3 m
Soil texture upper soil layer (0-30 cm)	Silt	Silt	Silt loam
pH upper soil layer (0-23 cm)	6.1 ± 0.1	7.0 ± 0.1	6.4 ± 0.08
Carbon content (C) upper soil layer (0-23 cm) (mg/100 g)	1.6 ± 0.2	1.5 ± 0.2	1.4 ± 0.12
Potassium (K) content upper soil layer (0-23 cm) (mg/100 g)	51.2 ± 3.2	28.3 ± 5.4	35.5 ± 4.0
Magnesium (Mg) content upper soil layer (0-23) (mg/100 g)	31.0 ± 2.5	16.7 ± 2.9	9.8 ± 0.4
Other characteristics	Situated on a slope, since planting regular root pruning.	Shallow ground water table (1.5 m-2 m)	-

Since 2007 to 2011 the following measurements and observations were conducted the three orchards:

- Soil water potential (Ψ_{soil}) measured with Watermark granular matrix sensors,
- Stem water potential (Ψ_{stem}) determined with a pressure chamber (Schollander et al., 1965),
- Soil water content (θ) measured by drying at 105°C and sampling with a gauge augur,
- Fruit yield with distribution in diameter classes,
- Number of flower buds,
- Sap flux density (J_p) with thermal dissipation probes,
- Fine root distribution obtained by washing out soil cores,
- Mineral content of leafs and fruits,
- Fruit quality parameters,
- NO_3^--N content of the soil.

The details of the used protocols, set up of the experiments and experimental results are discussed in chapter 2, 3, 4, 5 and 6 (Table 1.6).

Table 1.6: Time and locations of the measurements and observations conducting during the PhD research in Bierbeek, Meensel-Kiezgem and Sint-Truiden.

Orchard	Bierbeek			Meensel			Sint-Truiden				Discussed
Measurement	2007	2008	2009	2007	2008	2009	2007	2008	2009	2011	in chapter
Ψ_{soil}	x	x	x	x	x	x	x	x	x	x	2, 4, 5, 6
Ψ_{stem}	-	x	-	-	x	x	-	x	x	x	2, 4, 5
θ	x	x	x	x	x	x	x	x	x	x	2, 3, 4, 5
Fruit yield	x	x	x	x	x	x	x	x	x	-	2, 6
# Flower buds	x	x	-	x	x	x	x	x	x	-	2
J_p	-	-	-	-	-	-	-	-	-	x	4, 5
Fine roots	-	-	-	-	-	-	-	-	x	x	5
Minerals in Fruit/Leaf	-	x	x	-	x	x	-	x	x	-	6
Fruit quality parameters	-	x	x	-	x	x	-	x	x	-	6
NO_3^--N soil	-	x	x	-	x	x	-	x	x	-	6

The observations and measurements were conducted in experimental plots, situated in the middle of the orchard, were a variation of irrigation and fertilization regimes was installed (Fig. 1.12). The detailed description of the installed irrigation and fertilization treatments is discussed in chapter 2, 3, 4, 5 and 6.

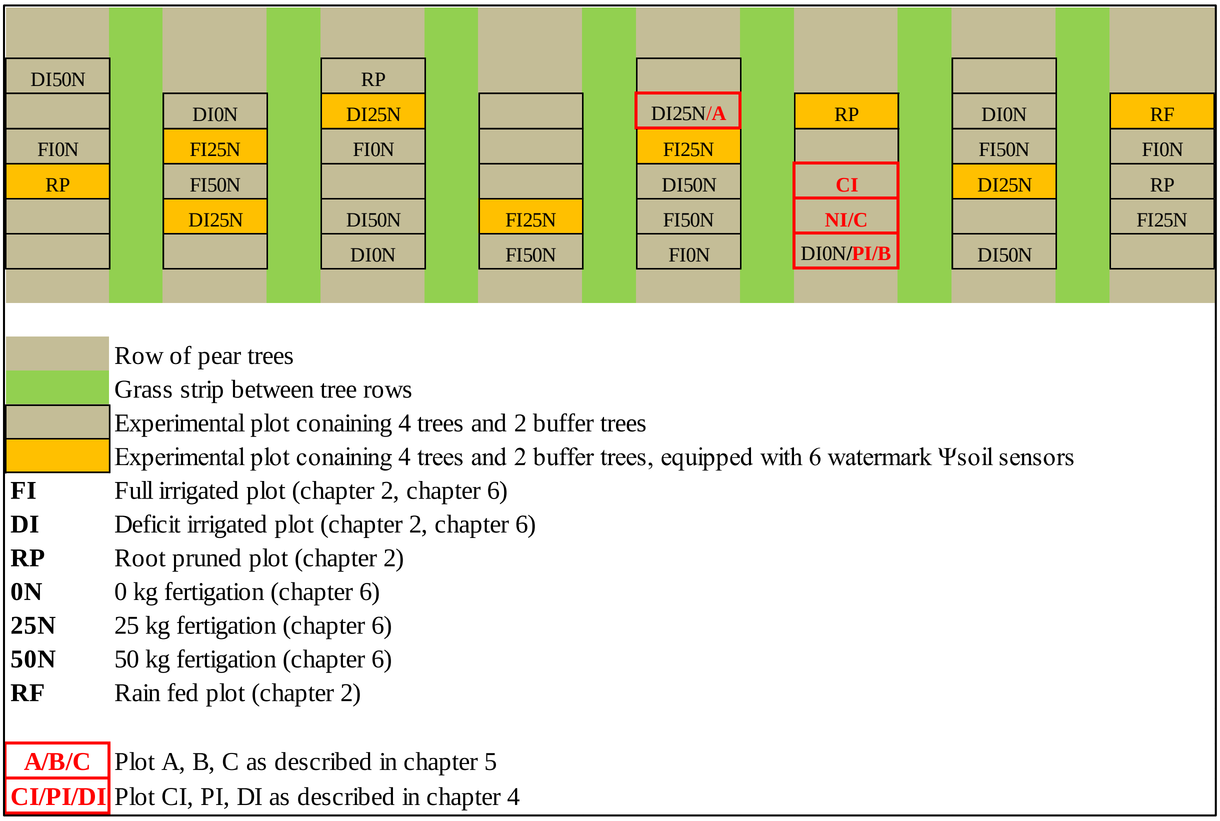


Fig. 1.12 Schematic overview of lay out of the experimental plots used in the PhD research, schematic presented for the orchard in Sint-Tuiden.

Chapter 7 is in that sense different from the previous chapters since data collection is conducted in 9 orchards near Beveren where data collection started in 2011 and ended in 2013.

In **Chapter 8** a general conclusion is made which discusses the specific research questions and outlooks for future research. Furthermore a specific section is added which summarizes recommendations for fruit growers derived from the PhD research.

2 Sensitivity of root pruned ‘Conference’ pear to water deficit in a temperate climate

Adapted from: Janssens, P., Deckers, T., Elsen, F., Elsen, A., Schoofs, H., Verjans, W., Vandendriessche, H., 2011. Sensitivity of root pruned 'Conference' pear to water deficit in a temperate climate. Agric. Water Manage. 99, 58-66.

2.1 Introduction

Over the past years pear fruit (*Pyrus communis* L. 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, such as for example CCC, trees are subjected to different management practices 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 (Asin et al., 2007; Rodriguez-Gamir et al., 2010; Schupp et al., 1992). Root pruning alters the dimensions of the tree root system 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 root pruning probably makes a tree more vulnerable to a water deficit.

Market price of fruits having a diameter of >60 mm is 50% higher than 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. 2.1a). 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 the fruit tissue cell elongation, 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, Marsal et al., 2002; Naor, 2001). Naor (2001) observed yield decline when average Ψ_{soil} was lower than -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 (Asin 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 fruits and had a negative effect on total yield, which indicates the delicate optimum 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’Connel and Goodwin, 2007, Ramos et al., 2000).

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 Manini (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, 2010), 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 analyze 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.

2.2 Material and methods

In Belgium in the pear trees (*Pyrus Communis* L. 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 characterized by a period of extensive shoot growth. In August the fruits increase in fruit size during 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).

2.2.1 Experimental sites and plant material

2.2.1.1 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 3.5 m. The orchard was situated on a slope. Soil texture in the upper soil layer was silt, in the deeper soil layer texture was silt loam. The soil had an organic carbon content of 1.6% in the upper soil layer (0-23 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 cm^{-3}and 1.5 g cm^{-3} in the deeper soil layer (30-60 cm). Irrigation water had an Electric Conductivity (EC) of 0.76 dS/m at 25 °C which is lower than 1 dS/m excluding any salinity risk (Ayers and Westcot, 1988).

2.2.1.2 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 silt. A shallow ground water table was present in the soil profile at a depth varying 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 1.5% (0-23 cm). 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 cm^{-3} in the upper soil layer (0-30 cm) and 1.5 g cm^{-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.

2.2.1.3 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 1.25 m. The average tree height was 3.3 m. The trees were never root pruned and were trained in a free spindle system. The orchard was situated on a silt loam textured soil. The organic carbon content in the upper soil layer was 1.4% (0-23 cm). 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 cm^{-3} for the lower soil layer. The EC of the irrigation water was 0.87 dS/m at 25°C.

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

2.2.2 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 (ET_o) 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 buffer trees. Four plots in the FI treatment were irrigated according to daily ET_c to insure a $\Psi_{soil} > -60$ kPa 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, of about 1.5 m wide, 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. 2.1a). In 2007 average rainfall over the three orchards during June-July was 182 mm, in 2008 187 mm and in 2009 122 mm. In periods without rainfall the screens were removed from the orchard. Outside this period the DI treatment was fully irrigated (100% ET_o), identically as FI.

Besides the irrigated plots, Ψ_{soil} was monitored in one rainfed, non-irrigated, 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 in the FI and the DI plots.

2.2.3 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.

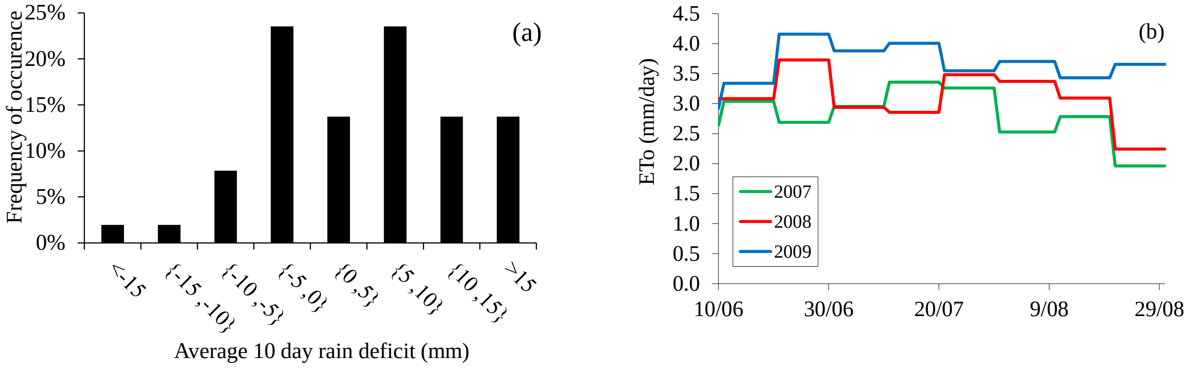


Fig. 2.1 Distribution of rain deficit calculated per 10 days during the summer recorded in Melsbroek, in the center of Belgium, the last 51 years (a) and average evapotranspiration calculated over 10 days 2007-2009 based on weather data recorded in Beauvechain, Belgium, in the proximity of the experimental sites (b).

2.2.4 Measurements

2.2.4.1 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. Watermark sensors were placed between 20 and 50 cm outside the tree row, on both sides of the trunk. 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 measurement range of the Watermark Ψ_{soil} sensors ranges between -10 and -200 kPa (Scanlon et al., 2002). The Watermark registrations were accompanied by gravimetric moisture samples. Samples were taken with a gauge auger of 30 cm, diameter 1.6 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 24h. Ψ_{soil} of the samples was calculated with the aid of the Water Retention Characteristics (WRC) and bulk density.

2.2.4.2 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 leaves 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 (Schollander 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.

2.2.4.3 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 in 2007, 2008 and 2009 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).

2.3 Results

2.3.1 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 ET_o and rainfall (Table 2.1). Rain deficit in 2009 went up to 20 mm per 10 days which is high for Belgium (Fig. 2.1a). 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 characterized as rather humid. Average ET_o per 10 days was between 2.5 and 3.5 mm/day in 2007 and in 2008. In 2009 ET_o ranged between 3.5 and 4.5 mm/day (Fig. 2.1b).

Table 2.1 Average Rain Deficit (ET_o-Rain) calculated over 10 days. Rain (mm) measured on site, ET_o (mm) calculated with data recorded at a nearby weather station (Bierbeek 10 km, Meensel 20 km, Sint-Truiden 30 km).

	Bierbeek			Meensel			Sint-Truiden		
Year	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

2.3.1.1 Soil water potential (Ψ_{soil})

In the rainfed, non-irrigated, plots in Bierbeek, Ψ_{soil} decreased sharply in each year (Fig. 2.2a) which in Meensel and Sint-Truiden decreased only in 2009 below -100 kPa (Fig. 2.2b, c).

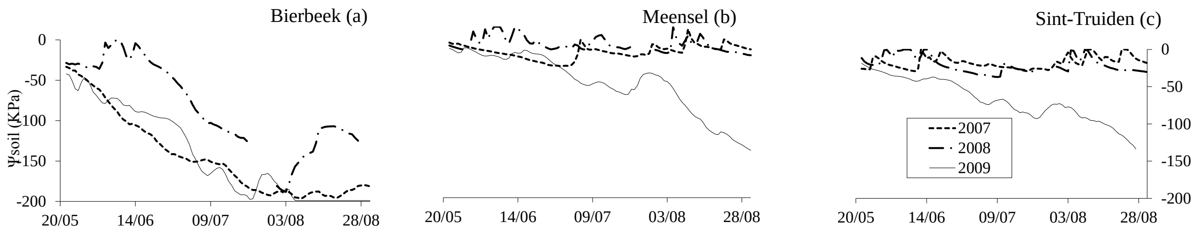


Fig. 2.2 Ψ_{soil} measured by Watermark sensor in rainfed, non-irrigated, plots in Bierbeek (a), Meensel (b) and Sint-Truiden (c). Line represents average of three sensors at 30 cm depth.

In Bierbeek in 2007, and in 2008 Ψ_{soil} declined rapidly to -150 kPa in the DI treatment (Fig. 2.3a, 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. 2.3c). 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 (Fig. 2.3d, e, 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. 2.3 g, h, 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 2.1). In general the variation in Ψ_{soil} between the irrigation plots of the same treatment was lowest in Sint-Truiden.

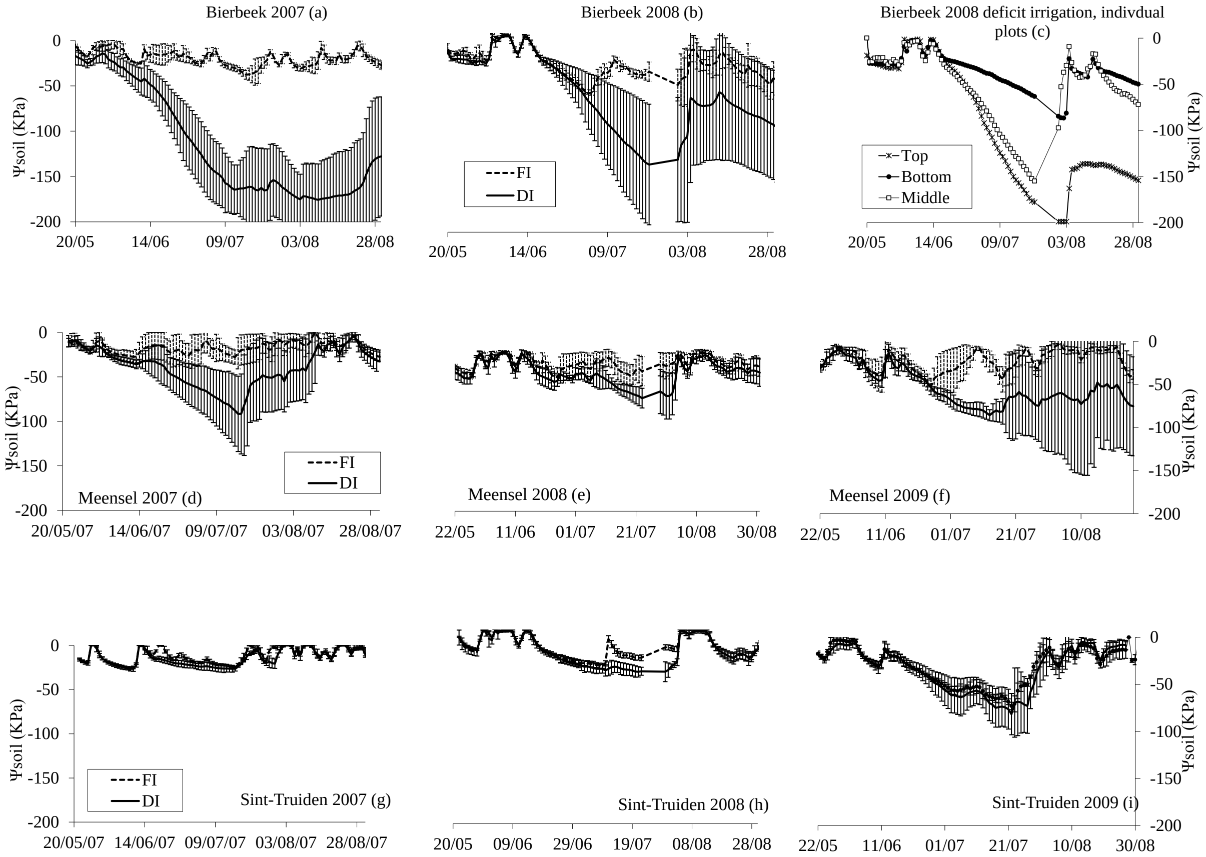


Fig. 2.3 Ψ_{soil} for the FI treatment and the DI treatment in Bierbeek 2007 (a), Bierbeek 2008 (b) and for the individual plots in the DI treatment in Bierbeek 2008 (c) where location on the slope is indicated in the legend. Ψ_{soil} evolution in FI treatment and DI treatment is shown for Meensel 2007 (d), Meensel 2008 (e), Meensel 2009 (f), Sint-Truiden 2007 (g), Sint-Truiden 2008 (h) and Sint-Truiden 2009 (i). FI was irrigated 100% ET_o 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 average Ψ_{soil} observed in the three plots.

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. 2.4a). Correlation between Watermark and gravimetric sampling became stronger when only data recorded on days without irrigation were considered (Fig. 2.4b). However the slope 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).

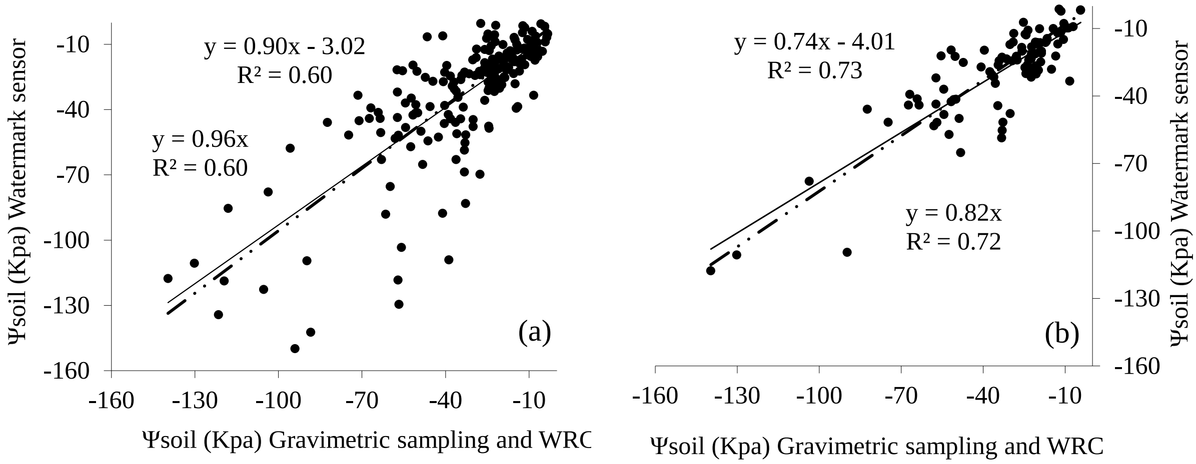


Fig. 2.4 Relation between Ψ_{soil} measured by Watermark sensor and Ψ_{soil} derived from gravimetric sampling, bulk density and Water Retention Curve (WRC) during 2007-2009 in three orchards at 0-60 cm. (a) all measurements (b) measurements on days without irrigation.

2.3.1.2 Stem water potential (Ψ_{stem})

Only in Bierbeek and in Meensel in 2009 (Fig. 2.5b) Ψ_{stem} measurements during the experiment tended to differ between the FI treatment and the DI treatment. In Bierbeek in 2008 Ψ_{stem} tended to be lower in the DI treatment but there was important variation between the three plots (Fig. 2.5a), in accordance with the higher standard deviation in Ψ_{soil}, which may be attributed to the presence of a slope in the orchard. These Ψ_{stem} observations are in accordance with the Ψ_{soil} registrations (Fig. 2.3). 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. 2.3). Ψ_{stem} observations were only collected in 2008 and 2009, not in 2007 when important differences in Ψ_{soil} between treatments were observed.

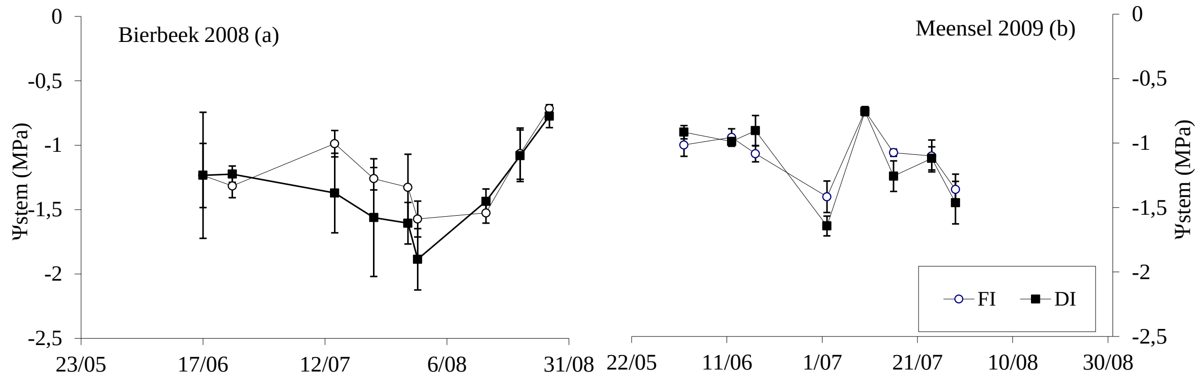


Fig. 2.5 Evolution of Ψ_{stem} *in Bierbeek 2008 (a) and Meensel 2009 (b) in the irrigation experiment. Each dot represents average of three plots on three measurements per tree. Bars indicate standard deviation between the three plots.*

2.3.1.3 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 2.2) 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.

Table 2.2 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% ET_o 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.

					Yield in size class (kg/tree)		
		# Flower buds/tree	Yield (kg/tree)	Crop Level (#fruits/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,b indicate a significant difference according to the Mann-Withney U test at $p < 0.05$. * flower buds/shoot instead of flower buds/tree.

Only in Bierbeek in 2007, the fruit yield in the size class > 60 mm was negatively related with Ψ_{soil} (Fig. 2.6a). 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. 2.6b). 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 ET_o (Table 2.3). A low Ψ_{soil} on a day with high ET_o is correlated with low Ψ_{stem}. Correlation was strongest in Bierbeek 2008 and Meensel 2009.

Fig. 2.6 Relation between average Ψ_{soil} and yield in size class 60mm+ for Bierbeek in 2007 (a). Relation between average Ψ_{stem} and yield in size class 65mm+ for Meensel 2009 (b).

Table 2.3 Linear regression between Ψ_{stem}, ET_o and Ψ_{soil} (Ψ_{stem} [MPa]= aET_o[mm/day] + $b\Psi_{soil}$[kPa]+c). Ψ_{stem} observation is average of three measurements per tree. Ψ_{soil} is measured by three Watermark sensors at 30 cm. ET_o 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	R²	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

*, ** *indicate significance at $p< 0.05$ or 0.001 respectively.*

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 (Fig. 2.6).

2.3.2 Root pruning

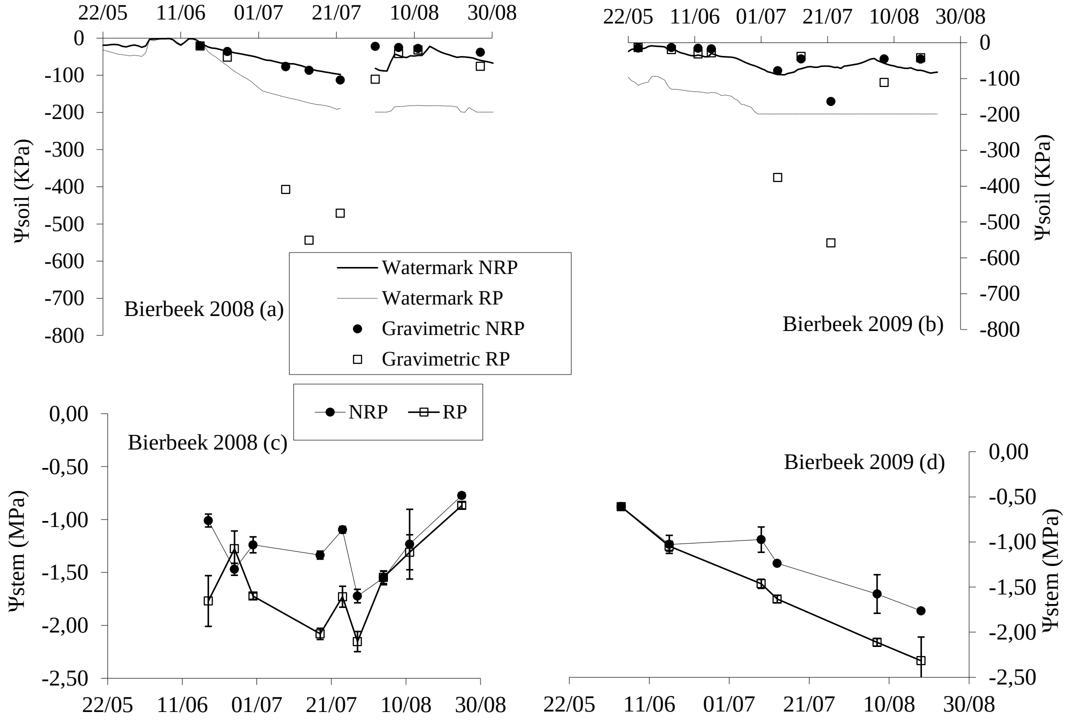
2.3.2.1 Soil water potential (Ψ_{soil}) and stem water potential (Ψ_{stem})

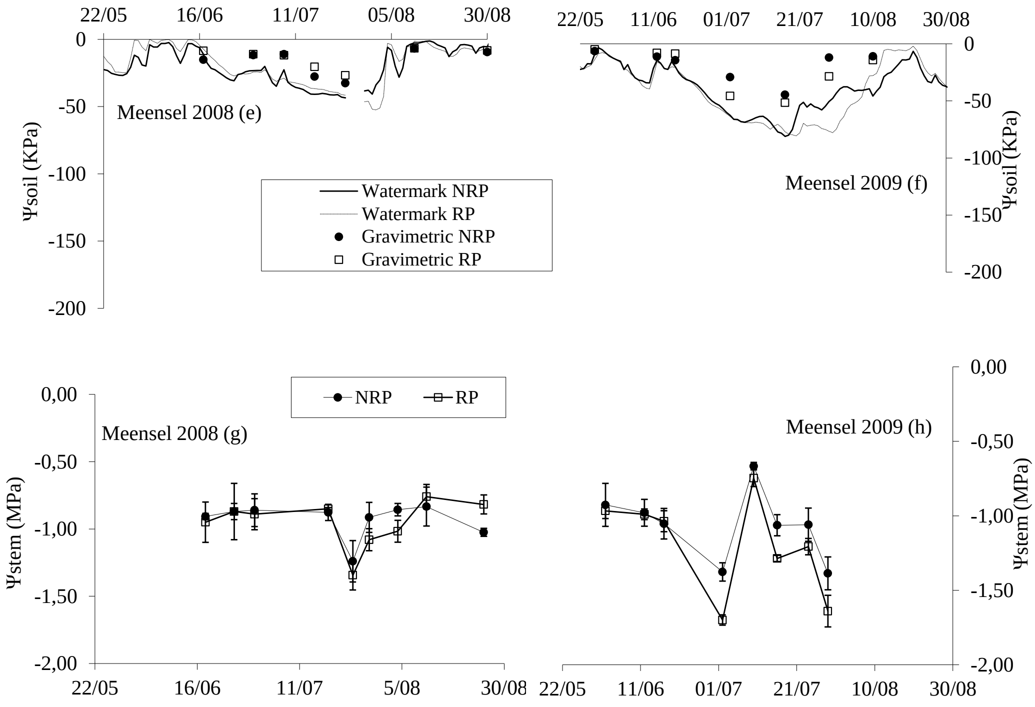
Calculated Ψ_{soil} based on the soil moisture measurements and the water retention curve in Bierbeek indicated that Ψ_{soil} decreased sharply to -600 kPa after root pruning which is lower than the recordings of the watermark sensors of which the measurement range is limited to -200 kPa (Fig. 2.7a, b). The difference in Ψ_{soil} was reflected in the Ψ_{stem} measurements which decreased to -2 MPa and lower in the pruned plots (Fig. 2.7c, 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. 2.7e, f) up to -100 kPa. The influence of root pruning on Ψ_{stem} was more pronounced especially in 2009 (Fig. 2.7g, 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. 2.7k, l). In 2008 there was no clear differentiation.

2.3.2.2 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 2.4). In Sint-Truiden the trees tended to show a biannual bearing tendency, however to fully observe this biannual bearing tendency a longer observation period, longer than 10 years, is required. 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.

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.


Bierbeek 2008 (a)
Bierbeek 2009 (b)
Bierbeek 2008 (c)
Bierbeek 2009 (d)
Ψsoil (KPa)
Ψstem (MPa)
Watermark NRP
Watermark RP
Gravimetric NRP
Gravimetric RP
NRP
RP
22/05
11/06
01/07
21/07
10/08
30/08
0
-100
-200
-300
-400
-500
-600
-700
-800
0,00
-0,50
-1,00
-1,50
-2,00
-2,50


Meensel 2008 (e)
Meensel 2009 (f)
Meensel 2008 (g)
Meensel 2009 (h)
Ψsoil (KPa)
Ψstem (MPa)
Watermark NRP
Watermark RP
Gravimetric NRP
Gravimetric RP
NRP
RP
22/05
16/06
11/07
05/08
5/08
30/08
11/06
01/07
21/07
10/08
0
-50
-100
-150
-200
0,00
-0,50
-1,00
-1,50
-2,00

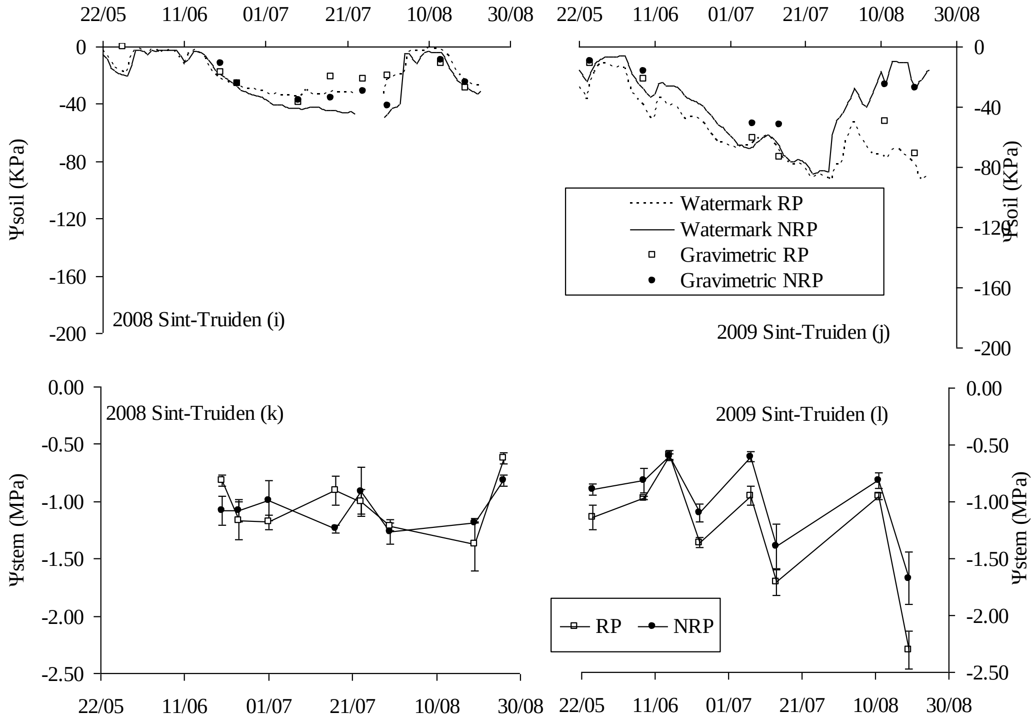


Fig. 2.7 Ψ_{stem} and Ψ_{soil} for a tree in RP treatment and a tree in NRP treatment located less than 10 m from each other in Bierbeek (a), (b), (c), (d), Meensel (e), (f), (g), (h) and Sint-Truiden (i), (j), (k) and (l). Ψ_{soil} measured with Watermark sensor, six sensors per tree, and derived from gravimetric sampling, bulk density and WRC. Ψ_{stem} measured on three leaves per tree, bars indicate standard deviation.

Table 2.4 Average fruit yield, fruit size and number of flower buds/tree in Root Pruned trees (RP) compared to Not Root Pruned trees (NRP).

			Yield	Crop Level	Yield in size klass (kg/tree)		
		# Flower buds	(kg/tree)	(#fruits/tree)	<55 mm	>60 mm	> 65 mm
<u>Bierbeek</u>							
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
<u>Meensel</u>							
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
<u>Sint-Truiden</u>							
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,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.*

2.4 Discussion

2.4.1 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 about -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 than Ψ_{soil} thresholds described in more arid conditions (-20 kPa). 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). Allen et. al (1998) outlined an root zone depletion ‘p’ factor of 0.5 for pear tree, at an evapotranspiration rate of 5 mm/day. This means that a transpiration deficit, and a yield reduction is expected when the water content in the root zone depletes to 0.5 TAW. This would correspond to about -60 kPa for the three experimental orchards, however in the experiment, for example in Meensel in 2008, no yield reduction was observed. For lower evaporative conditions, Allen et al. (1998) describes an increase of the root zone depletion factor by 0.04 (5-ETc). In the temperate climate conditions this results in a p factor of 0.58 using an average ET_c of 3 mm/day confirming present research results. The subjected threshold of -60 kPa was in this experiment only tested during the shoot growing period, in other growing stages as for example bloom, cell multiplication or fruit tissue cell elongations a more humid irrigation threshold may be recommended (Marsal et al., 2012).

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 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 rainfed 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, 2004; 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 Connel and Goodwin, 2007; Ramos et al., 1994), can be maintained in a temperate climate.

The relationship between Ψ_{stem}, Ψ_{soil} and ET_o 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 ET_o values and decreased with lower Ψ_{soil} values. The correlation was strongest in Bierbeek, probably because the measurements were performed in drier conditions where the Watermark sensor seems to be a better estimator for Ψ_{stem} (Intrigliolo and Castel, 2004).

2.4.2 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 (Asin 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 can’t 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 tended to induce 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 Asin 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.

2.5 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.

3 Adapted soil water balance model for irrigation scheduling in pear orchards ‘cv. Conference’

Adapted from: Janssens, P., Elsen, F., Elsen, A., Deckers, T., Vandendriessche, H., 2011. Adapted Soil Water Balance Model for Irrigation Scheduling in Pear Orchards ‘cv. Conference’. Acta Hortic. 919, 39-46.

3.1 Introduction

Pear fruit (*Pyrus communis* L. cv. ’Conference’) has become an important part of fruit growing in Belgium and the Netherlands. The financial return of fruits having a diameter larger than 60 mm is twice the return of smaller sized fruits (≤55 mm). An accurate response to daily water demand of the trees is necessary for an optimal fruit size and production. Several authors observed yield decline and smaller fruit size in relation to water stress (Naor, 2001; O’ Connell and Goodwin, 2007; Marsal et al., 2002). However during several development stages as for example during shoot growth period it is possible to reduce the irrigation supply without harming or even enlarging fruit yield (Anconelli and Mannini, 2002; Bosnjak et al. 1997). In Belgium pear trees are mainly grown on loam and sandy loam soils with high water storage capacity. Sensitivity of fruit size to water stress and limitations for deficit irrigation under these conditions was shown in chapter 2 of this PhD.

In combination with the unpredictable rainfall it is difficult to optimize the irrigation scheme. Water stress indicators are a useful tool to optimize the irrigation scheme. Stem water potential (Ψ_{stem}) is considered as a very efficient indicator of plant drought stress (Naor, 2006). Ψ_{stem} is measured on the tree and reflects the water status of the tree which is driven by the difference between evaporative demand (Ψ_{air}) and soil water potential (Ψ_{soil}) (Van den Honert, 1948). Soil water potential is often used for irrigation scheduling in commercial orchard because it can be easily measured by soil sensors as Watermark or tensiometers using a suction cup. The main problem of these indicators for operational irrigation scheduling is the lack of forecasting ability. A soil water balance model in combination with forecast of reference evapotranspiration (ET_o) can be a very efficient way to predict the moisture content. The main concern of irrigation scheduling with a soil water balance is the accuracy of the model. The contribution of capillary rise and runoff can be important but it is difficult to estimate (Gaudin et al., 2010; Ayars et al., 2006). To minimize errors the model is best calibrated with field measurements and Cai et al. (2009) demonstrated such an approach for winter wheat.

A classical soil water balance model as for example BUDGET (Raes et al., 2006) calculates the root zone depletion for the simulation period (Δt = 1 day) by considering the measured soil water content in the root zone at day i (D_i), the daily rainfall (R), irrigation (I), estimated capillary rise (CR), and the crop evapotranspiration which is calculated by multiplying reference evapotranspiration (ET_o) with the crop coefficient K_c (Allen et al., 1998). Deep percolation (DP) is considered when soil water content exceeds Field Capacity (Eq. 3.1).

$$D_i\ [mm] = D_{i-1}\ [mm] + R\ [mm] + CR\ [mm] - DP\ [mm] + I\ [mm] - K_c\ ET_o\ [mm] \quad (3.1)$$

For the individual tree it is possible to derive each input parameter separately but in the tree root zone it is not easy to calculate the soil water content because there is an interaction between tree root zone and the grass strips between the trees. In essence in the orchard there will be a more heterogeneous water distribution in the root zone compared to field crops. It is possible to simulate the water flux with macroscopic 2D/3D soil water balances which solve the Richards equation by dividing the entire root zone in smaller soil volumes or nodes as for example in the HYDRUS model (Simunek et al., 2006). These models calculate the exact amount of available water for tree transpiration but they need many input parameters and are difficult to calibrate. The approach was demonstrated for apple (Gong et al., 2006; Green et al., 2003). In this study, trough the integration of a dimensionless parameter α, an adapted classical soil water balance is presented as a simplified way to schedule irrigation in a fruit orchard:

$$D_i\ [mm] = D_{i-1}\ [mm] + \alpha_1 R\ [mm] + \alpha_2 CR\ [mm] - \alpha_3 DP\ [mm] + I\ [mm] - K_c ET_o\ [mm] \quad (3.2)$$

In Eq. (3.2) α_1, α_2 and α_3 are dimensionless parameters which stand for the surface fraction which is relevant for the water uptake of the roots of the tree. A fraction α_1 of R contributes to the soil water balance in the tree root zone and a fraction $1-\alpha_1$ contributes to the water balance of the grass strip. The same reasoning for α_2 which is the relevant fraction of CR in the water balance of the pear tree and for α_3 which is the relevant fraction of DP in the water balance. The exact value of α_1, α_2, α_3 cannot be determined since they depend on various factors which are difficult to determine such as: root dimensions of the tree, variation in soil properties in the root zone of the tree, ET of the tree and the grass strip under varying climatic conditions. Because it is not possible to determine the exact value of α_1, α_2, α_3 and to make the approach practicable it is assumed that:

$$\alpha_1 = \alpha_2 = \alpha_3 \quad (3.3)$$

Which implies:

$$D_i\ [mm] = D_{i-1}\ [mm] + \alpha R\ [mm] + \alpha CR\ [mm] - \alpha DP\ [mm] + I\ [mm] - K_c ET_o\ [mm] \quad (3.4)$$

A crop coefficient (K_c) is selected to calculate pear tree evapotranspiration. The proposed crop coefficient was derived in a lysimeter in which a 'Conference' pear tree was grown (Girona et al., 2004). The lysimeter did not included the grass strip between the tree rows. This way the tree evapotranspiration is isolated from the evapotranspiration from the grass strip and therefore $K_c\,ET_o$ is not multiplied with α. The trees are drip irrigated with drippers installed next to the tree stem, in the middle of the root zone, irrigation can be assumed 100% efficient and is also not multiplied with α. The exact value of α needs to be determined by the calibration of the soil water balance when all other input parameters are known. This approach is tested in three commercial orchards in 2008 and 2009 in search of an approach to schedule irrigation in an orchard with a soil water balance.

3.2 Materials and methods

The experiments described in this study where conducted from 2008 to 2009 in three commercial pear orchards.

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 by 1 m. Trees were trained in an intensive V system. Average tree height was 3.5 m. From 2000 to 2006 trees were root pruned every year. In 2008 and 2009, one month before full bloom, trees were root pruned on one side with a sloping knife at approximately 35 cm from the trunk. In 2008 trees were not root pruned. Soil texture in the upper soil layer was silt; in the deeper soil layer texture was silt loam. The soil had an organic carbon content of 1.6% in de upper soil layer (0-23 cm). 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/cm³ and 1.5 g/cm³ in the deeper soil layer (30-60 cm).

The second orchard is situated in Sint-Truiden (50°45'59.46"N, 5° 9'24.68"E). The orchard was planted with 'Conference' trees on a Quince Adams rootstock. The trees were planted in 1996 spacing 3.5 by 1.25 m. The average tree height was 3.3 m. The trees were never root pruned and were trained in a free spindle system. The orchard was situated on a silt loam textured soil. The organic carbon content in de upper soil layer was 1.4%. 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/cm³ for the upper soil layer and 1.5 g/cm³ for the lower soil layer.

The third orchard in Meensel (50°53'40.20"N, 4°55'38.12"E) was composed of pear tree 'Conference' on a Quince Adams rootstock. The trees were planted in 1996 with a planting distance 3.5 by 1.5 m and trained in a free spindle system. 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 (<3 %), soil texture of the upper soil layer was silt and the organic carbon content of the upper soil layer was 1.5%. 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/cm³ in the upper soil layer (0-30 cm) and 1.5 g/cm³ in the deeper soil layer (30-60 cm). One sided root pruning was carried out in 2008 and 2009 with a vertical knife at approximately 35 cm from the trunk one month before full bloom.

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

3.2.1 Calculation procedures of the soil water balance model

The soil water balance used in the experiment has the same basic algorithms as BUDGET (Raes et al., 2006). The model is developed by Frank Elsen, SSB, who used the model during 25 years for calculation of soil water content in various crops in Belgium. The model was used for irrigation consulting for Belgian farmers and therefore extensively validated during its use throughout the years. The most important differences with BUDGET (Raes et al. 2006) are:

- Field capacity was set to pF 2 and when soil water content exceeds field capacity water drains out of the root zone to field capacity the day after.
- The model accounts for two root zone compartments 0-30 cm and 30-60 cm, the water that flows out of the 0-30 cm compartment flows into the 30-60 cm compartment. Water extraction occurs at the upper soil layer but shifts to the 30-60 cm layer when Ψ_{soil} in the 0-30 cm compartment decreases below -31.6 kPa (pF 2.5) with is assumed as the threshold for non-limiting water uptake. When Ψ_{soil} in the soil layer 30-60 cm equals Ψ_{soil} in the soil layer 0-30 cm, water extraction resumes in the 0-30 cm layer.
- In the soil water balance model capillary rise is calculated with algorithms derived from UPFLOW (Raes and Deproost, 2004) which calculates the capillary rise as a function of the groundwater table depth, and water retention characteristics. Especially in Meensel there was a significant contribution of capillary rise due to the shallow ground water table. Capillary rise in Meensel was expected vary between 0 and 1.2 mm/day depending from the ground water table depth, which summarized to about 140 mm/year between bloom and harvest. In Bierbeek and Sint-Truiden no capillary rise was calculated in the soil water balance because the ground water table was not present is the first three meters of the soil profile.

The calculation of ET_c was based on a crop coefficient (K_c) of 0.85 as described by Girona et al. (2004) and reference evapotranspiration (ET_o). In this experiment the K_c described by Girona was adjusted in relation to the actual planting distance in the orchards. Planting distance was 5% higher in Sint-Truiden and Meensel and even 20% in Bierbeek compared to Girona et al. (2004). Therefore also

K_c is set at 0.91 being 5% higher than the K_c achieved by Girona et al. (2004). This assumption was made to correct for the difference in light interception which correlates with K_c. Previously Palmer (1980) showed how planting distance influenced light interception. ET_o was calculated with the Penman-Montheith equation (Allen et al., 1998) on weather data collected at approximately 20 km from the orchards. Rain was measured on site.

3.2.2 Model calibration

In the orchards gravimetric moisture samples were taken on a regular basis. Samples were taken with a gauge auger of 30 cm, diameter 1.6 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 the soil at 105°C, 24h. Volumetric water content calculated by multiplying the gravimetric water content with bulk density was compared with the result of the calculation from the soil water balance. The calculation of the soil water balance was made for a selection of α values (Eq. 3.2). The α value corresponds to the surface fraction which is relevant for the water uptake. The α value with the lowest Root Mean Square Error (RMSE) was selected for comparison with the measurements. In each orchard the available water content in the upper soil layer (0-30 cm) for the tree was calculated with the soil water balance and compared with the gravimetric moisture measurement. For the three orchards over two years also total volumetric water content in the soil profile (0-60 cm) was compared to the gravimetric moisture measurements.

3.3 Results

Determination of the optimal α value is shown in Fig. 3.1. In Bierbeek in 2008 the optimal α value is 0.86 and in 2009 it is 0.81. These α values are similar to the one obtained in Meensel. In both orchards RMSE of the model increases sharply when the calculation is made with α value close to one. The RMSE in Sint-Truiden shows a different behavior with a higher optimal α value and lower RMSE when α approaches one.

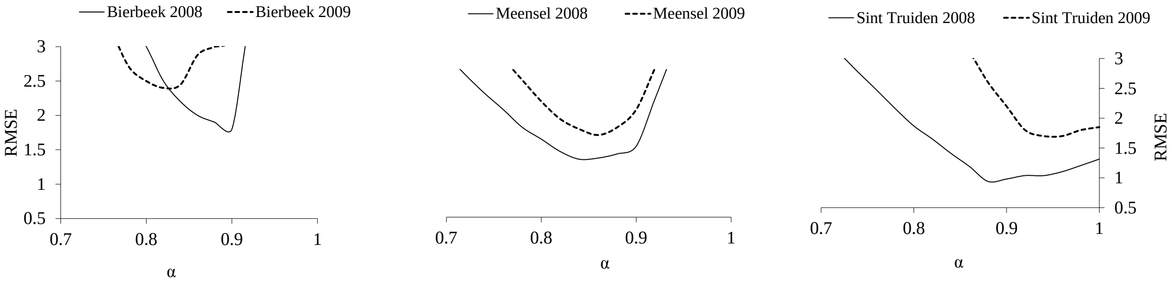


Fig. 3.1 Calibration of α for the three orchards, RMSE calculated based on volumetric water content in 0-30 cm and 30-60 cm.

Available water content in every orchard simulated by the soil water balance is closely related to the gravimetric soil measurements (Table 3.1). When all the measurements made are compared to the simulation overall R^2 is 0.71 and the slope of the regression line forced to the origin is one (Fig. 3.2). Fig. 3.3 demonstrates the calculation of the soil water balance versus moisture measurements for the orchards in Bierbeek after calibration. In Bierbeek there was no severe root zone depletion as being representative for commercial irrigated orchards. In the orchards in Meensel and Sint-Truiden the soil moisture evolution through the growing season was similar.

Table 3.1 Root Mean Square Error (RMSE), R^2 coefficient and slope of regression line of relation between measurement and soil water balance calculation of available water content in root zone in the soil layer 0-30 cm. Regression line was forced through the origin.

	R^2	Slope	RMSE	# measurements
Bierbeek 2008	0.81	0.97	3.3	10
Bierbeek 2009	0.89	1.03	3.9	8
Meensel 2008	0.72	0.95	3.6	14
Meensel 2009	0.68	0.97	1.7	9
Sint-Truiden 2008	0.81	0.99	2.2	12
Sint-Truiden 2009	0.77	0.98	2.3	7

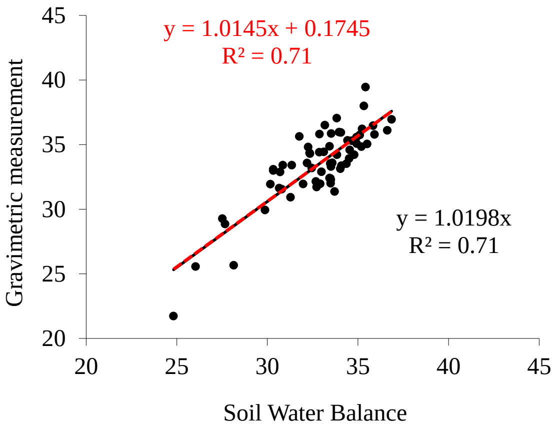


Fig. 3.2 Relation between simulated volumetric soil water content with soil water balance and measured volumetric soil water content in root zone (0-60 cm). Data from the orchard in Bierbeek, Meensel and Sint-Truiden (RMSE = 1.3%).

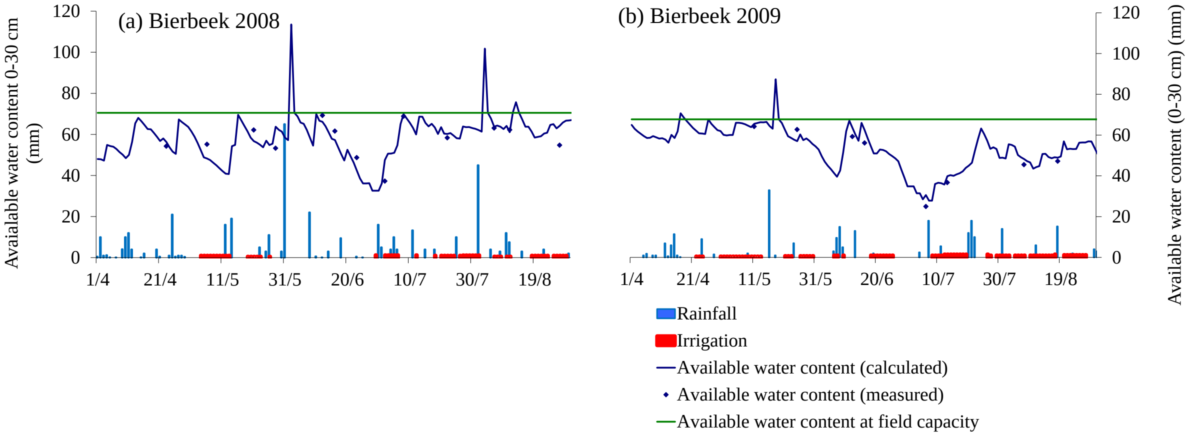


Fig. 3.3 Evolution of the soil water content in Bierbeek 2008 (not root pruned) (a) and Bierbeek 2009 (root pruned) (b) calculated with the soil water balance model compared to gravimetric moisture determination.

3.4 Discussion

Theoretically the model calibration, where the optimal α value is derived, computes the magnitude of the active root compartment of the trees in relation to the magnitude of the active root compartment in the grass strip. In the calibration it was shown that this surface fraction was higher for the not root pruned trees in Sint-Truiden. In Bierbeek there was also a difference between 2008, when the trees were not root pruned and 2009 when they were root pruned. One can assume that management practices as root pruning have a severe impact on the available soil volume of which the tree can take up water. Green (2003) concluded that surface roots are the most important for water uptake and those roots will be most affected by root pruning. Besides the impact of root pruning, the α value differed between two years in the same orchard. Also seasonal and meteorological differences will have an impact on the water movement from grass strip to the root zone.

However since capillary rise (CR), deep percolation (DP) and effective rainfall (R) are difficult to estimate in the calculation of the soil water balance. Possible errors in the estimation of CR, DP, R are minimized in the calibration procedure to determine α. Therefore α may not give an exact representation surface fraction which is relevant for the water uptake of the roots of the tree.

After calibration there was a reasonable correlation between simulated and observed water content showing the capabilities of this approach for irrigation scheduling when it is used in combination with ET_o forecast. However the model stays dependent on soil moisture measurements for the calibration. It means that the accuracy of the model will increase during the growing season when more measurements become available.

4 Water stress detection in a ‘Conference’ pear orchard in a temperate climate using sap flow monitoring

Adapted from: Janssens, P., Elsen, A., Deckers, T., Vanderborght, J., Diels, J., Vandendriessche, H., 2013. Water stress detection in a 'Conference' pear orchard in a temperate climate using sap flow monitoring. Acta Hortic. 991, 425-432.

4.1 Introduction

Over the past years pear fruit (*Pyrus communis* L. 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). 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. In those years the price difference between large and small fruits increases significantly. The high market price for large fruit sizes has pushed the fruit growers to the implementation of irrigation systems.

The implementation of irrigation systems in pear orchards has raised the demand for irrigation guidelines and irrigation scheduling techniques for pear trees in a temperate climate. In chapter 2 we suggested an optimal Ψ_{stem} of -1.5 MPa similar to Ψ_{stem} guidelines in arid or semi-arid areas (Marsal et al., 2000; Naor, 2001; O’ Connell and Goodwin, 2007). However under the lower evaporative conditions Ψ_{soil} can drop to -60 kPa without causing a Ψ_{stem} drop below -1.5 MPa in contrast to a more water demanding climate (Naor, 2001).

To apply guidelines related to Ψ_{soil} irrigation can be scheduled with water balance models (e.g. chapter 3, this PhD) or soil moisture sensors. To improve the precision of this scheduling the use of information from plant based measurements has been suggested since they are more connected to metabolic and physiological processes (Jones, 2007). Measurement of Ψ_{stem} using a pressure bomb is time consuming and difficult to apply in commercial orchards, however plant based measurements can be recorded continuous using sensors and data loggers. Continuous plant measurements can be based on stem diameter fluctuations (e.g. Goldhamer and Fereres, 2001; Intrigliolo and Castel, 2004), on sap flow (e.g. Caspari et al., 1993; Fernandez et al., 2008) or combinations between them to estimate Ψ_{stem} (Steppe et al., 2008).

In the previously mentioned studies, the continuous plant based measurements were conducted in arid and semi-arid areas or greenhouses where a large difference in Ψ_{soil} between the control and the water stressed treatment was reached. For apple and pear few experiments have been set up in temperate climates in field conditions. In the present experiment the continuous plant based measurements for water stress monitoring are executed in a temperate climate under low evaporative conditions with a small difference in Ψ_{soil} between control and water stressed treatment. A better understanding of the possibilities of continuous plant based measurements in a temperate climate could result in improved irrigation practices in pear production, of which 30% is situated in the temperate climate zone (WAPA, 2010).

The objective of the current experiment was to study sap flow differences due to a moderate difference in Ψ_{soil} under low evaporative conditions in a ‘Conference’ pear orchard. If sap flow differences can be detected after applying moderate water stress it opens the door for plant based irrigation scheduling in pear trees in a temperate climate.

4.2 Materials and methods

4.2.1 Plant material and site description

The experiment was conducted in an orchard planted with ‘Conference’ pear trees on a Quince Adams rootstock, situated in Belgium, Sint-Truiden (50°45'59.46"N, 5° 9'24.68"E). 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 (ET_o) was calculated using the FAO Penman-Montheith equation (Allen et al., 1998) based on data recorded at a regional weather station in Bierset, 25 km from the experimental site.

The trees were planted in 1996 with a planting distance of 3.5 m by 1.25 m. The average tree height was 3.3 m. The trees were trained in a free spindle system. The orchard was situated on a uniform silt loam textured soil. Average stem diameter of the trees was 9.5 ± 1.5 cm.

The organic carbon content in the upper soil layer was 1.4%. Water retention characteristics were measured on pressure plates: the volumetric soil water content for the upper soil layer (0-30 cm) at 0 kPa, -10 kPa, and -1600 kPa was 50%, 36% and 6% respectively and 43%, 32% and 9% for the lower soil layer (30-60 cm). The bulk density was 1.3 g/cm^3 for the upper soil layer and 1.4 g/cm^3 for the lower soil layer.

Management practices such as pruning, disease control, fertilization and mulching were carried out in the same way as in a commercial orchard. In the orchard a drip irrigation system was installed with drippers every 20 cm with a discharge rate of 2 l/h. The EC of the irrigation water was 0.87 dS/m at 25°C.

4.2.2 Experimental design

To initiate differences in Ψ_{soil} three irrigation treatments were set up: a control irrigated treatment (CI) with drippers installed next to the trunk, a partially irrigated treatment (PI) with drippers 50 cm from the trunk only on the west side of the tree and a non-irrigated treatment (NI) without any irrigation. In the CI treatment irrigation was scheduled with Watermark granular matrix sensors (Irrometer Co., USA) and an adapted soil water balance (chapter 3, this PhD) so that Ψ_{soil} was maintained above -60 kPa according to the irrigation guidelines derived in chapter 2 of this PhD. The trees in the PI treatment received the same amount of water on the same day but only on one side of the tree 50 cm from the trunk. The experiment was set up in 2011 from 20 April until 15 July. The experiment terminated 15 July since it started raining on a regular basis until the end of August. Each treatment was situated in the middle of the orchard and consisted of 4 consecutive pear trees with minimal 2 buffer trees between 2 treatments. The maximal irrigation rate was 1.7 mm/day which never exceeded daily ET_o.

4.2.3 Monitoring sap flow

Sap flow was monitored with thermal dissipation (TD) probes. Two needles of 2 mm diameter and 20 mm long were inserted in the trunk 10 cm apart. Needles were installed at a depth of 23 mm in the stem. The upper probe was heated with a constant power of 0.2 W. Based on the temperature difference between the two needles sap flux density (J_p, $cm^3\ cm^{-2}\ h^{-1}$) was calculated according to Granier (1985) who derived an empirical relationship between J_p and a dimensionless flow index K.

$$J_p = 0.0119\ K^{1.231}\ 3600 \qquad (4.1)$$

$$\text{With } K = \frac{\Delta To - \Delta T}{\Delta T} \qquad (4.2)$$

ΔT is temperature difference between the two needles, ΔT_0 is the temperature difference under zero flow conditions which was taken as the temperature difference at night, when temperature difference between upper and lower probe was highest.

Sap flow observations using the TD technique cannot be considered as an absolute estimate of sap flow or sap flux density (Gonzalez-Altozano et al., 2008; Steppe et al., 2010). The major drawbacks of the technique are that Eq. (4.1) is an empirical relationship which can differ between tree species. Furthermore the basic assumptions using this technique are debatable: uniform sap flow in the entire conducting sap wood area, zero sap flow at night and no vertical temperature gradient. To overcome these limitations sap flow was monitored with 3 sap flow gauges per treatment and the sap flux density of the NI treatment is only considered in comparison with the sap flux density in the CI and the PI treatment using the same probes, equal installation of the probes and making the same basic assumptions in all treatments. According to Fernandez et al. (2008) this approach leads to satisfactory water stress observations.

4.2.4 Measuring soil and plant water status

Ψ_{soil} was monitored at one tree per treatment with six Watemark granular matrix sensors at 30 cm depth; 3 sensors on the east side and 3 sensors on the west side of the trees. 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.

Soil water content was measured with gravimetric moisture samples. Samples were taken with a gauge auger of 30 cm, diameter 1.6 cm, in the soil layers 0-30 cm and 30-60 cm. One sample consisted of at least 8 subsamples taken randomly within the treatment in the weed free strip beneath the canopy on both sides of the tree line. Gravimetric water content was measured by drying the samples at 105°C during 24h.

On 3 trees in every treatment Ψ_{stem} measurements were carried out during periods without rainfall. For each measurement 3 leaves 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. The approach used for Ψ_{stem} measurement is similar to the approach used in chapter 2 of this PhD where the relationship between Ψ_{stem} and fruit yield was shown.

4.3 Results

On 10 April 2011 the pear trees in Belgium were in full bloom. The first month after bloom, which is the start of the observation period, was dry without important rainfall events. The first irrigation period started 16 May and ended 7 June. Between 10 June and 30 June more than 60 mm rainfall was recorded in the pear orchard so that no irrigation events were started. Between 1 and 15 July nearly no rainfall was recorded in the orchard and irrigation was again started. In the entire observation period between 20 April and 15 July 112 mm rainfall was recorded while total ET_o was 327 mm. During the observation period in the CI treatment 52 mm irrigation was supplied to prevent water stress in the CI treatment. The PI treatment received an equal irrigation amount on the west side of the tree 50 cm from the trunk.

Ψ_{stem} was recorded four times during the growing season. During the last two measurements at the end of June and the beginning of July, when irrigation was engaged, there was difference between the treatments. The overall lowest Ψ_{stem} was -1.36 MPa and was observed in the NI treatment (Fig. 4.1a). Soil water content was, just as Ψ_{stem}, recorded 4 times but only once before the start of the irrigation period (Fig. 4.1b). Similar to Ψ_{stem} observations there was differentiation between the treatments at the end of June and the beginning of July. Water content was at that time lowest in the NI treatment.

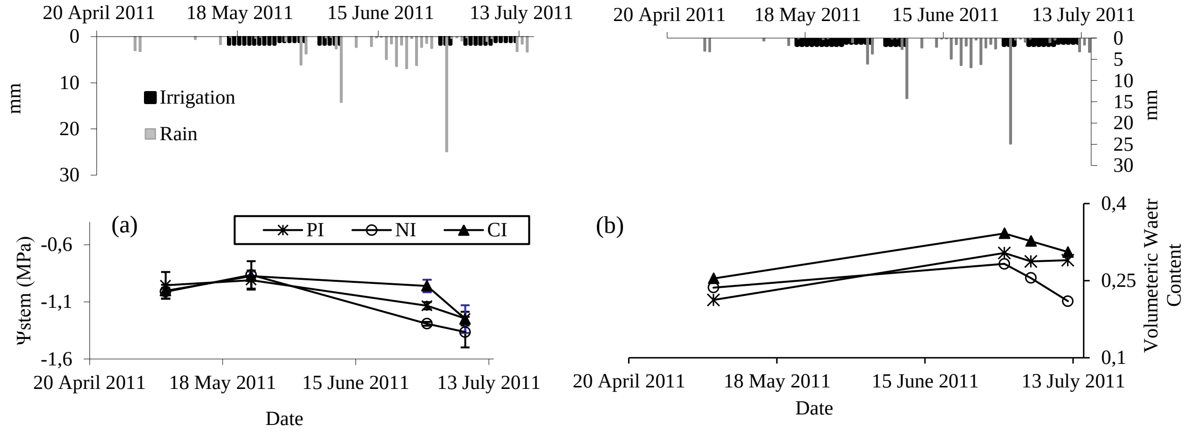


Fig. 4.1 Ψ_{stem} measured in the three irrigation regimes Partial Irrigation (PI), No Irrigation (NI) and Control Irrigation (CI) (a). Each dot represents an average of 3 trees and 3 measurements per tree. Standard deviation is indicated with the vertical bars. Volumetric water content on the east side and the west side of the trees measured with a gauge auger at 0-60 cm (b).

Ψ_{soil} was monitored on two sides of the tree line. In the CI treatment there was only little difference in Ψ_{soil} between the eastern and the western side of the tree line (Fig. 4.2a). In the PI treatment Ψ_{soil} soil was 20 kPa higher on the western irrigated side of the tree compared to the eastern non-irrigated side (Fig. 4.2b). In the NI treatment Ψ_{soil} decreased to -77 kPa on the eastern side of the tree (Fig. 4.2c). With a correlation coefficient (R^2) of 0.69 ($p<0.01$) there was a reasonable correlation between the observations of Ψ_{soil} by Watermark sensor and the gravimetric moisture measurements.

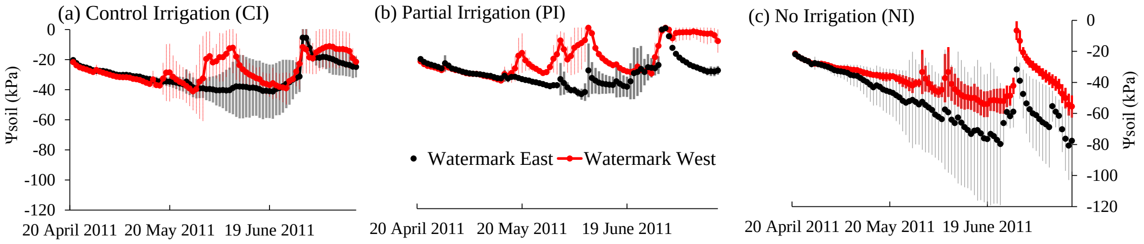


Fig. 4.2 Ψ_{soil} measured by Watermark sensor at 30 depth on 3 positions on the eastern side and 3 positions of western side of the tree line in 3 irrigation regimes: (a) Control Irrigation (CI), (b) Partial Irrigation (PI) and (c) No Irrigation (NI). Every dot represents average of three measurements, vertical bars indicate standard deviation between the three measurements.

Before the start of the irrigation in the CI and PI treatment, between 30 April and 6 May, sap flux density (J_p) was equal in the three irrigation treatments (Fig. 4.3a). Between 3 July and 9 July irrigation was engaged in the CI and PI treatment. During this period, with exception of 6 July J_p was lower in the NI treatment compared to the CI and PI treatment (Fig. 4.3b). The difference in J_p was only observed at noon, in the middle of the day, when evaporative demand was highest.

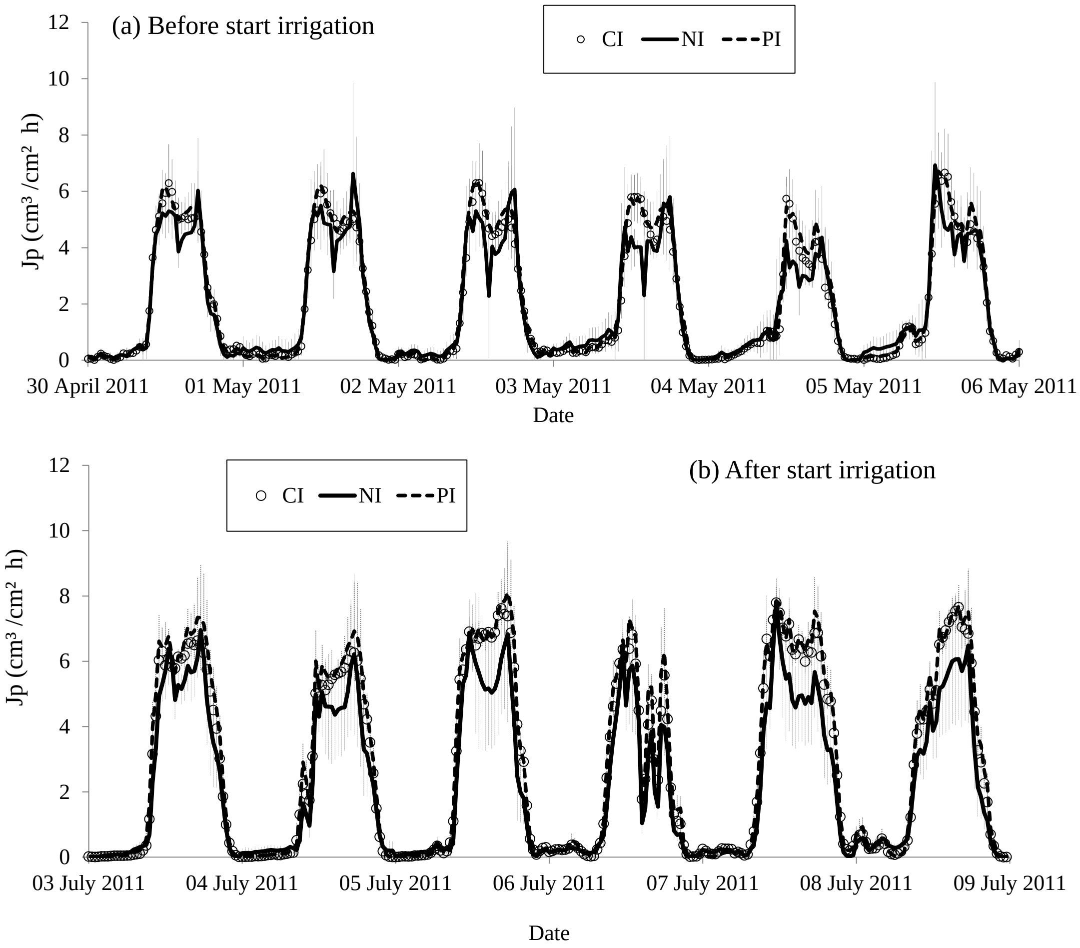
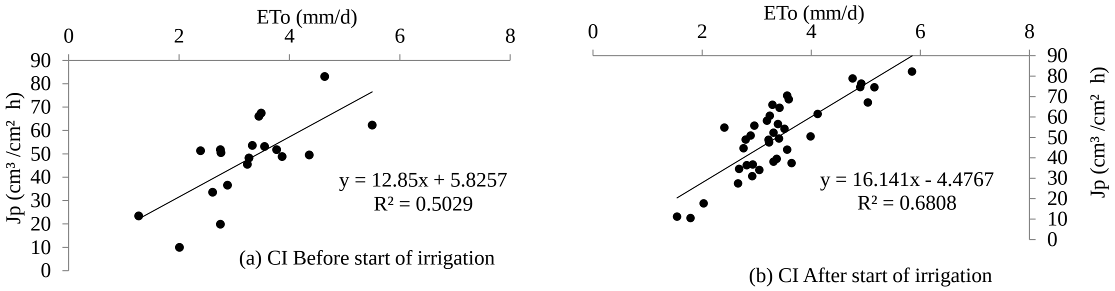


Fig. 4.3 Sap flux density (cm³ cm^{-2} h^{-1}) of CI (Control Irrigation), PI (Partial Irrigation) and NI (No Irrigation) treatment before the start of the irrigation in the CI and PI treatment (a) and after de start of the irrigation in the CI, PI and NI treatment (b). Each line represents average of 3 measurements, standard deviation between the three measurements is indicated with the vertical bars. ETo was similar before and after the start of irrigation.

There was no difference in J_p between the CI and the PI treatment. Between 27 April and 15 May, before the start of the first irrigation event, the J_p was correlated with ETo for all treatments (Fig. 4.4a, Fig. 4.4c). When the observations between 31 May and 08 July, when irrigation was engaged, were related to ETo the R² increased for the FI (Fig. 4.4b) and PI (data not shown) treatment but decreased for the NI treatment (Fig. 4.4d). Despite the only moderate decrease of Ψ_{stem} and $\Psi_{soil,}$ J_p tended to be lower in the NI treatment.



(b) CI After start of irrigation

(c) NI Before start of irrigation

(d) NI After start of irrigation

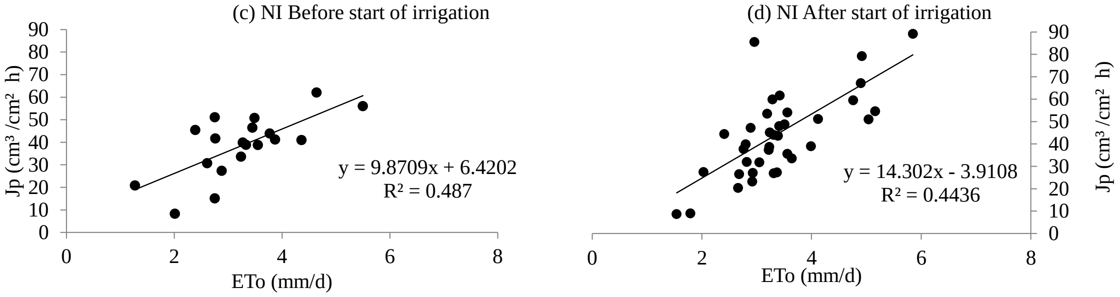


Fig. 4.4 Relation between J_p (cm³ cm^{-2} h^{-1}) and daily ET_o (mm d^{-1}) for Control Irrigated treatment (CI) before (a) and after (b) the start of the irrigation. Relation between J_p and ET_o for Non Irrigated (NI) treatment before (c) and after the start of the irrigation (d). Each dot of sap flow density is average of 3 measurements.

4.4 Discussion

The main objective of the present experiment was to detect water stress using sap flow monitoring in a pear tree orchard in Belgium. If water stress can be detected, sap flow monitoring can be used to improve the precision of irrigation scheduling in pear tree.

In our experiment Ψ_{soil} dropped below -60 kPa in the NI treatment which is considered to be the threshold for irrigation scheduling in Belgium during the shoot growing period of the trees (chapter 2, this PhD). This threshold is lower compared to Naor (2001) who observed yield decline when Ψ_{soil} exceeded -20 kPa in a more arid environment with a higher evaporative demand.

The lowest Ψ_{stem} measured in the experiment was -1.36 MPa in the NI treatment, which was lower than the measured Ψ_{stem} in the CI and PI treatment. For pear tree fruit size decline was related to Ψ_{stem} values below -1.5 MPa in both in arid and temperate climates (Marsal et al., 2000; Naor, 2001; O Connel and Goodwin, 2007; chapter 2, this PhD). Therefore, the minimal Ψ_{stem}

of -1.36 MPa measured in this experiment cannot be considered as severe water stress which is in accordance with the Ψ_{soil} observations showing a decrease little below -60 kPa.

Due to frequent rainfall and moderate evapotranspiration, average ET_o was only 3.4 mm/day, there was only a moderate decrease in Ψ_{soil} and Ψ_{stem} in the NI treatment. Nevertheless J_p tended to be lower in the NI treatment. There was no difference between the CI and the PI treatment in Ψ_{stem} nor in J_p. Also the difference in Ψ_{soil} between the CI and the PI treatment was limited. Due to the moderate evaporative demand there was sufficient water supply to the pear trees in the PI treatment.

The lower J_p observations in the NI treatment are similar to the observations of Caspari et al. (1993), Fernandez et al. (2008) who compared sap flow of well irrigated trees with water stressed trees in semi-arid and arid environments. The current results suggest that the methodology of comparing well irrigated treatments with stressed treatments is suited for pear trees in a temperate climate. However for irrigation scheduling a well irrigated reference tree needs to be set up. The future challenge for operational irrigation scheduling using sap flow monitoring or other continuous plant based measurements is to set up an approach without the need of an irrigated reference tree. Since most of the irrigation guidelines are expressed in Ψ_{stem}, the approach of Steppe et al. (2008) using plant based measurements as input for a mathematical water flow and storage model to predict Ψ_{stem}, seems promising. Other possibilities can be the coupling of sap flow measurements and meteorological variables which express evaporative demand (e.g. Pereira et al., 2006). In this experiment J_p was correlated to ET_o and the R^2 coefficient was lower in the NI treatment under moderate stressed conditions. If a fast detection of the deflection between ET_o and sap flow is possible, it would be valuable for irrigation scheduling. This implies an accurate acquisition of the meteorological parameters.

The present work shows that a tendency of water stress can be detected in a pear tree orchard in a temperate climate using continuous plant based measurements. This is the first step in irrigation scheduling using continuous plant based measurements in Belgian pear orchards.

5 Numerical calculation of soil water potential in an irrigated ‘Conference’ pear orchard

Adapted from: Janssens, P., Diels, J., Vanderborght, J., Elsen, F., Elsen, A., Deckers, T., Vandendriessche, H., 2015. Numerical calculation of soil water potential in an irrigated 'Conference’ pear orchard. Agric. Water Manage. 148, 113-122.

5.1 Introduction

In Belgium ‘Conference’ pear tree (*Pyrus Communis* L. cv. ‘Conference’) is irrigated to maintain a high fruit yield in dry years (chapter 2, this PhD). 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). Irrigation in the orchards is supplied by drip irrigation on a weed free strip under the canopy of the trees. Irrigation scheduling in the orchards is often managed by soil water potential (Ψ_{soil}) sensors. The sensor the most widespread among fruit growers in Belgium is the Watermark sensor (Irrometer Co., USA). This sensor is an electrical resistance sensor with two electrodes embedded in a granular matrix. The granular matrix is a gypsum tablet incared in polyvinyl chloride plastic fill. The use of the sensor entails some limitations (Scanlon et al., 2002): The relation between water content and matrix potential in the sensor is hysteric (Bourget et al., 1958; Whalley et al., 2001); errors may occur during rapid drying or rewetting of the soil (McCann et al. 1992) and the maximal pressure head that can be measured is -10 kPa which is the air entry pressure value of the sensor. Errors due to the hysteric response of the sensor can be minimized by calibration based on the specific drying or wetting curves of the soil or by creating a sensor with a ceramic-based porous matrix (Whaylley et al., 2001). A comparative study between various soil moisture sensors indicates that the accuracy of the sensor is comparable to the widely spread frequency domain reflectometer (FDR), time domain reflectometer (TDR) and gypsum block but lower than the neutron probe (Leib et al., 2003). Due to the low cost and ease of operation the Watermark sensors are useful as a qualitative indicator for matrix potential and therefore suitable for irrigation scheduling on commercial farms (Jabro et al., 2009; Thompson et al., 2006). Since drip irrigation causes rapid and variable changes in Ψ_{soil} distribution knowledge of soil water dynamics in the root zone of pear orchards permits better insight in the use of the Watermark soil sensor. Root water extraction patterns have been calculated previously in various fruit crops e.g. apple (Arbat et al., 2008; Besharat et al., 2010; Gong et al., 2006; Green and Clothier, 1999; Green et al., 2003) almond (Phogat et al., 2012; Vrugt et al., 2001ab), grape (Zhou et al., 2007), orange (Consoli et al., 2014) and pear (Yao et al., 2011). In almost all these studies the calculations have been compared with FDR, TDR or neutron probe recordings of soil water content. The question remains to what extent Ψ_{soil} observations, achieved with Watermarks sensors, can be related to numerical calculations of water extraction patterns.

Root water uptake patterns of trees can be calculated using a sink term presented by Feddes et al. (1978). This sink term includes functions which account for crop transpiration, response to water stress and the root distribution of the crop:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial x}\left[K(h)\left(\frac{\partial h}{\partial x}\right)\right]+\frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}\right)\text{-}K(h)\right]\text{-}S(x,z,t) \tag{5.1}$$

$$S(x,z,t)=T_p\,\beta(x,z)\alpha(h,x,z) \tag{5.2}$$

where θ is the volumetric water content, h (m) is hydraulic head, t is the time, x (m) is the horizontal position , z (m) is the vertical position (Fig. 5.2), K (m d^{-1}) is the hydraulic conductivity. S (d^{-1}) is the sink term depending on potential transpiration rate (T_p) (m d^{-1}). β(x, z) is a normalized root distribution function β(x, z) (m^{-1}) and a α(h, x, z) a dimensionless water stress response function.

The calculation of Eq. (5.1) can be executed with HYDRUS (Simunek et al., 2006). HYDRUS is designed to describe water movement in the vadose zone and has a broad range of applications. HYDRUS is often used to study irrigation design and root water uptake patterns (Arbat et al., 2008; Phogat et al., 2012; Vrugt et al., 2001ab; Yao et al., 2011; Zhou et al., 2007). Input parameters needed for the calculation are soil hydraulic properties, rainfall, irrigation rate, evaporation, transpiration of the tree and root distribution of the tree. Soil hydraulic properties, θ(h) and K(h) relationships, can be measured in the field, laboratory, or derived from pedotransferfunctions such as ROSETTA (Schaap et al., 2001) which is embedded in the HYDRUS software. Rocha et al. (2006) pointed out that especially the shape of the water retention curve, θ_{sat} and K_{sat} have a big influence on the HYDRUS calculation. Rainfall and irrigation can be measured on site, transpiration of the tree can be measured by sap flow gauges or derived from reference evapotranspiration (ET_o) with crop coefficients (Allen et al., 1998). Root distribution of the tree is probably one of the parameters the most difficult to obtain. In this case root distribution may be crucial since it can be expected to play a major role in the water extraction pattern of the tree. Previously root distributions for numerical calculations have been derived from observed root length densities (Gong et al., 2006; Green and Clothier, 1999; Green et al., 2003; Yao et al., 2011; Zhou et al., 2007), derived from literature (Phogat et al., 2012), assumed to decrease linearly with depth (Arbat et al., 2008) or derived from soil moisture observations using inverse modelling techniques (Besharat et al., 2010; Vrugt et al., 2001 ab). This raises the question which procedure is most suited for a reliable calculation of Ψ_{soil} distribution in the ‘Conference’ pear orchards.

First objective of this study is to evaluate to what extent Ψ_{soil} observations obtained with Watermark sensors in irrigated pear orchards can be related to numerical calculations of Ψ_{soil} distribution. Secondly the sensitivity of the HYDRUS calculation to the implemented root distribution is investigated.

5.2 Materials and methods

5.2.1 Plant material and site description

The experiment was conducted in an orchard planted with ‘Conference’ pear trees on a Quince Adams rootstock, situated in Belgium, Sint-Truiden (50°45'59.46"N, 5° 9'24.68"E). Belgium is situated in a temperate climate zone with frequent rainfall events and a relatively low evapotranspiration during the growing season. Average rainfall in Belgium during the growing season from April to August is 67 mm/month, average reference evapotranspiration (ET_o) is 85 mm/month. However in 48% of the years between 1959 and 2012 rain deficits of 60 mm/month occurred. The trees were planted in 1996 with a planting distance of 3.5 m by 1.25 m. The average tree height was 3.3 m. The trees were trained in a free spindle system and were never root pruned. The orchard was situated on a uniform silt loam textured soil. The organic carbon content in the upper soil layer (0-23 cm) was 1.4%. Rainfall was recorded on site; ET_o was calculated using the Penman-Montheith equation (Allen et al., 1998) based on data recorded in a regional weather station at 20 km from the site. In the orchard a drip irrigation system was installed with line drippers every 20 cm with a discharge rate of 2 l h^{-1}. Distance between the line drippers and the trunk was 35 cm (Fig. 5.1). Management practices such as pruning, disease control, fertilization and mulching were carried out in the same way as in a commercial orchard. The EC of the irrigation water was 0.87 dS m^{-1} at 25°C.

5.2.2 Soil water potential (Ψ_{soil}) observations

Three plots (plot A, B and C) in the centre of the orchard were selected for the experiment. Every plot consisted of four trees with in the centre one tree around which Watermark sensors were installed (Fig. 5.1). Sensors were installed on 6 positions perpendicular to the tree line. The Ψ_{soil} calculations were executed in 2D in the plane XZ, with X being the horizontal coordinate perpendicular to the tree line and Z being the vertical coordinate. The calculation of Ψ_{soil} in 2D is a simplification of the reality but was done to ease the computation time. Previously the calculation of water distribution after drip irrigation, with the drippers in line, has been calculated successfully in 2D in a plane perpendicular to the drip line (Skaggs et al., 2004; Zhou et al., 2007). All sensors were installed at a depth of 30 cm in search of a gradient in Ψ_{soil} independent from suction due to gravity. It is expected that root concentration is highest in the soil layers close to 30 cm depth. Installing more sensors in the root zone would possibly disturb the soil too much for a representative experiment. To supply information on water content in the deeper soil layers gravimetric soil moisture samples were taken at a depth of 30-60 cm, at reasonable distance from the sensors to prevent further soil disturbance. The Watermark sensors were connected to a data logger which recorded Ψ_{soil} every 4 h. The standard manufacturer calibration was used to compute Ψ_{soil} from the electrical resistance measured by the sensors. In every plot the sensors were brand new and used for the first time. Sensors were installed 1 day before the start of the observation period according to manufactory guidelines. In plot A Ψ_{soil} was recorded in

2009 while in plot B and C Ψ_{soil} was recorded in 2011. In the irrigated plots irrigation was scheduled using the Watermark sensors. Irrigation was initiated when Ψ_{soil} decreased to -40 kPa, the irrigation dose ranged between 1 and 3 mm/day.

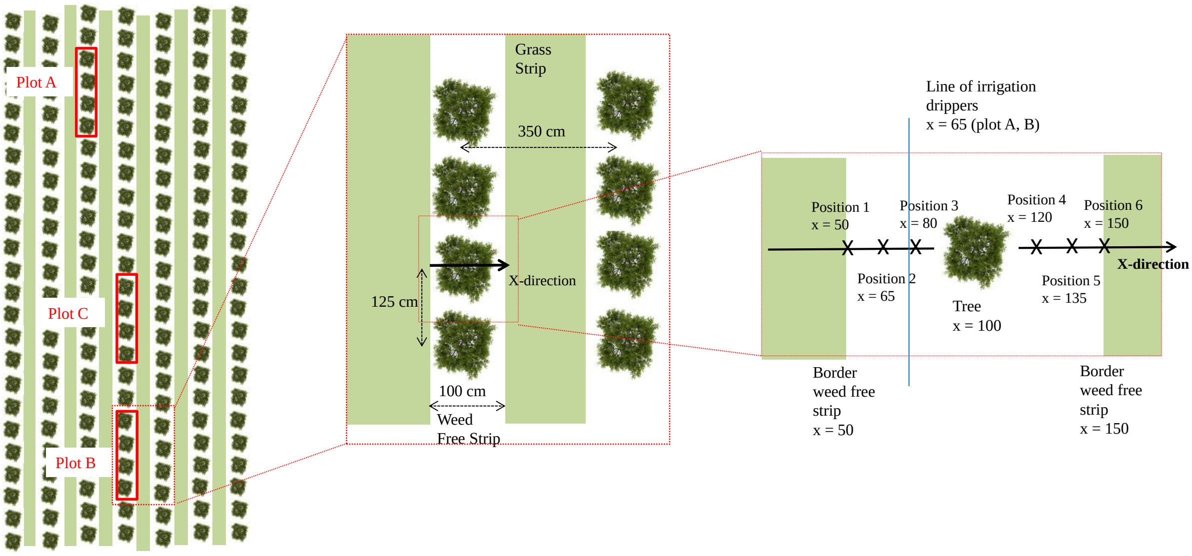


Fig. 5.1 Schematic top view with positions of the Watermark sensors which recorded Ψ_{soil} in every plot on 6 positions on the axis perpendicular to the tree line at a depth of 30 cm.

5.2.2.1 Plot A Ψ_{soil} observed in 2009 in an irrigated plot

In plot A Ψ_{soil} was observed between 04/06/2009 and 15/08/2009. Sensors were only installed at positions 2, 3, 4 and 5 according to Fig. 5.1. Total irrigation amount during this period was 77 mm, 132 mm rainfall was recorded and total ET_o during this period was 255 mm.

5.2.2.2 Plot B Ψ_{soil} observed in 2011 in an irrigated plot

In plot B Ψ_{soil} was observed between 20/04/2011 and 15/07/2011. Sensors were installed at positions 1, 2, 3, 4, 5 and 6 according to Fig. 5.1. Total irrigation amount during this period was 45 mm, 112 mm rainfall was recorded and total ET_o during this period was 300 mm.

5.2.2.3 Plot C Ψ_{soil} observed in 2011 in a non irrigated plot

Similar to plot B Ψ_{soil} was observed between 20/04/2011 and 15/07/2011. Sensors were installed at positions 1, 2, 3, 4, 5 and 6 according to Fig. 5.1. In this period 112 mm rainfall was recorded and total ET_o during this period was 300 mm. In plot C no irrigation was supplied to assure lower Ψ_{soil} values in one of the three experimental plots.

5.2.3 Soil water content (θ)

In plot B and C soil water content (θ) was measured on the irrigated side and the non-irrigated side of the trees with gravimetric moisture samples. Samples were collected on 30/06/2011, 05/07/2011 and 12/07/2011, towards the end of the observation period. Samples were taken with a gauge auger of 30 cm, diameter 1.6 cm, in the soil layers 0-30 cm and 30-60 cm. One sample consisted of minimal 8 subsamples taken randomly within the treatment in the weed free strip beneath the canopy of the four trees within a plot. Gravimetric water content was measured by drying the samples at 105°C during 24h.

5.2.4 Soil hydraulic properties

The retention points were measured on pressure plates at 0, -10 kPa, -20 kPa, -31.6 kPa, -70.8 kPa, -100 kPa, -200 kPa and -1600 kPa on soil samples taken in four replications at 30 cm depth and at 60 cm depth. Saturated hydraulic conductivity (K_{sat}) was measured *in situ* in four replications with the inversed auger hole method (Kessler and Oosterbaan, 1974) and was 144 ± 24 cm day^{-1} for the soil layer 0-70 cm and 20 ± 0.1 cm day^{-1} for the soil layer 0-200 cm.

5.2.5 Root distribution

5.2.5.1 Contours of the root zone

To estimate the maximal contours of the root zone in the horizontal (X) and vertical (Z) direction the central tree in plot A was excavated in January 2010 using low water pressure. The architecture of the coarse root system was measured in the lab with a compass, inclinometer and calliper and registered in the software ARCHIROOT (Dupuy, 2003, www.archiroot.org.uk) which translates the measurements in a multi-scale tree graph (MTG) developed by Godin and Caraglio (1998). The MTG is a multi-scale presentation of the tree, or root system and permits representation and analysis in a grid with the plant architectural model PlantGL (Pradal et al., 2009).

5.2.5.2 Fine root distribution

To obtain fine root distributions cylindrical soil cores of 880 cm³ were sampled. Roots were washed from the soil using fresh water. All roots with a diameter < 2 mm were weighted with an accuracy of 0.001 g. Root length of these fine roots was determined on photographic scans of the roots with the ASSESS software (Lamari, 2002). Cores were taken at the six positions where the Watermark sensors were installed (Fig. 5.1) to a depth of 90 cm for plot A and to a depth of 45 cm for plot B and C. The height of the soil cores was 15 cm. In plot A 36 soil cores were taken, in plot B and C 18 cores per plot.

5.2.6 Numerical calculations with HYDRUS

5.2.6.1 Boundary conditions

An automated mesh was generated with HYDRUS 2D with as boundaries the atmospheric boundary, free drainage boundary, no flux boundary and the variable flux boundary to account for drip irrigation (Fig. 5.2).

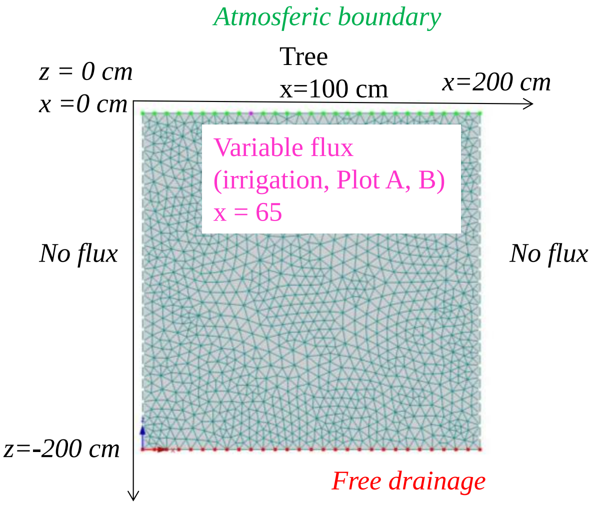


Fig. 5.2 Mesh generated in HYDRUS with the selected boundary conditions.

5.2.6.2 Hydraulic soil properties

For establishing the K(h) relationship expressed in Eq. (5.1) the soil hydraulic functions described by Van genuchten (1980) were used as implemented in HYDRUS:

$$\theta(h)=\theta_r+\frac{\theta_s-\theta_r}{[1+|\alpha h|^n]^m} \text{ when } h<0 \text{ and } \theta_s \text{ when } h\geq 0 \qquad (5.3)$$

$$K(h)=K_{sat}S_e^l\left[1-(1-S_e^{1/m})^m\right]^2 \text{ where } m=1-\frac{1}{n} \text{ and } S_e=\frac{\theta-\theta_r}{\theta_s-\theta_r} \qquad (5.4)$$

S_e is the effective water content, θ_r residual water content considered at h = -16000 cm = -1600 kPa, θ_s saturated water content measured at h = 0 cm = 0 kPa and K_{sat} (cm/day) is saturated hydraulic conductivity. The parameters α and n according to Van genuchten (1980), necessary for the HYDRUS calculation, were fitted through measured water retention points (Table 5.1) (Fig. 5.3a). In the simulations hysteresis was considered and the wetting curve differed from the drying curve, α_w from the wetting curve equaled two times α_d from the drying curve after Kool and Parker (1987).

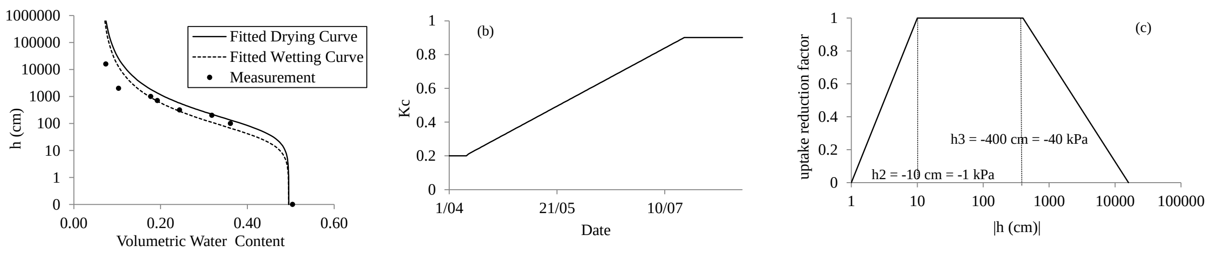


Fig. 5.3 The fitted drying and wetting curve using Van genuchten (1980) for the soil layer (0-30 cm) (a), the crop factor (K_c) derived from Girona (2004) which relates reference evapotranspiration (ET_o) to maximal crop evapotranspiration (ET_c) (b) and the water stress response function as used by Feddes (1978) and as used in the calculation of Ψ_{soil} (c).

Table 5.1 Soil properties used in HYDRUS simulation.

	Fitted Van genuchten (1980) parameters							
Soil layers	θr	θs	α_d (cm^{-1})	α_w (cm^{-1})	n	l	R²	K_{sat} (cm/day)
1 (0-45 cm)	0.06	0.5	0.015	0.03	1.4	0.5	0.96	144
2 (45-75 cm)	0.09	0.43	0.01	0.02	1.4	0.5	0.91	144
3 (75-200 cm)	0.09	0.43	0.01	0.02	1.4	0.5	0.91	20

θ_r is residual water content considered at h = -16000 cm = -1600 kPa, θ_s is saturated water content measured at h = 0 cm = 0 kPa and K_{sat} is saturated hydraulic conductivity. α_d reflects the inverse of the air-entry value during drying of the soil, α_w during wetting of the soil, n pore size distribution and l pore-connectivity (Van genuchten, 1980).

5.2.6.3 Evapotranspiration

Evaporation and transpiration was combined in the calculation as evapotranspiration (ET). Evapotranspiration (ET_c) of the tree was estimated with the crop specific K_c factor and ETo (Allen et al., 1998).

$$ET_c = K_c \, ET_o \tag{5.5}$$

The K_c factor was assumed to be 1.06 times higher than measured by Girona et al. (2004) (Fig. 5.3b) who obtained a ‘Conference’ pear tree K_c factor in a lysimeter in an orchard planted where distance between the trees in the row was 1.06 lower than the orchard in Sint-Truiden. This assumption was made due to the lack of actual measurements of light interception. The water stress response reduction function, α(h) in Eq. (5.2), used in the study is described by Feddes et al. (1978) as implemented in HYDRUS:

$$\alpha(h)=\begin{cases}\frac{h-h_4}{h_3-h_4} \text{ when } h_3>h>h_4\\ 1 \text{ when } h_2\geq h\geq h_3\\ \frac{h-h_1}{h_2-h_1} \text{ when } h_1>h>h_2\\ 0 \text{ when } h\leq h_4 \text{ and } h\geq h_1\end{cases} \tag{5.6}$$

h_1, h_2, h_3 and h_4 are four critical pressure heads for root water uptake. Eq. (5.6) is displayed in Fig. 5.3c. h_1 is pressure head at saturation of the soil at h = 0 cm = 0 kPa, h4 is wilting point at h = -16 000 cm = -1600 kPa. In this study the threshold for water stress h_3 was set to -400 cm = -40 kPa independently from transpiration. In Chapter 4 of this PhD a reduction in sap flux density was observed at a Ψ_{soil} of -60 kPa. In the present experiment it is assumed that sap flow declines starts at -40 kPa, since it was already observed at -60 kPa. The threshold for waterlogging h_2 was set to -10 cm = -1 kPa since it concerns a well structured soil.

5.2.6.4 Initial conditions

Initial conditions were calculated with HYDRUS for a simulation period prior to the Ψ_{soil} observation period. Ψ_{soil} was calculated between 01/04/2009 and 03/06/2009 prior to the Ψ_{soil} observations in plot A. Ψ_{soil} was calculated between 01/04/2011 and 19/04/2011 prior to the Ψ_{soil} observations in plot B and C. On April 1st the soil was assumed to be at Field Capacity, -10 kPa, over the entire flow domain. 1 April can be considered as the end of winter in Belgium and the beginning of ‘Conference’ pear transpiration.

5.2.6.5 Root distribution

The normalized root distribution β(x, z) can in HYDRUS be described by the following function proposed by Vrugt et al. (2001a):

$$\beta(x,z)=\left[1-\frac{x}{x_m}\right]\left[1-\frac{z}{z_m}\right]e^{-\left(\frac{p_x}{x_m}|x^*-x|+\frac{p_z}{z_m}|z^*-z|\right)} \tag{5.7}$$

With x_m (m), z_m (m) maximum rooting depths in the X and Z-direction, x and z are distances from the origin in the X and Z-direction. p_x, p_z, x^* and z^* are empirical parameters.

Maximum rooting depths (x_m and z_m) were for all plots derived from the coarse root excavation and the RLD observations to -90 cm in plot A. Maximal rooting length in X direction (x_m) was assumed 2 m and maximal rooting depth in Z (z_m) direction was assumed 0.9 m. For each plot the empirical parameters p_x, p_z, x^* and z^* were first parameterized based on the observations of root length density of the fine roots (cm/cm³) (RLD). Next the function was parameterized based on the observations of root weight density (g/cm³) (RWD). Thirdly the function was parameterized based on two root distributions found in literature. Root observations in literature for pear tree are scarce but root distribution of apple was sampled by various authors. Gong et al. (2006) documented RLD observations for a 7 year old apple tree on a loam soil. Besharat et al. (2010) documented RLD observations for a 6 year old apple tree on a clay loam soil. Both root distributions were used to parameterize root density in the present Ψ_{soil} calculations.

This way four Ψ_{soil} calculations per plot where executed: (1) Ψ_{soil} calculated with β(x, z) based on observed RLD, (2) Ψ_{soil} calculated with β(x, z) based on observed RWD, (3) Ψ_{soil} calculated with β(x, z) based on RLD observations of Gong et al. (2006) and (4) Ψ_{soil} calculated with β(x, z) based on root RLD observations of Besharat et al. (2010). Purpose of the four simulations was to evaluate to what extent an *in situ* observation of root distribution contributes to a good calculation of Ψ_{soil} which was one of the objectives of the study.

5.2.6.6 Comparison between observation and calculation

Each Ψ_{soil} calculation in the flow domain was registered with six observation nodes placed at the location of the Watermark Ψ_{soil} sensors. The average daily output of the Watermark sensor was compared with the average daily Ψ_{soil} calculated on the corresponding observation node. The coefficient of determination (R^2) and the root mean square error (RMSE) were used to quantify the quality of the simulation.

Besides Ψ_{soil} also average θ in the flow domain was calculated in the time steps when θ was measured. Average θ and observed θ was compared for the soil layers 0-30 cm and 30-60 cm.

5.2.7 Plant water status

Plant water status was recorded in plot B and C on 3 trees per plot by measurements of sap flow and stem water potential (Ψ_{stem}). Objective was to observe possible water stress in the non irrigated plot C and to see whether it was reflected in the HYDRUS calculation of root water uptake.

5.2.7.1 Sap flow

Sap flow was monitored with thermal dissipation (TD) probes. Two needles of 2 mm diameter and 20 mm long were inserted in the trunk 10 cm apart. The upper probe was heated with a constant power of 0.2 W. Based on the temperature difference between the two needles sap flux density (J_p, $m^3\ m^{-2}\ h^{-1}$) was calculated according to Granier (1985) who derived an empirical relationship between J_p and a dimensionless flow index K.

$$\mathrm{Jp} = 0.0119\ \mathrm{K}^{1.1231} 3600 \tag{5.8}$$

$$\mathrm{K} = \frac{\Delta \mathrm{To} - \mathrm{T}}{\Delta \mathrm{T}} \tag{5.9}$$

ΔT0 is the temperature difference under zero flow conditions which was taken as the temperature difference at night, when temperature difference between upper and lower probe was highest.

Sap flow observations using the TD technique cannot be considered as an absolute estimate of sap flow or sap flux density (Gonzalez-Altozano et al., 2008; Steppe et al., 2010). The major drawbacks of the technique are that Eq. (5.9) is an empirical relationship which can differ between tree species. Furthermore the basic assumptions using this technique are debatable: uniform sap flow in the entire conducting sap wood area, zero sap flow at night and no vertical temperature gradient. Consequently water stress can only be detected by comparing a well irrigated plot, in this case plot B, with less irrigated plot, in this case plot C. According to Fernandez et al. (2008) this approach leads to satisfactory water stress observations.

5.2.7.2 Stem water potential (Ψ_{stem})

On 3 trees in plot B and C Ψ_{stem} measurements were carried out on 06/05/2011, 24/05/2011, 30/06/20111 and 08/07/2011 on sunny days without rainfall. For each measurement 3 leaves per tree 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.

5.3 Results

5.3.1 Ψ_{soil} and θ observations

In all plots irrigation was initiated approximately one month after the start of the observation period. During the observation periods irrigation events alternated with periods of rainfall (Fig. 5.4). Although observed in different years, Ψ_{soil} observations in plot A (Fig. 5.4a) and plot B (Fig. 5.4b) were quite similar. Ψ_{soil} on the irrigated side of the three (position 1, 2 and 3) decreased to -30 kPa while on the non irrigated side (position 4, 5 and 6) Ψ_{soil} decreased to -50 kPa. Ψ_{soil} increased rapidly to 0 kPa when irrigation was applied. In the non irrigated C plot Ψ_{soil} depleted to -70 kPa on position 2 and to -120 kPa on position 1 (Fig. 5.4c).

Observations of θ were correlated with the Ψ_{soil} observations. R^2 between θ sampled in the soil layer 0-30 cm and observed Ψ_{soil} was 0.80, R^2 between θ sampled in the soil layer 30-60 cm and observed Ψ_{soil} was 0.45.

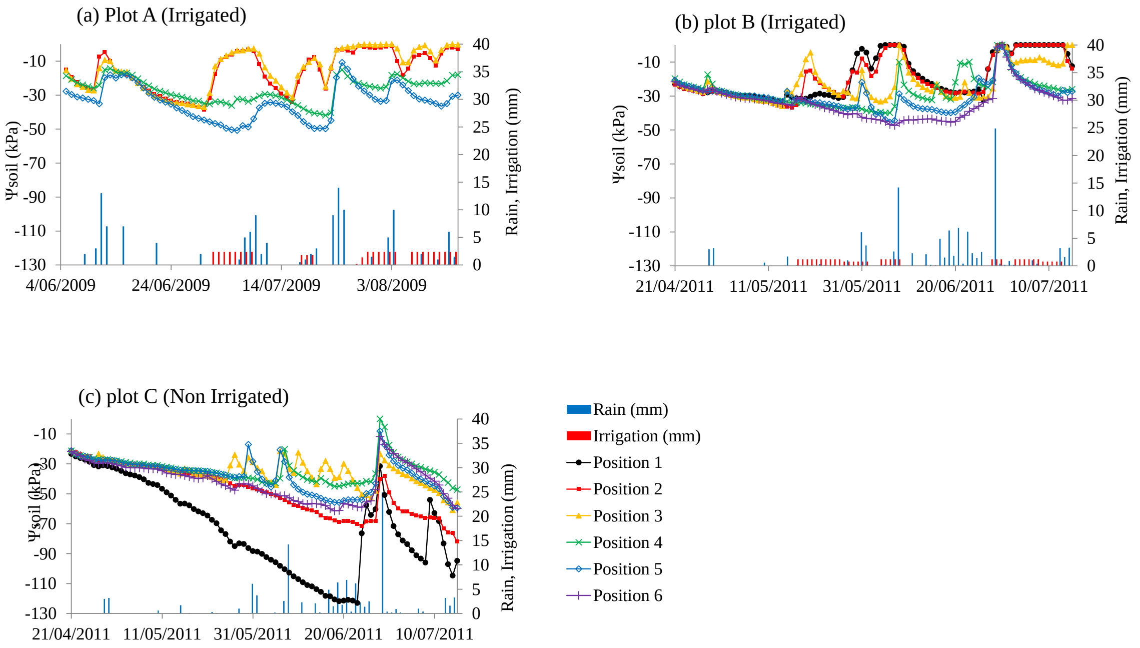


Fig. 5.4 Rainfall, Irrigation and Ψ_{soil} observations with watermark sensors at a depth of 30 cm in plot A (a), plot B (b) and plot C (c). Position of the sensors is outlined in Fig. 5.1.

5.3.2 Root distribution

Coarse roots of the tree excavated in plot A rooted to a depth of 70 cm and reached the borders of the weed free strip beneath the canopy (Fig. 5.5). Fine roots were observed to a depth of 90 cm as presented in the relative root distributions (Fig. 5.6a, b). Maximal fine root density in plot A was observed at a depth of 22.5 cm while in other plots maximal fine root density was observed just beneath the soil surface (Fig. 5.6c, d, e, f). Maximal fine root density was not always observed close to tree. RLD was for plot B and C higher at 35 cm and 50 cm from the trunk. In plot A there was a good correspondence between RLD and RWD, R^2 between both was 0.52. In plot B and plot C accordance was only moderate with R^2 being 0.20 and 0.19 respectively. Root distributions derived from literature showed the highest RLD close to the tree (Fig. 5.6g). Distribution in the Z direction was similar to the observations in plot B and C (Fig. 5.6h).

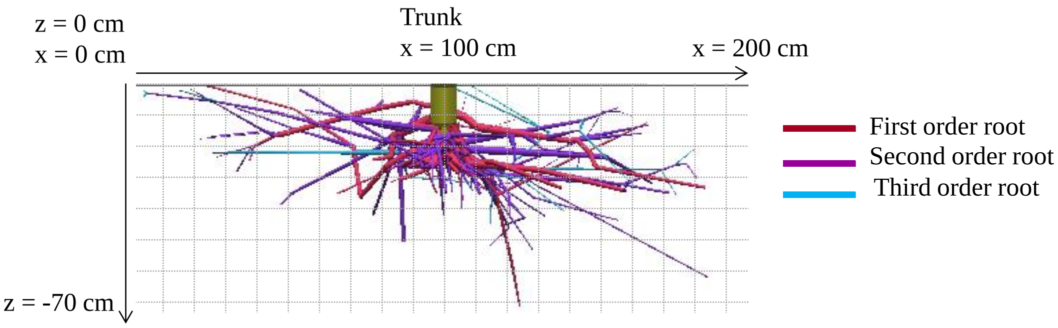


Fig. 5.5 Schematic of coarse roots of the tree in plot A obtained after excavation of the tree. Root architecture was measured in the lab with a compass, inclinometer and caliper and registered in the software ARCHIROOT (Dupuy, 2003).

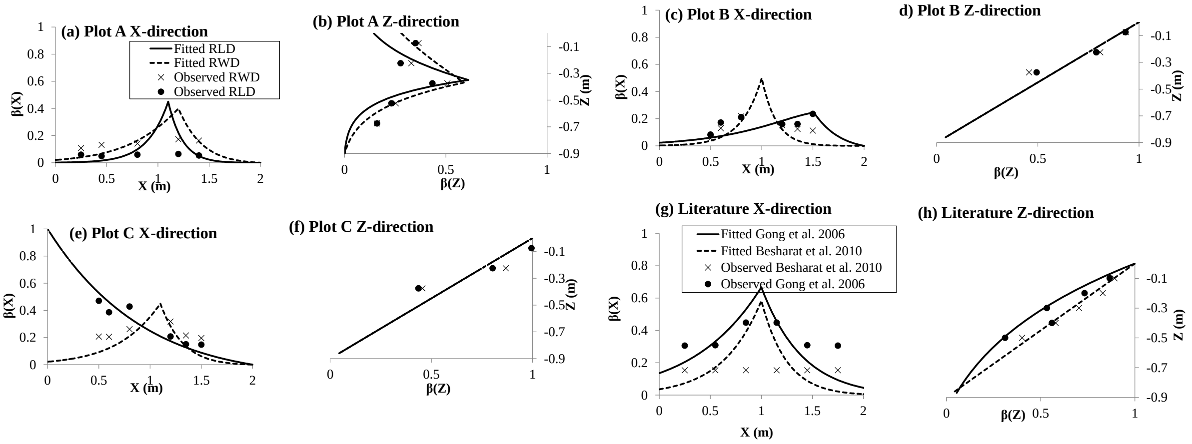


Fig. 5.6 Root distributions β(x,z) used in the HYDRUS calculations. β(x,z) was fitted using the equations suggested by Vrugt (2001) through RLD and RWD observations in plot A (a, b), plot B (c, d), plot C (e, f) and through RLD observations reported in literature (g,h). Parameters of β(x,z) according to Vrugt (2001) are presented in Table 5.2.

It was possible to fit the root distribution function β(x,z), suggested by Vrugt et al. (2001a) (Eq. 5.7), through the fine root observations (Table 5.2). For all plots the quality of the fit was satisfying with R^2 0.70 or higher. Only for plots A and B the R^2 of the fit through the observed RLD was lower in the X-direction. In the Z-direction R^2 between the fit and the observations was higher than 0.73 for all plots. An interesting relation was observed between Ψ_{soil} recorded on 15/05/2011 in plot B and C and the corresponding RLD (Fig. 5.7). Between the start of the observation period and 15/05/2011 no irrigation was executed yet and rainfall was limited so that the observed variation in Ψ_{soil} reflects the water uptake pattern of the trees. No similar correlation could be observed between Ψ_{soil} and RWD.

Table 5.2 Parameters that define the root distributions β(x,z) used in the HYDRUS calculations according to Vrugt (2001). x_m, z_m *maximum rooting depths in the X and Z-direction, x and z are distances from the origin in the X and Z-direction.* p_x, p_z, *r* and z* are empirical parameters,* R^2*: Pearson correlation coefficient between observed and fitted β(x,z). β(x,z) is plotted in Fig5.6.*

Plot nr	Observations	Horizontal (X) direction				Vertical (Z) direction			
		x_m	x*	p_x	R^2	z_m	z*	p_z	R^2
Plot A	RLD	2	1.1	12	0.58	0.9	0.35	5	0.69
	RWD	2	1.2	6.5	0.74	0.9	0.37	3.1	0.93
Plot B	RLD	2	1.51	5	0.27	0.9	0	0	0.92
	RWD	2	1	12	0.74	0.9	0	0	0.87
Plot C	RLD	2	0	1.4	0.90	0.9	0	0	0.97
	RWD	2	1.1	7	0.97	0.9	0	0	0.95
Literature	Gong et al. (2006)	3	1	6	0.78	1	0	1	0.95
	Besharat et al. (2010)	2.4	1	8	0.88	0.9	0	0	0.96

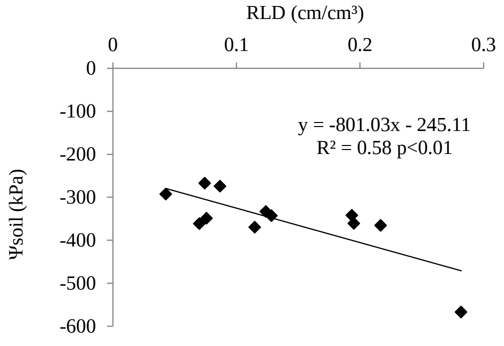


Fig. 5.7 Relation between Ψ_{soil} *recorded with the Watermark sensors on 15/05/2011 in plot B, C and RLD on the same position.*

5.3.3 Numerical calculations with HYDRUS

The calculation of Ψ_{soil} corresponded reasonable with the Ψ_{soil} observations (Table 5.3). However in the non irrigated plot C a satisfying calculation of Ψ_{soil} was only possible when β(x,z) was based on RLD. Calculation of Ψ_{soil} with β(x,z) based on RWD or root distributions found in literature yielded large errors. In plot A and B the calculation of Ψ_{soil} was only slightly better when β(x,z) was based on RLD compared to RWD or observations derived from literature.

Table 5.3 Quality of the HYDRUS calculation in each plot quantified by the R² between observation and simulation and the RMSE expressed in kPa. The numerical calculation of Ψ_{soil} by HYDRUS was based on root distributions parameterized with Root Length Density (RLD), Root Weight Density (RWD) and root observations described in literature (Gong et al. 2006, Besharat et al. 2010).

	Observed RLD		Observed RWD		Gong et al. 2006		Besharat et al. 2010	
Plot	R²	RMSE (kPa)	R²	RMSE (kPa)	R²	RMSE (kPa)	R²	RMSE (kPa)
A	0.57	11.26	0.52	11.23	0.50	11.35	0.52	11.68
B	0.49	10.20	0.42	11.35	0.41	10.94	0.42	11.22
C	0.46	16.87	0.03	22.15	0.07	21.38	0.05	21.66

Overall correlation between all Ψ_{soil} observations and the corresponding Ψ_{soil} calculations was 0.56, RMSE was 13.40 kPa (Fig. 5.8a) when β(x,z) was parameterized with RLD. Accordance between calculated and observed Ψ_{soil} was erratic when observed Ψ_{soil} ranged between -20 kPa and 0 kPa. Ψ_{soil} observed by the Watermark sensor was in this range always lower compared to Ψ_{soil} achieved by the numerical calculation. Observations of θ agreed likewise with the calculated θ (Fig. 5.8b), at the depth of 30-60 cm R² was slightly lower compared to 0-30 cm depth.

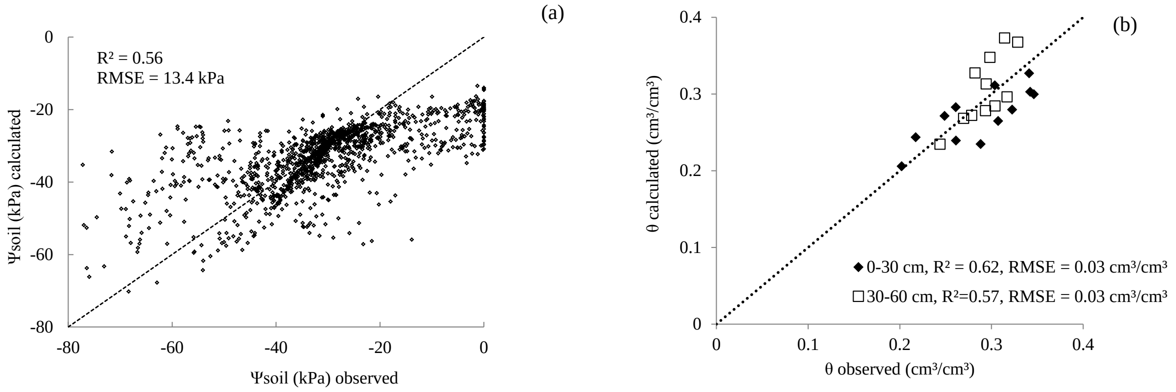
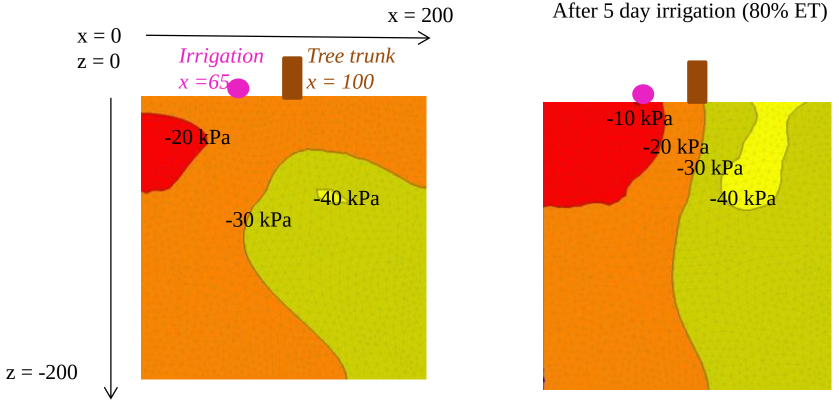


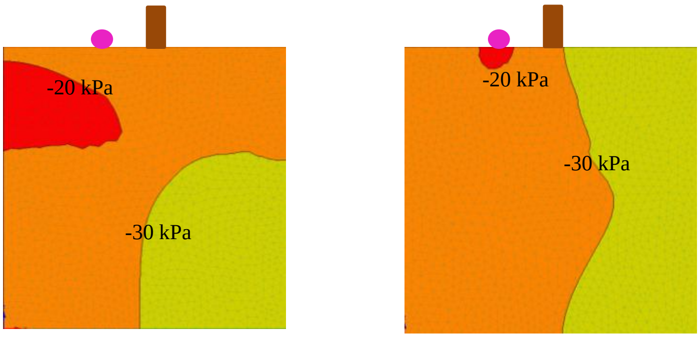
Fig. 5.8 Agreement between all (n = 1320) Ψ_{soil} observations (a) and all (n=24) θ observations (b) and the corresponding numerical calculations of Ψ_{soil} and θ. Root distributions of the numerical calculations were based on RLD.

The numerical calculation showed how water was distributed in the root zone after irrigation. After a 80% ET irrigation period in plot A Ψ_{soil} increased above –20 kPa in the entire irrigated side of the tree to a depth of 70 cm (Fig. 5.9a,b). By applying 50% ET irrigation in plot B Ψ_{soil} increased to -20 kPa only on a distance of 15 cm from the dripper (Fig. 5.9c, d).



(a) Plot A on 27/07/2009

(b) Plot A on 01/08/2009
After 5 day irrigation (80% ET)



(c) Plot B on 01/07/2011

(d) Plot B on 06/07/2011
After 5 day irrigation (50% ET)

Fig. 5.9 Output of the Ψ_{soil} *calculation in plot A on 27/07/2009 (a), 01/08/2009 (b) and plot B on 01/07/2011 (c) and 06/07/2011 (d) before and after a 5 day irrigation period of respectively 80% ET and 50% ET.*

5.3.4 Plant water status

During the first two measurements there was no differentiation in Ψ_{stem} between plot B and C (Fig. 5.10a). During the last two measurements at the end of the month June and the beginning of July, when irrigation was applied in plot B, there was differentiation between the treatments. The overall lowest Ψ_{stem} was -1.36 MPa and was observed in the non irrigated plot C.

Between 3 July and 9 July J_p tended to be lower in the non irrigated plot C compared to the irrigated plot B (Fig. 5.10b). The difference in J_p was only observed at noon, in the middle of the day, when evaporative demand was highest.

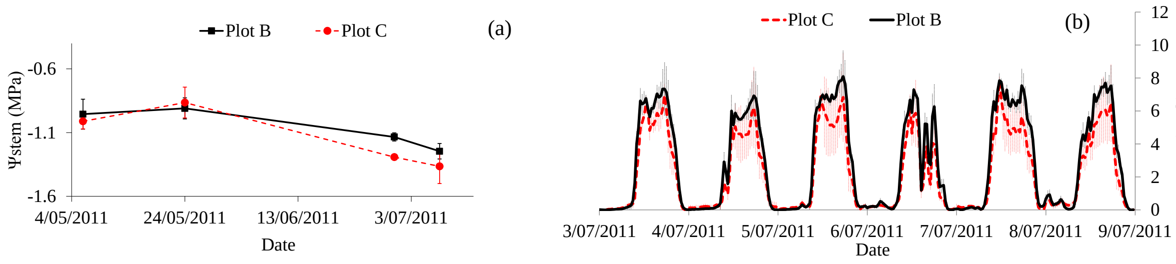
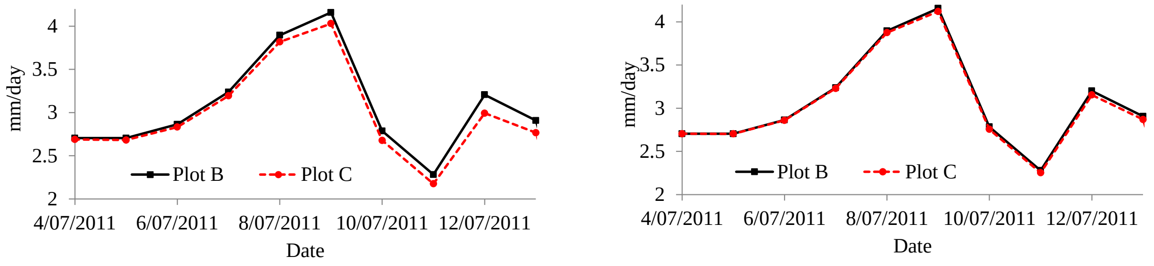


Fig. 5.10 Ψ_{stem} (a) and sap flux density (J_p) (b) observed in plot B and C. Vertical bars indicate standard deviation measured over three measurements per plot.

In the numerical calculation of root water uptake plot C differed from plot B when the root distribution function β(x,z) was derived from RLD (Fig. 11a) but not when β(x,z) was derived from RWD (Fig. 5.11b).


(a) Root distribution based on RLD

(b) Root distribution based on RWD

Fig. 5.11 Calculated root water uptake for HYDRUS calculation with root density function β(x,z) based on RLD (a) and RWD (b).

In general the numerical calculated Ψ_{soil} agreed reasonable with the observed Ψ_{soil} but the accordance between calculated and observed Ψ_{soil} was erratic when Ψ_{soil} was higher than -20 kPa. In one of the three plots, the non irrigated C plot, a reasonable accordance between calculated and observed Ψ_{soil} was only possible when the root distribution function β(x,z) was parameterized based on RLD. In this plot mild effects of water stress could only be shown in the numerical calculation when β(x,z) was parameterized using RLD. For other plots the chosen root distribution had less influence on the quality of the simulation although RLD still yielded the best results.

5.4 Discussion

First objective of the experiment was to evaluate the correspondence between the numerical calculated Ψ_{soil} and observed Ψ_{soil} with watermark sensors. Second objective was to investigate the sensitivity of the Ψ_{soil} calculation to the implemented root distribution. Both objectives should contribute to a better knowledge of the calculation of Ψ_{soil} patterns in ‘Conference’ pear orchards. This should result in more optimal placement of watermark Ψ_{soil} sensors, frequently used for irrigation scheduling in pear orchards.

5.4.1 Numerical calculation of Ψ_{soil}

Reported measurement variation from the Watermark sensor (Leib et al. 2003, Nolz et al. 2013) lies between 14 and 27%. The overall average Ψ_{soil} observation in this experiment was -32.5 kPa which means that 35% to 67% of the overall RMSE in this experiment can be allocated to measurement variation from the sensor. Possible sources of the variation in Ψ_{soil} calculation are the variability of soil hydraulic properties, variability of active root distribution, variability of runoff, variability of deep percolation and estimations of crop transpiration.

General accordance between the calculated Ψ_{soil} and the observed Ψ_{soil} was equal to previous similar root water uptake calculations in fruit trees. Gong et al. (2006) calculated root water uptake of a mature apple tree in 2D with the root zone parameterized from root length observations. Calculated soil water distribution in the soil was compared to TDR observations of soil water content. R^2 ranged between 0.63 and 0.70 for 220 observations. In the present study overall R^2 between calculated Ψ_{soil} and observed Ψ_{soil} was 0.56 for 1320 observations. Zhou et al. (2007) calculated root water uptake of irrigated grape in 2D with HYDRUS and parameterized the root zone from root length observations. Calculated soil water distribution was compared to soil moisture measurements recorded with FDR probes. RMSE between observed and calculated soil water content ranged between 0.01 and 0.03 cm^3/cm^3. In the present study RMSE between observed and calculated soil moisture was 0.03 cm^3/cm^3.

Main drawback of the Ψ_{soil} calculation was the poor accordance between calculated and observed Ψ_{soil} in the range between 0 and -20 kPa. Just after irrigation events, or heavy rainfall, the observed Ψ_{soil} increased rapidly to 0 kPa while dryer Ψ_{soil} values were calculated by HYDRUS. The mismatch between observed and calculated Ψ_{soil} can be allocated to the inability of the Watermark sensor to measure matrix potentials higher than the air entry pressure of the sensor which is about -10 kPa (Scanlon et al., 2002). The unreliable Ψ_{soil} observation in the wet range just after rainfall and irrigation events has previously been observed in similar conditions (chapter 2, this PhD) and can be explained further by hysteresis in the wetting curve from the sensor and failure in dynamic response after partial rewetting of the soil (McCann et al., 1992; Scanlon et al., 2002). In this wet range the calculated Ψ_{soil} probably approximates the true Ψ_{soil} better. This implicates that sensor placement in the wet range of the soil, with Ψ_{soil} above -20 kPa, leads to overestimation of Ψ_{soil}. This increases the risk of inaccurate irrigation scheduling, especially when Ψ_{soil} is maintained close to -30 kPa such as e.g. Janssens et al. (2009) which reflects farmers practices in Belgium. The Ψ_{soil} calculation in the experiment showed that after irrigation to a rate of 80% ET the wet range of the soil extended to the entire irrigated side of the tree to a depth of 70 cm.

5.4.2 Sensitivity of the calculation to the selected root distribution

Root length concentrations in the three plots showed a gradual decrease with depth similar to Gong et al. (2006), Besharat et al. (2011), Yao et al. (2011) and others. In the horizontal direction root maximal length densities were observed at 30 and 50 cm distance from the tree trunk. Green and Clothier (1999) showed already for apple that maximal root length concentrations not are necessarily situated close to the trunk. On the contrary root weight concentration, was always higher close to the tree trunk in accordance to coarse root observations in one of the plots. The discrepancy between mass and length of fine roots was previously observed by Oppelt et al. (2005) in tropical fruit tree species.

In the majority of root water uptake studies in fruit trees, the root zone is parameterized based on observed root length distribution (Gong et al., 2006; Green and Clothier, 1999; Green et al., 2003; Yao et al., 2011; Zhou et al., 2007). Only Satchithanantham et al. (2014) expressed recently root distribution in terms of weight distribution by discussing the water uptake of potato. Determining fine root length is slightly more time consuming then achieving fine root weight since roots need to be scanned photographically. For two of the three plots (plot A and B) the quality of the numerical calculation was comparable between calculations based on RLD and RWD. However in one of the three plots (plot C) a satisfying calculation of Ψ_{soil} was only possible using RLD to parameterize the root zone. Furthermore mild water stress in this plot, observed by depressed Ψ_{stem} and altered sap flux density, could not be reproduced by HYDRUS when parameterizing the root zone using RWD. Likewise RLD could be correlated to Ψ_{soil} observations, similar to observations in olive (Searles et al., 2009), while RWD could not. The relationship between RLD and Ψ_{soil} variation was dominated by the observations in the non-irrigated Plot C where the highest RLD were observed at the sensors where the lowest Ψ_{soil} was measured. This observation needs to be confirmed by other similar observations but may illustrate how fine root growth is related to water uptake. Previously Green and Clothier (1995) addressed the altered root water uptake patterns in kiwi fruit vine mainly to changes in root distribution. Garré et al. (2011) showed the relation between soil wetting and root growth in a lysimeter. It makes sense that fine root growth is better captured with RLD rather than RWD.

Likewise the calculation of root water uptake using root distributions derived from literature yielded good results in two out of the three plots (plot A and B) it failed in the third plot (plot C). In this case literature root observations were taken from apple orchards (Besharat et al., 2010; Gong et al., 2006) due to the lack of root observations in pear orchards but a similar deficient Ψ_{soil} calculation can be expected when using root observations from other pear tree orchards. The present experiment shows how root distribution is tree specific and that it has significant impact on the numerical calculation of Ψ_{soil}.

5.5 Conclusion

With the present experiment it was shown how Ψ_{soil} observations measured with Watermark sensors agreed reasonable with numerically calculated Ψ_{soil}. Only when observed Ψ_{soil} increased above -20 kPa the observed Ψ_{soil} did not correspond with the calculated Ψ_{soil}, possibly due to the limitations of the Watermark sensors to measure Ψ_{soil} in the wet range, above -20 kPa. This suggests positioning sensors close to the irrigation drippers should be avoided to prevent overestimation of Ψ_{soil} and inaccurate irrigation scheduling. In the present experiment this wetting front in the soil, with Ψ_{soil} above -20 kPa, extended to a depth of 70 cm on the entire irrigated side of the tree when irrigation was applied to a rate of 80% ET. The wetting front remained concentrated around the drippers when irrigation was applied to a rate of 50% ET. Furthermore it was shown how site specific observations of RLD are preferred to parameterize the root zone for a reliably calculation of Ψ_{soil}. The Ψ_{soil} calculation with the root distribution parameterized by RLD gave satisfactory results for all plots, while a Ψ_{soil} calculation based on other root observations, like RWD or root distributions found in literature, did not. It evidences that root zone parameterization has a significant influence on the Ψ_{soil} calculation in pear orchards.

6 In search of the optimal N fertigation dose for ‘Conference’ pear tree

Adapted from: Janssens P, Deckers T, Elsen F, Verjans W, Schoofs H, Elsen A, Vandendriessche., 2012. In search of the optimal N fertigation dose for ‘Conference’ pear trees. H. NUTRIHORT Proceedings 272-277.

6.1 Introduction

Over the past years pear fruit (*Pyrus communis* L. 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). Market price of fruits having a diameter of >60 mm is twice the price of smaller sized fruits (<55 mm). In dry years the price difference between large and small fruits increases significantly. The high market price for large fruit sizes has pushed the fruit growers to the implementation of irrigation systems.

The presence of an irrigation installation allows fruit growers to fertigate by dissolving fertilizers in the irrigation water. Fertigation allows a precise distribution of the nutrients in the root zone and increases nutrient uptake efficiency (Yin et al., 2009). Nitrogen (N) is one of the nutrients which strongly relates to fruit yield (Liu et al., 2013; Sanchez et al., 2002) in different pear varieties. However over-fertilization can lead to extensive vegetative growth of the tree with consequences to fruit set decline (Sanchez et al., 2002). Furthermore excessive N fertilization leads to NO_3^--N leaching which conflicts with current environmental policies in Europe (EC, 1991). The reported N fertilization for *Pyrus communis* doses vary between regions, rootstock and cultivar. Duarte et al. (2010) uses a fertilization dose of 44 kg N/ha for a fertilization experiment in ‘Rocha’ pear. Yin et al. (2009) uses 112 kg N/ha for ‘Anjou’ pear and Sanchez et al. (1991) considers 100 kg N/ha as a low fertilization dose and 145 kg N/ha as a high fertilization dose for ‘Comice’. An N fertilization experiment is recommenced to achieve specific guidelines for N recommendation for ‘Conference’ pear in the temperate climate in Belgian and the Netherlands. Especially since N is applied by fertigation, which increases efficiency of the N fertilization (Yin et al. 2009).

Optimal N fertigation should permit to achieve maximal fruit yield but also aim for an optimal fruit quality. Consumers are prepared to pay more when a good taste quality of the fruit is guaranteed (Pinto et al., 2008). Taste quality seems positively related to the total concentration of solids (TSS) and the total acidity (Jaeger et al., 2003; Kappel et al., 1995; Steyn et al., 2011). Furthermore fruit appreciation by consumers is positively related to fruit firmness and a greener fruit color (Kappel et al., 1995).

Fruit quality has been reported to vary with tree water status an tree N status. Deficit irrigation schemes have been reported to increase TSS, improve sugar acid ratio (Cui et al., 2008; Marsal et al., 2000). On the other hand fruit color was more yellow (Ramos et al., 1994). N status of the pears has been reported to influence fruit firmness (Liu et al. 2013; Sanchez et al. 2002).

Therefore the objective of the current experiment is twofold: firstly study the yield response of ‘Conference’ pear to different levels of N fertigation during the preharvest period and secondly outline its implications for fruit quality. The effect of the different N fertigation levels is studied in different irrigation regimes to reveal possible interactions.

6.2 Materials and methods

6.2.1 Experimental sites

In Belgium in the pear trees (*Pyrus Communis* L. cv. ‘Conference’) full bloom takes place mid of April, followed by a period of intensive cell multiplication until the end of May. June and July are characterized 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 (Table 6.1) were selected for this study: an intensively planted orchard on a dry profile on a slope situated in Bierbeek (50°49'36.35"N, 4°47'40.35"E), and two older less intensively planted orchards in Meensel (50°53'40.20"N, 4°55'38.12"E) and in Sint-Truiden (50°45'59.46"N, 5° 9'24.68"E). In these three orchards a fertigation experiment was set up in 2008 and 2009.

Table 6.1 Characteristics of the three orchards

Orchard	Bierbeek	Meensel	Sint-Truiden
Rootstock	Quince C	Quince Adams	Quince Adams
Planting year	2000	1996	1996
Planting Distance	3.3 m x1 m	3.5 m x 1.5 m	3.5 m x 1.25 m
Training system	Intensive V system	Free spindle	Free spindle
Average tree height	3.5 m	3.5 m	3.3 m
Soil texture upper soil layer (0-30 cm)	Silt	Silt	Silt Loam
Root pruning	Yes, yearly except 2008	No	No
Other characteristics	Situated on a slope	Shallow ground water table (1.5 m-2 m)	-

6.2.2 Mineral soil analysis in the three orchards

According to soil analysis (Table 6.2) and compared to the soil fertility classes published by SSB (Maes et al. 2012) K content in the soil in the three orchards was rather high. Mg content in the soil was normal for Sint-Truiden and Meensel but rather high for Bierbeek. In Sint-Truiden pH was rather low, in the two other orchards pH was in the optimal zone. In the three orchards % C was in the reference zone.

Mineral NO_3^--N content in the soil was low in Meensel and Sint-Truiden, rather high in Bierbeek since NO_3^--N leaches out of the soil profile in winter.

Table 6.2 pH, %C, K, Mg and NO3$^-$-N content of the soil in the three orchards at the beginning of the experiment. pH, K, Mg were measured in A.L.-extract, NO_3^--N content was measured in a water extract.

Orchard	Bierbeek	Meensel	Sint-Truiden
pH upper soil layer (0-23 cm)	6.7 ± 0.1	7.0 ± 0.1	6.4 ± 0.1
Carbon content (C) upper soil layer (0-23 cm) (mg/100 g)	1.6 ± 0.2	1.5 ± 0.2	1.4 ± 0.1
Potassium (K) content upper soil layer (0-23 cm) (mg/100 g)	51.2 ± 3.2	28.3 ± 5.4	35.5 ± 4.0
Magnesium (Mg) content upper soil layer (0-23) (mg/100 g)	31.0 ± 2.5	16.7 ± 2.9	9.8 ± 0.4
Mineral NO_3^--N content soil profile (0-90 cm) (march 2008)	66.6 kg	30.9 kg	24.1 kg

6.2.3 Experimental treatments

In all orchards a drip irrigation system was installed with drippers every 20 cm with a discharge rate of 2 l/h. The orchards were also equipped with a “Dosatron” pumping unit to disperse fertilizers through the drippers alongside with the irrigation water. In all orchards two different irrigation regimes where installed. A Full Irrigation regime (FI), where 100% ET_c was applied. A Deficit Irrigation (DI) regime was set up where rain repelling screens were installed under the trees in the months June and July to insure root zone depletion. During the months of June and July no irrigation was supplied in the DI treatment. In the months of April, May and August the DI treatment was irrigated equal to the FI treatment.

One month before bloom in 2008 and 2009 all orchards received a basic fertilization containing 30 kg N/ha using mineral fertilizers applied directly on the weed free strip below the canopy. In Bierbeek in

2008 only 20 kg N/ha was applied as basic fertilization. The basic N fertilization was supplied using NH_4NO_3 which contains 27% N. Only in Sint-Truiden in 2009 a slow release N formulation “Entec-Perfect” was used which contains 14% N. In all orchards every irrigation regime (FI and DI) was subjected to three fertigation doses; 0 kg N/ha, 25 kg N/ha and 50 kg N/ha supplied by solving $Ca(NO_3)_2$ in the irrigation water. In the 25 kg N/ha treatment, fertigation was applied during 5 days. Each day 5 kg N/ha was solved in the irrigation water using liquid $Ca(NO_3)_2$ which contains 8.7 %N on a mass basis. In the 50 kg N/ha treatment fertigation was applied during 10 days. The fertigation was applied at the end of the shoot growing period, approximately 6 weeks before harvest.

The irrigation-fertigation regimes were applied in plots of four trees separated by two buffer trees. Each irrigation-fertigation combination was replicated four times in a randomized bloc design.

6.2.4 Meteorology

Cumulative rain deficit in 2008 between 01 April and 31 August was 127 mm while 242 mm in 2009. Especially during July and August evaporative demand was higher in 2009 while rainfall was less (Fig. 6.1).

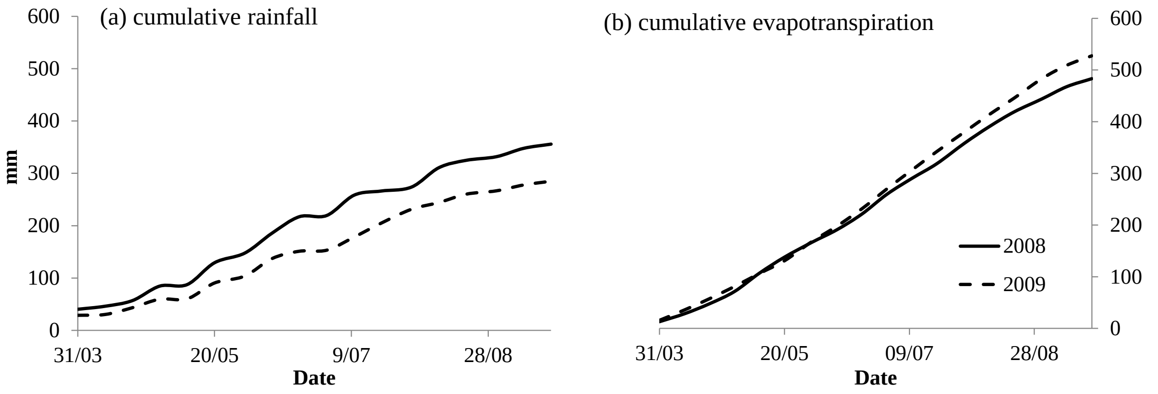


Fig. 6.1 Cumulative rainfall (a) and evapotranspiration (b) during the growing season in 2008 and 2009 for the center of Belgium.

6.2.5 Observations

6.2.5.1 Soil water potential

In the FI and DI treatment soil water potential (Ψ_{soil}) was monitored in three plots in the treatment which received 25 kg N/ha by fertigation. Ψ_{soil} was monitored with three “Watermark” granular matrix sensors per tree (Irrometer Co., USA) at 30 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.

6.2.5.2 Fruit yield and quality parameters

One day before harvest in the commercial orchard, pears of two trees per plot were harvested. After harvest fruit were stored in a cooling room at 1°C for 1.5 month after which 20 fruits per plot were investigated on fruit color, TSS and fruit firmness. Fruit color was measured at the shadow side of the fruits with a Konia Minolta chromameter through chroma and hue values (McGuire, 1992). A higher hue value corresponds with a more green color of the fruit. Afterwards, fruit firmness was measured with a penetrometer (0.5 cm^2 cylinder) after removal of the skin, and Total Soluble Solids (TSS, °brix) was determined with a hand-held refractometer.

6.2.5.3 Mineral content of the fruit and the leaf

After measurement of fruit firmness, the 20 fruits were blended into 1 sample and afterwards all fruits were blended into 1 sample on which N, K, Mg and Ca was determined. Inductive coupled plasma (ICP) for the measurement of Ca, K, Mg- content and a Kjeldahl digestion for the determination of N content.

Mineral content in the leaf was measured on a sample composed of 40 leaves. Leaves were selected after long internodes, being the 2nd and the 3th leaf on the twig. In 2008 the leaves were selected before the start of the fertigation, in 2009 the leaves were selected after the start of the fertigation. On the leaf samples N content was analyzed using Kjeldahl digestion.

Statistical analysis of yield data, fruit quality parameters and the mineral contents of the fruits and leaves was performed using a multifactorial ANOVA test with the STATISTICA software (Statsoft, 2009) with irrigation and fertilization as factor. Data were checked for being normal distributed and homogeneity using the Levene’s test. Data which caused homogenous variances were removed from the dataset before further data analysis.

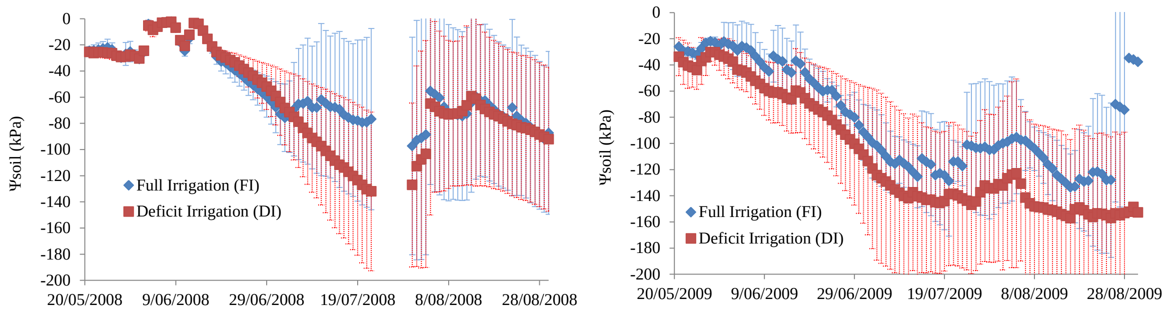
6.3 Results

6.3.1 Soil water potential (Ψ_{soil})

The irrigation had an effect on Ψ_{soil} in 2008 and 2009 (Fig. 6.2). In Bierbeek in 2008 and in 2009 Ψ_{soil} declined -150 kPa in the DI treatment (Fig. 6.2a,b). In 2008, Ψ_{soil} did not decrease as far as in 2009 because irrigation was resumed at the end of July at a higher rate. In 2009 there was also a decrease in Ψ_{soil} in the FI treatment due to a malfunction of the irrigation system during one week. In Meensel in the DI treatment Ψ_{soil} decreased to below -90 kPa in 2009, in 2008 Ψ_{soil} decreased to -60 kPa (Fig. 6.2c,d). In Sint-Truiden, despite similar irrigation regimes as in Bierbeek no decrease in Ψ_{soil} occurred (Fig. 6.2e,f) in the DI treatment. In Meensel and in Sint-Truiden the decrease in Ψ_{soil} in the DI treatment was less pronounced compared to Bierbeek. In the dry range, with $\Psi_{soil} < -60$ kPa, standard deviation between the three plots monitored increased significantly.

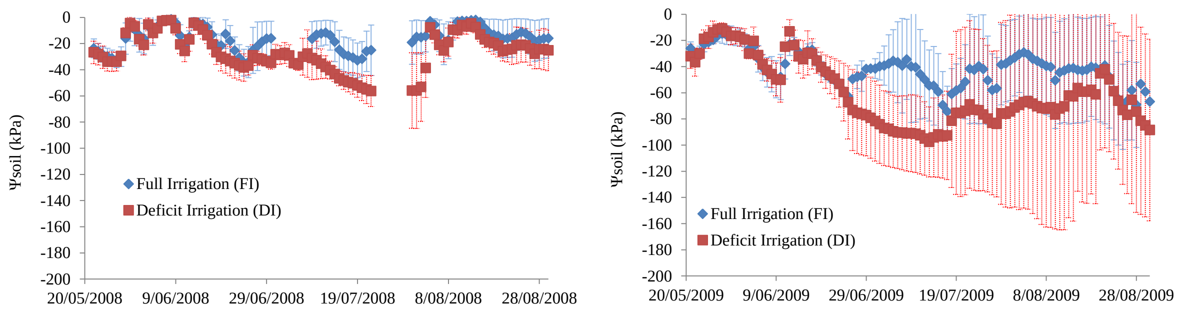
(a) Bierbeek 2008

(b) Bierbeek 2009



(c) Meensel 2008

(d) Meensel 2009



(e) Sint-Truiden 2008

(f) Sint-Truiden 2009

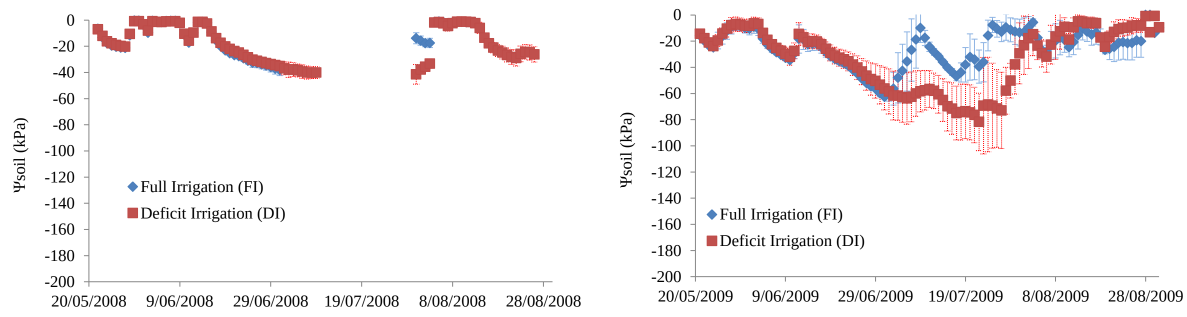


Fig. 6.1 Evolution of Ψ_{soil} observed in three plots in the 25 kg N treatment at a depth of 30 cm in a reference plot per irrigation regime in the three orchards in 2008 and 2009. Vertical bars indicated standard deviation between three sensors.

6.3.2 Fruit yield

Irrigation had an effect on the total fruit in yield in Bierbeek (Table 6.3). In 2009 fruit yield was significantly higher in the FI treatment. In the 0 kg N fertilization treatment fruit yield was 4 kg/tree higher in the FI treatment. In Meensel and in Sint-Truiden fruit yield between the FI and the DI treatment was similar.

Fruit yield varied with the applied fertigation regime in Bierbeek and in Sint-Truiden (Table 6.3). In Bierbeek fruit yield was highest in the 25 kg N fertigation treatment in 2008 and 2009, in the FI treatment and in the DI treatment. In Bierbeek 5 kg more fruit was harvested in the 25 kg N treatment compared to the 0 kg N treatment. In Meensel no pronounced differences in fruit yield were observed when applying the three fertigation doses although yield tended to be higher in the 25 kg N treatment in both the FI and the DI treatment. In Sint-Truiden fruit yield was highest in the 50 kg N fertigation treatment in 2008 and 2009 in both irrigation regimes. In 2008 the difference was significant and conceded 5 kg between the 50 kg N fertigation treatment and the 0 kg N fertigation treatment.

6.3.3 Mineral N content in the leaf

In 2009 at the end of the fertigation period a higher N content in the leaves was observed in Bierbeek and in Meensel when a higher fertigation dose was applied but not in Sint-Truiden (Table 6.4). In 2008 when leaf samples were collected before start of the fertigation no irrigation nor fertigation effect was observed. In Meensel the higher leaf N content was also related to a lower irrigation dose. This was not the case in Bierbeek, maybe because difference in Ψ_{soil} between FI and DI treatment was higher in Meensel-Kiezgem than in Bierbeek.

6.3.4 Mineral and quality parameters of the fruit

Only in 2009 mineral content of the fruits and fruit quality parameters were affected by irrigation and fertigation (Table 6.5). In Bierbeek 2009 Ca content was higher in the DI treatment just as TSS. At same time in Bierbeek in 2009 N content in the fruits increased by a higher N fertigation dose. Also fruit color was more green when N fertigation dose was higher. A similar effect on fruit color was observed in Meensel in 2009. In Meensel in 2009 also the interaction term between irrigation and fertigation was significant. There was no irrigation nor fertigation effect observed on K content in the fruit, Mg content in the fruit and on fruit firmness.

Table 6.3 Fruit yield in function of the applied fertigation regime 6 weeks before harvest. Data were subjected to a multifactorial ANOVA analysis with irrigation and fertilization as factors.

Orchard	Irrigation treatment	Fertigation treatment	Fruit yield 2008 (kg/tree)	Fruit yield 2009 (kg/tree)
Bierbeek	FI	0 kg N	23.94	21.40 ac
	FI	25 kg N	28.89 a	22.36 a
	FI	50 kg N	25.93	20.70
	DI	0 kg N	22.24 b	17.96 bc
	DI	25 kg N	26.95	22.33 a
	DI	50 kg N	23.32	19.34 c
	Sign. Irrigation (Irri)		ns	**
	Sign. Fertigation (Ferti)		**	***
	Sign. Irri x Ferti		ns	*
Meensel	FI	0 kg N	27.07	22.58
	FI	25 kg N	22.46	24.58
	FI	50 kg N	21.54	20.75
	DI	0 kg N	24.68	21.95
	DI	25 kg N	24.99	22.97
	DI	50 kg N	23.29	23.40
	Sign. Irrigation		ns	ns
	Sign. Fertigation		ns	ns
	Sign. Irri x Ferti		ns	ns
Sint-Truiden	FI	0 kg N	14.14	10.03
	FI	25 kg N	18.14	9.01
	FI	50 kg N	20.41 a	10.34
	DI	0 kg N	13.02 b	10.84
	DI	25 kg N	15.29	12.02
	DI	50 kg N	18.49	14.63
	Sign. Irrigation (Irri)		ns	ns
	Sign. Fertigation (Ferti)		**	ns
	Sign. Irri x Ferti		ns	ns

** , **, *** denote signification (Sign.) of the factor in the ANOVA analysis according to $p < 0.05$, $p < 0.005$, $p < 0.001$ respectively, a, b, c denote significant differences between individual groups according to Tukey HSD test.*

Table 6.4 Leaf N content in the three orchards, in 2008 leaf N sample was taken before start of the fertigation period, in 2009 leaf N samples was assembled 1 day after the end of the fertigation period. Data were subjected to a multifactorial ANOVA analysis with irrigation and fertilization as factors.

Orchard	Irrigation treatment	Fertigation treatment	Leaf N 2008 (before fertigation) (% DW)	Leaf N 2009 (after fertigation) (% DW)
Bierbeek	FI	0 kg N	2.17	2.59
	FI	25 kg N	2.20	2.68
	FI	50 kg N	2.20	2.74 b
	DI	0 kg N	2.20	2.50 a
	DI	25 kg N	2.13	2.65
	DI	50 kg N	2.12	2.79 b
	Sign. Irrigation (Irri)		ns	ns
	Sign. Fertigation (Ferti)		ns	***
	Sign. Irri x Ferti		ns	ns
Meensel	FI	0 kg N	2.20	2.37 a
	FI	25 kg N	2.18	2.49
	FI	50 kg N	2.21	2.49
	DI	0 kg N	2.19	2.48
	DI	25 kg N	2.25	2.62 b
	DI	50 kg N	2.25	2.62 b
	Sign. Irrigation		ns	**
	Sign. Fertigation		ns	**
	Sign. Irri x Ferti		ns	ns
Sint-Truiden	FI	0 kg N	2.45	2.40
	FI	25 kg N	2.38	2.40
	FI	50 kg N	2.36	2.40
	DI	0 kg N	2.35	2.30
	DI	25 kg N	2.35	2.36
	DI	50 kg N	2.38	2.42
	Sign. Irrigation		ns	ns
	Sign. Fertigation		ns	ns
	Sign. Irri x Ferti		ns	ns

** , **, *** denote signification (Sign.) of the factor in the ANOVA analysis according to p < 0.05, p <0.005, p<0.001 respectively, a, b, c denote significant differences between individual groups according to Tukey HSD test.*

Table 6.5 Fruit quality and mineral parameters of the fruits in the three orchards Data were subjected to a multifactorial ANOVA analysis with irrigation and fertilization as factors.

Irrigation	Fertigation	K fruit	Ca fruit	N fruit	Mg fruit	Fruit firmness	TSS	Fruit color
treatment	treatment	mg/100 g				kg/0.5 cm²	°Brix	Hue angle
Bierbeek 2008								
FI	0 kg N	137.91	5.06	41.06	5.16	6.08	13.14	111.21
FI	25 kg N	125.92	5.25	41.97	5.12	5.95	13.09	111.19
FI	50 kg N	130.21	5.08	40.83	5.01	5.99	12.60	112.13
DI	0 kg N	132.70	5.15	40.09	5.26	5.72	13.79	110.19
DI	25 kg N	126.07	4.82	38.26	4.90	5.99	13.27	110.69
DI	50 kg N	130.81	4.74	39.69	5.08	5.69	13.05	110.75
Sign. Irrigation		ns	ns	ns	ns	ns	ns	ns
Sign. Fertigation		ns	ns	ns	ns	ns	ns	ns
Sign. Irri x Ferti		ns	ns	ns	ns	ns	ns	ns
Bierbeek 2009								
FI	0 kg N	150.15	6.51	47.55	6.28	6.29	13.28 a	112.83
FI	25 kg N	141.39	5.95	51.70 a	6.14	6.14	13.84	113.18 a
FI	50 kg N	150.03	5.68	48.46	6.09	6.28	13.41 a	112.66
DI	0 kg N	149.40	6.64	41.35 b	6.16	6.28	14.74 b	111.62 b
DI	25 kg N	150.07	6.70	49.55	6.44	6.20	14.26	112.96
DI	50 kg N	139.31	6.46	53.81 a	6.37	6.07	14.09	113.02
Sign. Irrigation (Irri)		ns	*	ns	ns	ns	***	ns
Sign. Fertigation (Ferti)		ns	ns	*	ns	ns	ns	*
Sign. Irri x Ferti		ns	ns	ns	ns	ns	ns	ns
Meensel 2008								
FI	0 kg N	117.21	5.17	45.64	5.35	5.92	13.28	113.16
FI	25 kg N	123.58	5.23	57.14	6.15	5.96	13.49	112.64
FI	50 kg N	120.82	4.98	54.65	5.95	6.27	13.03	113.89
DI	0 kg N	120.93	4.83	50.35	5.56	6.08	13.81	113.13
DI	25 kg N	117.06	4.68	56.63	5.99	5.93	13.31	114.14
DI	50 kg N	123.22	5.24	55.43	5.69	5.94	13.21	113.11
Sign. Irrigation		ns	ns	ns	ns	ns	ns	ns
Sign. Fertigation		ns	ns	ns	ns	ns	ns	ns
Sign. Irri x Ferti		ns	ns	ns	ns	ns	ns	ns

Irrigation	Fertigation	K fruit	Ca fruit	N fruit	Mg fruit	Fruit firmness	TSS	Fruit color
treatment	treatment	mg/100 g				kg/0.5 cm²	°Brix	Hue angle
Meensel 2009								
FI	0 kg N	138.82	6.72	44.06	6.00	6.34	13.38	112.31
FI	25 kg N	150.72	6.05	51.77	6.32	6.11	13.34	112.15
FI	50 kg N	153.51	6.71	44.44	5.98	6.30	13.07	112.26 a
DI	0 kg N	141.34	7.39	44.06	6.20	6.07	13.42	110.67 b
DI	25 kg N	143.71	6.40	44.11	6.06	6.21	13.22	112.11
DI	50 kg N	139.51	6.26	49.57	5.58	6.22	13.20	113.16 a
Sign Irrigation (Irri)		ns	ns	ns	ns	ns	ns	ns
Sign. Fertigation (Ferti)		ns	ns	ns	ns	ns	ns	*
Sign. Irri x Ferti		ns	ns	ns	ns	ns	ns	**
Sint-Truiden 2008								
FI	0 kg N	147.05	4.99	58.22	5.63	5.53	13.29	109.66
FI	25 kg N	140.76	4.82	61.96	5.73	5.53	13.26	109.23
FI	50 kg N	144.90	4.92	59.45	5.48	5.58	13.03	109.65
DI	0 kg N	146.86	4.93	59.36	5.83	5.43	13.78	109.26
DI	25 kg N	143.93	5.08	61.87	5.65	5.47	13.20	109.97
DI	50 kg N	142.37	4.70	57.66	5.67	5.51	13.22	110.20
Sign. Irrigation		ns	ns	ns	ns	ns	ns	ns
Sign. Fertigation		ns	ns	ns	ns	ns	ns	ns
Sign. Irri x Ferti		ns	ns	ns	ns	ns	ns	ns
Sint-Truiden 2009								
FI	0 kg N	164.80	7.05	57.13	6.46	6.30	15.04	112.06
FI	25 kg N	165.75	7.09	55.76	6.33	6.38	15.00	111.45
FI	50 kg N	165.29	6.82	57.37	6.25	6.31	14.50	112.59
DI	0 kg N	163.51	6.89	55.04	6.28	6.22	15.28	111.47
DI	25 kg N	160.77	7.44	57.07	6.61	6.20	15.40	111.97
DI	50 kg N	159.23	7.28	55.17	6.24	6.18	15.02	111.93
Sign. Irrigation		ns	ns	ns	ns	ns	ns	ns
Sign. Fertigation		ns	ns	ns	ns	ns	ns	ns
Sign. Irri x Ferti		ns	ns	ns	ns	ns	ns	ns

** , **, *** denote signification (Sign.) of the factor in the ANOVA analysis according to $p < 0.05$, $p < 0.005$, $p < 0.001$ respectively, a, b, c denote significant differences between individual groups according to Tukey HSD test.*

In Bierbeek in 2009 N content in the leaf was related to N content in the fruit (Fig. 6.3a) and to fruit color (Fig. 6.3b). In Meensel no such relationship was observed despite the significant effect of the fertigation treatments on fruit color.

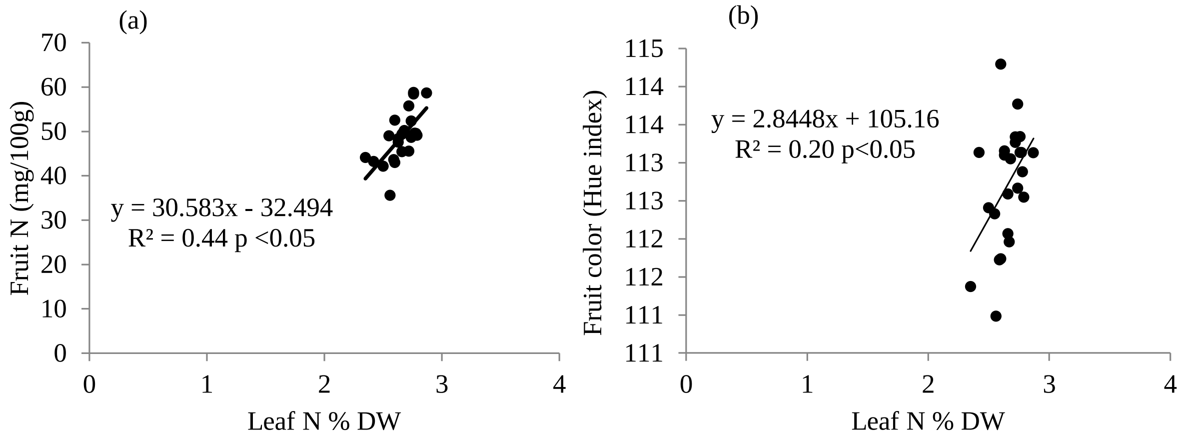


Fig. 6.3 Relation between leaf N and fruit N (a) and between leaf N and fruit color (b) in Bierbeek in 2009.

6.3.5 Calculated N export

Since organic residues coming from pruning and mowing of the grass strip remain in the orchard, fruit harvest causes the only N export out of the orchard. Calculated N export varied between 10 kg N/ha for Sint-Truiden in 2009 and 35 kg N/ha for Bierbeek in 2008 and 2009 (Table 6.6.). The N export was higher in Bierbeek due to the higher yield per tree and the higher tree density in the orchard. In Bierbeek N export increased by a higher irrigation dose and a higher fertilization dose in both 2008 and 2009. In Sint-Truiden in 2008 N export increased by a higher N fertilization dose. For Bierbeek in 2008 this is not in accordance to the yield response to irrigation since fruit yield was not significantly affected by irrigation. For Bierbeek in 2009 and Sint-Truiden in 2008 the N export response in function of irrigation and fertigation corresponds to the yield response.

Table 6.6 Calculated N export based on the N content in the fruits and fruit yield in the three orchards.

Orchard	Irrigation treatment	Fertigation treatment	N export 2008 (kg/ha)	N export 2009 (kg/ha)
Bierbeek	FI	0 kg N	29.51	30.76 a
	FI	25 kg N	36.65 a	35.12 a
	FI	50 kg N	32.11	30.44 a
	DI	0 kg N	27.14 b	21.03 b
	DI	25 kg N	31.25	33.51 a
	DI	50 kg N	28.01 b	31.62 a
	Sign. Irrigation (Irri)		*	*
	Sign. Fertigation (Ferti)		*	**
	Sign. Irri x Ferti		ns	*
Meensel	FI	0 kg N	23.47	19.07
	FI	25 kg N	24.48	24.06
	FI	50 kg N	22.27	17.73
	DI	0 kg N	23.77	18.23
	DI	25 kg N	27.00	19.34
	DI	50 kg N	24.61	21.70
	Sign. Irrigation		ns	ns
	Sign. Fertigation		ns	ns
	Sign. Irri x Ferti		ns	ns
Sint-Truiden	FI	0 kg N	18.49	13.09
	FI	25 kg N	25.54	11.46
	FI	50 kg N	27.58 a	14.57
	DI	0 kg N	17.62 b	13.60
	DI	25 kg N	21.66	15.35
	DI	50 kg N	24.39	18.21
	Sign. Irrigation (Irri)		ns	ns
	Sign. Fertigation (Ferti)		**	ns
	Sign. Irri x Ferti		ns	ns

** , **, *** denote signification (Sign.) of the factor in the ANOVA analysis according to $p < 0.05$, $p < 0.005$, $p < 0.001$ respectively, a, b, c denote significant differences between individual groups according to Tukey HSD test.*

NO_3^--N -concentration in the soil in autumn was in accordance with the applied fertigation regimes in 2008 and 2009 (Table 6.7). NO_3^--N content in the soil layer 0-90 cm was higher in the 50 kg N treatment in the tree orchards in 2008 and 2009 except in Bierbeek and in Meensel in 2008. NO_3^--N content in the soil in autumn tended to be higher in the DI treatment compared to the FI treatment. In March 09 there was no differentiation in soil NO_3^--N content between the fertigation treatments.

Table 6.7 NO_3^--N concentration in the soil (kg/ha 0-90 cm) in function of the fertigation regime measured at three moments in the orchards during 2008-2009.

		0 kg N		25 kg N		50 kg N	
Orchard		FI	DI	FI	DI	FI	DI
Bierbeek	October 08	16.3	14.2	25	25.9	16.5	100
	March 09	34.5	40.2	31.3	28.4	26	38
	October 09	81.5	25.5	30.2	45.7	26.7	58
Meensel	October 08	12.6	12.2	41.3	79.1	22	55.9
	March 09	29.4	23.7	23.2	34.2	32.5	42.9
	October 09	37.7	53.8	40.3	137.1	137.5	109.9
Sint-Truiden	October 08	44.5	39	61.8	88.6	101.4	165.6
	March 09	25.8	25.5	30.4	28.1	38	27.8
	October 09	62.9	99.8	56.5	162.2	86.2	161.9

In general fertigation affected fruit yield positively in two of the three orchards. In one orchard, Bierbeek, irrigation also enlarged fruit yield. Fruit color was in two orchards positively influenced by the fertigation treatment in 2009. In one of these orchards, Bierbeek, at the same time TSS was observed to be higher in the DI irrigation treatment. In this orchard a higher N content in the fruit was related to a higher level of fertigation. At the same time a higher level Ca was related to a lower level of irrigation. In other orchards there was no effect of the irrigation and fertigation on mineral content in the fruits. Fruit firmness was never related to the subjected irrigation and fertigation treatments.

6.4 Discussion

Main objective of the current study was to detect the N needs of 'Conference' pear fruit for the optimization of fertigation schemes used in commercial orchards. Current results indicate that a fertigation dose from 25 to 50 kg N is recommended supplementary to a basic fertilization of 30 kg N one month before bloom. Furthermore fertigation may contribute to a more green color of the fruit. Fertigation had no direct effect on TSS or fruit firmness, but a higher TSS was observed at a lower irrigation regime.

The water stress response of ‘Conference’ pear fruit yield in the three experimental orchards was previously discussed in chapter 2. The orchard in Bierbeek is characterized by a dry soil profile while the soil profiles in Meensel and Sint-Truiden remained humid for a longer time. In the DI treatment in Bierbeek fruit yield was affected by irrigation in 2009 but not in 2008. This can be related to the higher rain deficit in 2009. The difference in fruit yield between the FI treatment and the DI treatment had probably been higher if the irrigation did not malfunction in the last month before harvest. Due to the malfunction of the irrigation system Ψ_{soil} decreased to -100 kPa in the DI treatment which is lower than the thresholds described in chapter 2.

Fruit yield was significantly higher due the N fertigation in Bierbeek in 2008 and in 2009 and in Sint-Truiden in 2008. In Bierbeek in 2008 and 2009 the highest fruit yield was recorded in the 25 kg N treatment while in Sint-Truiden fruit yield was highest in the 50 kg N treatment. In Meensel-Kiezgem there was no interaction between fruit yield and N fertigation. The lack of significant interaction between fertigation and fruit yield in Meensel is probably related to variability in the experiment induced to external factors, such as fruit thinning, pruning, disease control. In 2009 in the 0 kg N fertigation treatment fruit yield tended to be lower however not significant. When the basic fertilization is summed with the fertigation treatment, optimal N dose in Bierbeek ranged about 50 kg N and ranged about 80 kg N in Sint-Truiden. This is lower compared to other values reported for *Pyrus communis.* Sanchez et al. (1991) reports fertilization doses between 100 and 145 kg N/ha for ‘Comice’ pear, Yin et al. (2009) reports 112 kg N/ha for ‘Anjou’ pear. Duarte et al. (2010) however uses a fertilization of 44 kg N/ha in ‘Rocha’ pear. An optimal N fertilization dose between 50 and 80 kg N/ha for ‘Conference’ pear tree seems plausible since calculated export in the orchards ranged between 10 and 40 kg N/ha. Quatieri et al. (2002) reported, after an experiment with labeled ^{15}N fertilizer, that 23 to 24% of the fertilized N is stored in the tree organs and remobilized the following spring. Furthermore there will be some N loss due to leaching out of the soil profile.

The DI irrigation treatment positively affected TSS in Bierbeek in 2009. This is the orchard were Ψ_{soil} decreased strongest in the year with the highest rain deficit. In other years, in other orchards this was not observed. Higher TSS after water stress has been reported previously by Mpelasoka et al. (2002) for apple and Marsal et al. (2002) for ‘Barlet’ pear. Mpelasoka (2001) relates the higher TSS after water stress not only to an advanced fruit maturation but also to possible osmotic compensation in the water stressed treatment and a possible dilution effect in the full irrigation treatment because fruits are bigger. This could be valid for the present experiment since other parameters related to fruit maturation such as fruit color and fruit firmness were not affected by irrigation. And a higher fruit diameter was previously related to an optimal water status (chapter 2, this PhD). Also the elevated Ca concentration in the DI treatment can be explained by this dilution effect, similar as Failla et al. (1992) observed for apple. The question remains why only Ca concentration was affected by irrigation and not the concentration of other mineral elements such as K and Mg. A hypothesis might be that, since K and Mg status of the soil in Bierbeek was rather high, that water stress has altered the competition between K, Mg and Ca in favor of Ca. It has been known that Ca uptake can be suppressed by competition with K and Mg (Bangerth, 1979).

In Bierbeek in 2009 and in Meensel-Kiezgem in 2009 N fertigation positively affected fruit color. This has not yet been observed for pear tree, but for apple N fertilization has been reported to interfere in fruit colorization by Fallahi (1997) and Raese and Drake (1997). Both authors hypothese that an elevated N status in the tree may delay fruit maturation. The response of the N fertigation was observed in the mineral N content in the fruit in Bierbeek in 2009 and in the mineral N content in the leaf in Bierbeek in 2009 and in Meensel-Kiezgem in 2009. In Bierbeek in 2009 there was even a significant correlation between mineral N content in the leaf and mineral N content in the fruit. Mineral N content in the leaf was in Bierbeek in 2009 also related to fruit color. The positive correlation between mineral N content in the leaf in August and greener color of the fruit has previously also been observed by Drake et al. (2002) for ‘Golden Delicious’ apple. It suggests leaf analysis may possibly serve a proxy to detect flawless fruit color before harvest. The relations between N fertigation and fruit color were however only observed in 2009 and only in Bierbeek and Meensel-Kiezgem, not in Sint-Truiden. This means that the effect of N fertilization on fruit color is independent to the effect of N fertilization on fruit yield since in Sint-Truiden fruit yield was positively influenced by N fertigation.

A lower N export was in Bierbeek related to a lower irrigation dose. Consequently with the lower N uptake a trend in a higher NO_3^--N concentration was observed in the soil in the DI treatment after harvest in Bierbeek. This was also observed in Meensel and Sint-Truiden while in these orchards no irrigation effect on N export was observed. In Meensel-Kiezgem and in Sint-Truiden n the FI treatment Ψ_{soil} values close to -10 kPa were registered. Therefore higher water and NO_3^--N percolation out the root zone after rain events is a probable explanation for the lower NO_3^--N content in the soil in the FI treatment. NO_3^--N content in the soil profile exceeds in several treatments the threshold of 90 kg NO_3^--N posed by the Flemish administration (published in Belgisch Staatsblad 29 July 2015). However in our case samples were only taken in the weed free strip just beneath the trees, while the threshold posed by the Flemish administration is posed for samples taken partly in the weed free strip and partly in the grass strip between the trees. Despite a higher N export observed by a higher fertigation dose in Bierbeek in 2008 and 2009 and in Sint Truiden in 2008, NO_3^--N content in the soil in October was higher in the 50 kg N treatment compared to the 25 kg N treatment in nearly all orchards. In Sint-Truiden NO_3^--N content in October was higher compared to the other orchards, this corresponds with the lower calculated N export.

6.5 Conclusion

The present experiment illustrates how fertigation can be used to apply a fractionated fertilization in ‘Conference’ pear tree. The optimal fertigation dose ranged between 25 kg/ha and 50 kg/ha depending on the orchard, assuming a basic fertilization of 30 kg/ha. Water stress affected TSS in one of these ochards where a sharp decrease in Ψ_{soil} was observed. N fertigation was related to fruit color in two of the three orchards. Leaf mineral N analysis after the fertigation event related to mineral N content in the fruit and to fruit color.

7 Relations between water and nitrogen status of ‘Conference’ pear tree and fruit quality parameters

Adapted from: Janssens P., Odeurs W., Elsen A., Verjans W., Deckers T., Bylemans D. and Vandendriessche H., 2015. Relations Between Taste Quality of ‘Conference’ Pear and Mineral Contents in Fruit, Leaf and Soil. Acta Hortic. 1094, 333-340.

7.1 Introduction

Belgian ‘Conference’ (*Pyrus communis* L. ‘Conference’) pear production approximates yearly 250 000 ton. Fruit growers use irrigation and fertilizing schemes which focus mainly on total fruit yield and fruit size (chapter 2 and 6 of this PhD). However to maintain consumers trust in ‘Conference’ pear a uniform good flavor is desirable. Consumers are prepared to pay more when a good taste quality of the fruit is guaranteed (Pinto et al., 2008). Taste quality seems positively related to the total concentration of solids (TSS) and the total acidity (Jaeger et al., 2003; Kappel et al., 1995; Steyn et al., 2011). Furthermore fruit appreciation by consumers is positively related to fruit firmness and a greener fruit color (Kappel et al., 1995).

Previous research results outlined the relation between fruit yield and water status (chapter 2) of the ‘Conference’ pear tree. In other chapters of the PhD it was shown how an adapted water balance (chapter 3) or sap flux observations (chapter 4) can be used to schedule irrigation. In chapter 6 was shown how water stress may influence TSS and Ca content of the fruit. The experiment in chapter 6 was conducted in a randomized block design with four replications per treatment, which revealed the relationship between TSS and water stress in Bierbeek in 2009, under conditions where Ψ_{soil} was low. It would be interesting to see whether it is possible to detect a similar relationship between water status and TSS when observations are not collected in one orchard but are scattered over multiple orchards with varying properties. If such a relationship is robust this would support the use of water status observations in function of the improvement of fruit quality of the ‘Conference’ pear.

In a similar way it was shown in chapter 6 that fertilization has not only an influence on fruit yield but influences also fruit color. Leaf analysis after the fertigation treatment was observed to be correlated to fruit color at harvest. Since leaf analysis is often used to observe N status of the tree early in the season it would be interesting to see whether the correlation with fruit color is remained when observations are scattered over multiple orchards. Also N-NO_3^- content of the soil would be interesting to be compare with fruit color since N-NO_3^--soil measurements are often used to schedule fertilization. If the relationships are robust this would support the use of nitrogen status observations, early in the season, in function of the improvement of fruit quality of the ‘Conference’ pear.

It was in this experiment the objective to see whether tools, used to manage N fertilization and irrigation in function of maximal yield, can also be related to mineral content in the fruit and fruit quality parameters. These insights should contribute to a better management of irrigation and N-fertilization in pear orchards in function of fruit quality.

7.2 Materials and methods

To meet the objective it was chosen to conduct a survey in 9 orchards which were commercially exploited. In these orchards water status was monitored using the adapted soil water balance, N status was observed by leaf and soil analysis during the growing season. These observations were compared with N and Ca content of the fruits. Secondly the observations were compared to TSS and fruit color at harvest. This methodology may give an insight in the added value of the adapted soil water balance and N analysis of soil and leaf with respect to irrigation and fertilization management in function of fruit quality.

The survey was conducted in 9 orchards in the north of Belgium. The orchards varied in management practices, training systems, planting years and irrigation practices (Table 7.1).

Table 7.1 Characteristics of the 9 orchards.

Orchard	Soil texture (USDA classification)	Irrigation	Planting system	Planting distance	Root pruning	Planting year
1	Silt	Yes	V system	3.5 m x 1 m	Yes	2000
2	Silt	Yes	V system	4 m x 2 m	Yes	2004
3	Silt Loam	No	Free spindle	3.5 m x 1.5 m	No	1963
4	Silt	No	Free spindle	3.5 m x 1.25 m	No	1989
5	Sand	Yes	V system	4 m x 2.5 m	No	2009
6	Silt	Yes	Free spindle	3.5 m x 1.5 m	No	1995
7	Sand loam	Yes	V system	3.5 m x 1 m	No	1994
8	Silt	No	V system	4 m x 1 m	No	2008
9	Loam sand	No	Free spindle	3.5 m x 1.5 m	No	1973

Between the orchards there was a big variation in %C and pH, ranging from 1 % C and a pH of 4.4 for orchard 9 and 2.1 % C and a pH of 7.2 for orchard 2 (Table 7.2). Also the N-fertilization strategy differed between the orchards. In orchard 2, 5 and 6 pig slurry was used while in other orchards mineral fertilizers were applied for N-fertilization.

Table 7.2 pH, %C and N-fertilization strategy in the 9 orchards

Orchard	pH	% C	Fertilization strategy
1	7.0	1.9	70-120 kg N/ha mineral fertilizer fractionated
2	7.2	2.1	30 kg N/ha mineral fertilizer combined with 10 m³/ha pig slurry
3	6.3	2.0	70-120 kg N/ha mineral fertilizer fractionated
4	7.4	2.1	70-120 kg N/ha mineral fertilizer fractionated
5	6.5	1.6	20-30 m³/ha pig slurry
6	5.9	1.5	20-30 m³/ha pig slurry
7	6.0	1.5	60 kg N/ha mineral fertilizer before bloom
8	7.5	1.4	70-120 kg N/ha mineral fertilizer fractionated
9	4.5	1.0	70-120 kg N/ha mineral fertilizer fractionated

The survey was conducted in four successive years (2011-2014) with varying growth conditions (Fig. 7.1a, b). 2011 was driest in spring just as 2014, 2013 was driest during summer. 2012 can be considered as the most humid year during the observation period.

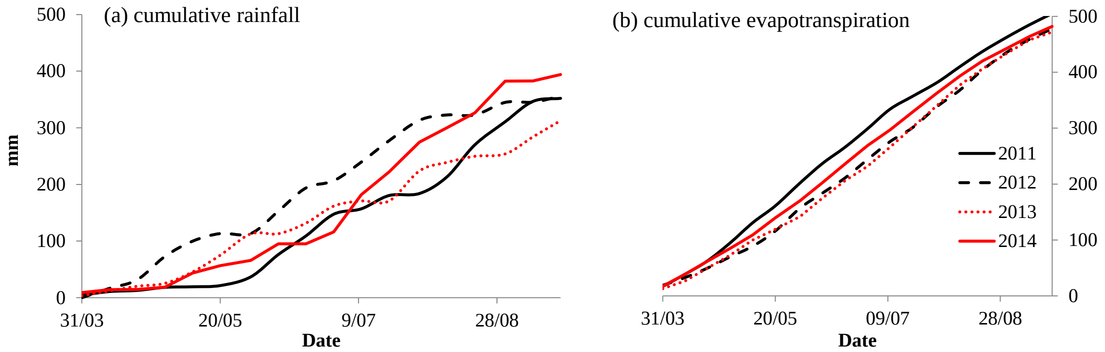


Fig. 7.1 Cumulative rainfall (a) and evapotranspiration (b) during the growing season in 2011, 2012, 2013, 2014 for the center of Belgium.

NO_3^--N content in soil and N-content of the leaf were measured in the beginning of June at the end of cell multiplication. NO_3^--N content in soil was sampled by 10 sub samples with a gauge augur in a ‘reference plot’ in the center of the orchard. The ‘reference plot’ is 10 m long and 10 wide. Soil samples were taken in the soil layer 0-30 cm in the weed free strip beneath the canopy.

NO_3^--N content in the soil sample was analyzed spectrophotometrically with a continuous flow system. Mineral content in the leaf was measured on a sample composed of 40 leaves gathered in the 'reference plot'. Leaves were selected after long internodes, being the 2nd and the 3th leaf on the twig. Kjeldahl digestion was used for the determination of N content of the leaf.

Soil water content evolution was monitored using a soil water balance described in chapter 3 of this PhD, validated with 5 gravimetric moisture samples collected during the growing season. Gravimetric moisture samples were taken at the reference plot with a gauge auger. Each sample consisted of 10 subsamples. After calibration R^2 between calculation and observation was 0.85 (Fig. 7.2). Based on the monitoring with the soil water balance the relative transpiration deficit of each orchard was calculated as the ratio between actual evapotranspiration (ET_a) and maximal evapotranspiration (ET_c) (Allen et al., 1998). The relative transpiration deficit was calculated for three periods. The first period was the cell multiplication period, starting from bloom mid-April until the end of May. The second period was the shoot growth period in June and July. The third period was the period of fruit tissue cell elongation during the month of August.

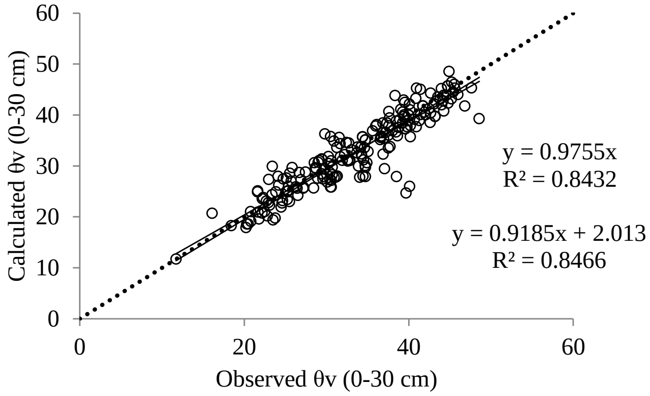


Fig. 7.2 Relation between simulated volumetric soil water content (θ_v) with the adapted soil water balance (chapter 3) and observed θ_v in root zone (0-30 cm) in orchard 1, 2, 3, 4, 5, 6, 7, 8 and 9.

Harvest date was chosen by the farmer. At harvest 15 fruits were collected at the reference plot. These fruits were used to determine the green background color at the shadow side of the fruits was measured with a Konia Minolta chromameter through chroma and hue values (McGuire, 1992). Afterwards, after removal of the skin, Total Soluble Solids (TSS, °brix) was determined with a hand-held refractometer. Afterwards all fruits were blended into 1 sample on which N, and Ca was determined using ICP for the measurement of Ca content and a Kjeldahl digestion for the determination of N content.

After each year a correlation analysis was conducted using STATISTICA (StatSoft, 2009). In the correlation analysis water status and N status were related to the mineral content of the fruit (N, Ca) and the fruit quality parameters (TSS, fruit color). Water status was quantified by ET_a/ET_m during cell multiplication, shoot growth and cell elongation. N status was quantified by NO_3^--N content of the soil and N content of the leaf. Correlations were screened at significance $p < 0.05$.

7.3 Results

$NO3^-$-N content in the soil, observed in the beginning of June, varied between the years and between the orchards (Table 7.3). In orchard 9 $NO3^-$-N content in the soil was lowest throughout the years, this may be related to the lower %C and lower pH in this orchard, which influences the release of $NO3^-$-N after mineralization of organic matter. Also N content in the leaf was lower in orchard 9 compared to the other orchards (Table 7.3). There was a low non-significant positive correlation between $NO3^-$-N content in the soil and N content in the leaf in 2011 and 2014. 2011 and 2014 were also the driest years in spring.

Table 7.3 $NO3^-$-N content in the soil and N content in the leaf observed at the end of cell multiplication period in the beginning of June.

	$NO3^-$-N soil (kg/ha)				N leaf (% Dry Weight)			
Orchard	2011	2012	2013	2014	2011	2012	2013	2014
1	44	11	35	142	2.47	2.78	2.56	2.59
2	39	37	17	86	2.54	2.71	2.45	2.84
3	20	15	16	62	2.4	2.28	2.49	2.47
4	62	19	20	148	2.48	2.63	2.61	2.80
5	25	29	45	97	2.78	2.81	2.79	3.15
6	35	21	13	157	2.83	2.95	3.01	3.19
7	11	7	15	156	2.36	2.88	2.86	2.96
8	31	13	30	116	2.63	2.67	2.84	3.34
9	8	5	5	42	2.1	2.39	2.74	2.55

The absence of rainfall and the elevated ET_o in the spring of 2011 and 2014 is quantified by a lower ET_a/ET_c in the first months of the growing season (Fig. 7.3). In 2011 ET_a/ET_c was lowest at the end of May and the beginning of June (Fig. 7.3a). In 2012 ET_a/ET_c decreased only in August, towards the end of the growing season (Fig. 7.3b). In 2013 ET_a/ET_c decreased during July and

August (Fig. 7.3c). 2014 was more or less comparable to 2011 only decreased ET_a/ET_c a little stronger at the end of the summer (Fig. 7.4d).

In 2011 there was non significant ($R^2=0.37$) positive correlation between $NO3^-$-N content in the soil and ET_a/ET_c during cell multiplication. This can be attributed to the dry spring which led to lower N uptake in water stressed trees. In other years such a relation was not observed between ET_a/ET_c and $NO3^-$-N content in the soil. In 2014 there was however a significant negative correlation ($R^2=54$) between ET_a/ET_c during cell multiplication and N content in the leaf.

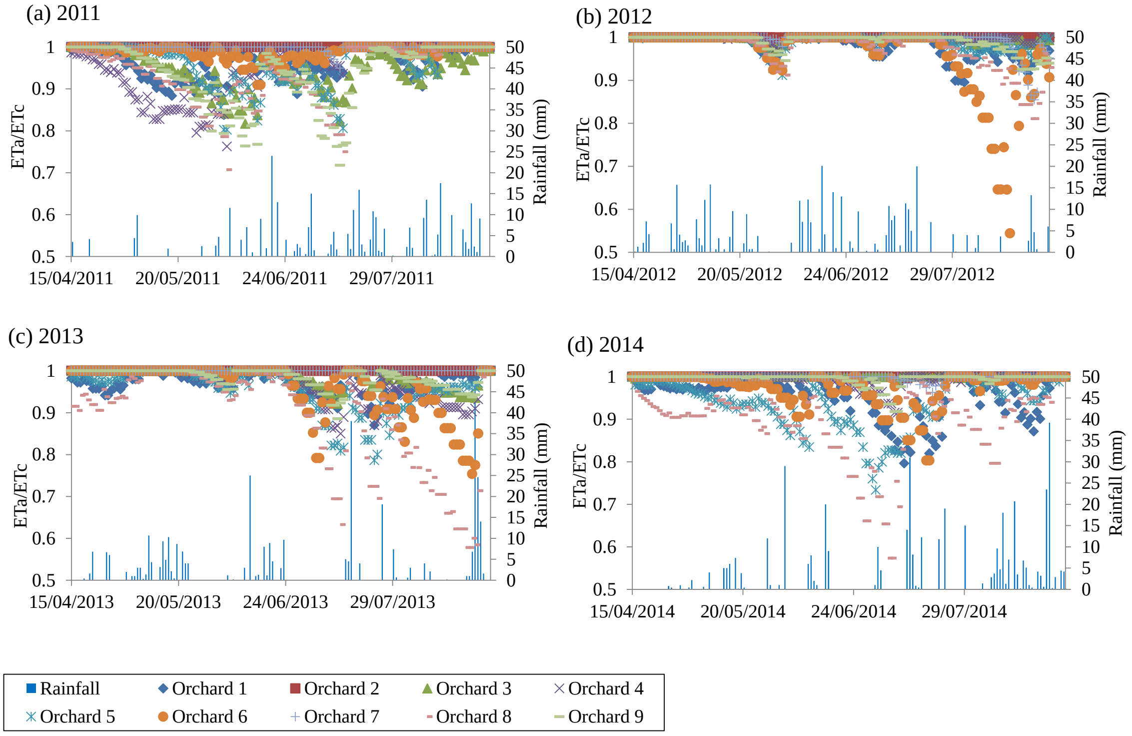

(a) 2011
(b) 2012
(c) 2013
(d) 2014

Fig. 7.3 ET_a/ET_c calculated with the adapted soil water balance (chapter 3) and rainfall in the 9 orchards in 2011 (a), 2012 (b), 2013 (c) and 2014 (d).

Only in 2014 there was a significant correlation between ET_a/ET_m during cell elongation and TSS (Table 7.4). The correlation was negative indicating higher TSS by elevated water stress, i.e. a lower ET_a/ET_c ratio. In other years there was no significant relationship between ET_a/ET_c and TSS. There was never a significant relation between ET_a/ET_m and Ca content in the fruit.

Table 7.4 Pearson correlation (r) between ET_a/ET_c *during cell multiplication (April-May), shoot growth (June-July), cell elongation (August), and Ca content in the fruit, TSS.*

	2011		2012		2013		2014	
	Ca fruit	TSS	Ca fruit	TSS	Ca fruit	TSS	Ca fruit	TSS
ET_a/ET_c cell multiplication	-0.14	0.04	-0.25	0.1	-0.31	-0.25	-0.13	-0.43
ET_a/ET_c shoot growth	-0.54	0.49	0.29	-0.31	-0.05	0.26	-0.11	-0.59
ET_a/ET_c cell elongation	-0.32	0.18	0.6	-0.47	0.10	0.20	-0.24	**-0.83***

** Denotes a significant correlation p<0.05*

In 2013 mineral N content in the leaf related positively to N content in the fruit (Table 7.5). In other years the correlation coefficient was positive but not significant. Fruit color was never related to mineral content in the leaf. Soil $N\text{-}NO_3^-$content did not correlate to mineral N content in the fruit nor to fruit color.

Table 7.5 Pearson correlation (r) between N content in the leaf observed at the end of cell multiplication, $N\text{-}NO_3^-$ *content in the soil observed at the end of cell multiplication and N content in the fruit and fruit color.*

	2011		2012		2013		2014	
	N fruit	Fruit color	N fruit	Fruit color	N fruit	Fruit color	N fruit	Fruit color
Leaf N	0.11	0.55	0.34	-0.16	**0.78***	0.26	0.56	0.10
Soil $N\text{-}NO_3^-$	0.35	0.26	0.34	0.54	0.26	0.16	0.65	-0.06

** Denotes a significant correlation p<0.05*

7.4 Discussion

Main objective of the current experiment was to see whether parameters used to schedule irrigation and fertilization in function of optimal yield can be related to fruit quality parameters which have previously (in chapter 6) been related to water stratus or nitrogen status.

In this experiment the relationship between water status and mineral status was conducted in a survey containing 9 orchards with different plant, management and soil characteristics. The variation in management regimes masked the assumed relations between water status, nitrogen status and N content in the fruit, Ca content in the fruit, fruit color and TSS. Although in 2014 a similar relation between TSS and water status was observed as in chapter 6. In 2013 mineral N content in the leaf correlated to mineral content in the fruit similar to observation described in chapter 6 although there was no link to fruit color. These were the only significant relationships observed in a four year survey. The lack of significant correlation’s between water status and nitrogen status can be explained by the differences in harvest date between the orchards. Previously harvest date was observed to influence TSS and fruit firmness in pear (Raese et al., 1999; Ribeiro et al., 2003) and optimal harvest date was orchard dependent.

The experiment illustrated the difficulty in detecting flawless fruit quality based on measurements conducted early in the season. Recently Van Beek et al. (2015) experienced similar difficulties when spectral indices observed during the growing season were correlated to TSS, fruit firmness and fruit color for ‘Conference’ pear. Relationships between spectral indices and fruit quality parameters varied between the year and between the orchards. However the significant correlation between water status and TSS in 2014 and the significant correlation between N content in the leaf and N content in the fruit in 2013 indicate that it should be possible to manage fruit quality based on observations early in the season. Only further research is necessary to establish more robust relationships.

8 Conclusion, recommendations and outlooks for further research

8.1 Conclusions

Main objective of the PhD was to reveal possible optimization of irrigation and fertilization practices in ‘Conference’ pear. Five specific research questions were addressed:

1. How sensitive is ‘Conference’ pear to a water deficit in a temperate climate and how does root pruning affect water stress sensibility?
2. How can irrigation be scheduled in ‘Conference’?
3. Is it possible to calculate the water extraction pattern of the ‘Conference’ pear tree?
4. What is the optimal N fertigation dose for ‘Conference’ pear?
5. How does ‘Conference’ pear fruit quality relate to varying water and nitrogen status?

The **first research question** was addressed in chapter 2: “Sensitivity of root pruned ‘Conference’ pear to water deficit in a temperate climate”. The need for irrigation in pear trees (*Pyrus communis* L. cv. ‘Conference’) under low evaporative demand conditions was studied. To determine the sensitivity of the pear yield under low evaporative demand conditions three different orchards were monitored. The experiment showed 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 in contradiction to higher thresholds proposed in environments with a higher evaporative demand (-20 kPa) (Naor 2001). Just as for arid environments (Marsal et al. 2000, 2002; Naor, 2001; O’Connel and Goodwin, 2007; Ramos et al., 2000), a Ψ_{stem} below -1.5 MPa was related to lower fruit yield in high fruit size classes. 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.

The **second research question** handles the scheduling of irrigation in orchards to maintain the irrigation thresholds proposed in chapter 2. In chapter 3 “Adapted soil water balance model for irrigation scheduling in pear orchards ‘cv. Conference” a methodology was proposed to use a soil water balance model for irrigation scheduling in fruit orchards. The algorithm permitted to calculate average soil water content in the root zone on a daily basis considering the specific preconditions in fruit orchards being drip irrigation and the interaction between tree root zone and grass strip between the tree rows. The performance of the model was evaluated in three orchards in the period 2008-2009. Advantage of this soil water balance is the possibility to forecast soil water content in function of the irrigation dose. Site specific calibration of the model is however a necessity. Calibration of the soil water balance can be done with soil moisture measurements but demands a computation effort which is easier done by an external consultant rather than by the fruit grower himself.

Continuous plant based measurements can improve the precision of these irrigation scheduling techniques because they are more connected to metabolic and physiological processes (Jones 2007). In chapter 4 "Water stress detection in a 'Conference' pear orchard in a temperate climate using sap flow monitoring" an experiment was set up detect possible water stress in a pear tree orchard. Thermal dissipation probes were used to detect differences in sap flux density (J_p) between different irrigation treatments. Detection of J_p differences under low evaporative conditions was possible after applying moderate water stress. Although the approach is not yet integrated in commercial horticulture, it opens the door for plant based irrigation scheduling in pear trees in a temperate climate.

Next to the soil water balance and continuous plant based measurements soil moisture sensors or Ψ_{soil} sensors can be used to schedule irrigation. The sensor was used in the irrigation experiment described in chapter 2. The output of the sensor was compared to gravimetric moisture measurements and a reasonable correlation was observed between both. Only at high Ψ_{soil} values just after recent wetting events a discrepancy between sensor output and moisture measurement was observed which confirmed previous research results (Scanlon et al., 2002).

To come to optimal installation guidelines for Watermark Ψ_{soil} sensors and other soil moisture sensors better insight in the water extraction pattern of 'Conference' pear tree is a requisite which is the **third research question** posed in the PhD. In chapter 5 "Numerical calculation of soil water potential in an irrigated 'Conference' pear orchard" the water extraction pattern of the 'Conference' pear trees was acquired by a calculation of Ψ_{soil} in three experimental plots. A reasonable accordance between calculated and measured Ψ_{soil} was observed with $R^2 = 0.56$ and RMSE = 13.4 kPa over 1320 observations. Furthermore the sensitivity of the calculation to the selected root distribution was shown. The Ψ_{soil} calculation with the root distribution parameterized by site specific fine root length observations gave satisfactory results for all plots, in contrast to Ψ_{soil} calculation based on root distributions parameterized on root weight or based on root zone descriptions found in literature.

In search for the optimal N fertigation strategy regarding the **fourth research question** the effect of three different fertigation doses is discussed in chapter 6 "In search of the optimal N fertigation dose for 'Conference' pear tree." Fertigation with 25 to 50 kg N resulted in a 20 % higher fruit yield in two of the three orchards independently from the irrigation regime. Water stress was in one orchard related to higher TSS, a higher fertigation dose was related to a more green color of the fruit.

The relation between TSS, fruit color and water and nitrogen status was further explored in a broad survey in **chapter 7** “Relations between water and nitrogen status of ‘Conference’ pear tree and fruit quality parameters” where the fifth research question was considered. Previous established relationships were confirmed however the relationship between tree water status and tree nitrogen status was not robust over the four year observation period.

8.2 Outlooks for further research

8.2.1 Refinement of irrigation thresholds in function of fruit set

In chapter 2 specific irrigation thresholds for pear tree in a temperate climate were outlined. A Ψ_{soil} of -60 kPa during shoot growth did not induce yield decline, while significant yield reduction was observed in the deficit irrigation treatment where Ψ_{soil} decreased to -150 kPa. However at the same time, in this treatment, more flower buds were observed the year after. A similar return bloom response has been reported by Marsal et al. (2002) on young ‘Blanquilla’ pears. At the same time a biannual bearing tendency seemed to be observed after root pruning in one of the tree orchards. Root pruning seemed to interfere in the flower bud formation and may induced a biannual bearing tendency. Root regeneration following root pruning can influence the amount of cytokinines in the xylem with consequences to fruit set (Webster et al., 2003). Also Mcartney and Belton (1992) and Asin et al. (2007) observed that return bloom was influenced by root pruning for respectively apple and pear. This suggests that an equilibrium is needed between the promotion of flower buds, which seems to be positively influenced by plant stress, and optimal fruit size. The amount of flower buds is not a decisive parameter for total crop load however the higher the fruit number the lower individual fruit load (Jiménez and Diaz, 2003). Flower bud formation seems to be promoted by lower Ψ_{soil} and Ψ_{stem} values but at the same time Ψ_{stem} has been reported to be influenced by the number of fruits (Marsal et al., 2008). Fruit load seemed to influence leaf conduction and transpiration rates. At higher fruit loads a higher leaf conduction and transpiration rate was observed explaining lower Ψ_{stem} values.

In this PhD, irrigation thresholds were outlined with an optimal fruit size as main objective. Further research could investigate how these thresholds should be adapted in trees with an irregular fruit set. After periods of frost damage trees may benefit from water stress to promote flower bud formation while higher water availability may be desirable when trees have a high fruit load. However a regular fruit set should be achieved while a biannual bearing tendency is to be avoided.

8.2.2 Implementation of crop models that link Ψ_{soil} to Ψ_{plant}

The research results of this PhD indicated that Ψ_{stem} thresholds for irrigation scheduling obtained in more evaporative environments can be maintained while Ψ_{soil} values cannot. Previous research indicated that Ψ_{stem} value is better related to the decline in fruit size compared to Ψ_{soil} (e.g. Intrigliolo and Castel., 2004; Naor et al., 2006).

In operational irrigation scheduling, irrigation is mostly scheduled based on Ψ_{soil} rather than Ψ_{stem} because soil sensors observing Ψ_{soil} are cheaper to use and easily available. Furthermore a soil water balance model, calibrated with observations of Ψ_{soil} or soil water content can be used to forecast soil water content and to schedule irrigation. However plant based water stress detection is possible in the temperate climate as shown in the PhD. A crop model which accurately simulates Ψ_{stem} that can be calibrated using easily accessible observations, such as Ψ_{soil}, would improve operational irrigation scheduling. The dependency of Ψ_{stem} to Ψ_{soil} and ET_o was demonstrated in the PhD. However the relationship between Ψ_{stem} and Ψ_{soil} also depends from plant tissue conductance. The research results in chapter 5 indicated that root distribution is best parametrized on site specific observations for the calculation of Ψ_{soil}. It can be expected also plant tissue conductance is site specific. Marsal and Stockle (2012) presented an approach to calculate Ψ_{stem} using the ‘Cropsyst’ model which is based on a soil water balance (Stockle et al., 2003). The approach was effective but a lysimeter was needed to parameterize the model. Another approach was presented by Steppe et al. (2008) who used a mechanistic water flow and storage model with Ψ_{stem} as output. As input the model requires continuous observations of stem diameter variations which is a more complex measurement compared to Ψ_{soil} but in advantage actual tree transpiration, which is difficult to obtain, is not required as input for the model. Javaux et al. (2008) presented an approach whereby the water flow between soil and roots is driven only by water potential gradient. Root potential is an output of the model which may be a starting point to calculate Ψ_{stem}. In this model a parameterization of the root zone is needed and as research results in the PhD showed, this needs to be done site specific. The coupling of detailed root models with plant models has been suggested (e.g. Janot et al. 2011) although the challenge remains to get the models operational, using feasible site specific calibration procedures.

8.2.3 Irrigation scheduling which combines optimal temporal with optimal spatial resolution

Next to the refinement of irrigation scheduling at the tree level a significant optimization can be expected to be achieved at the orchard level by including the spatial variation in decision support systems. In our research an important variation in Ψ_{soil} was observed on an orchard slope in Bierbeek (Fig. 8.1). In Belgium, the majority of the orchards is situated on slopes or on fields with varying soil profiles so that a variation in soil water content evolution can be expected.

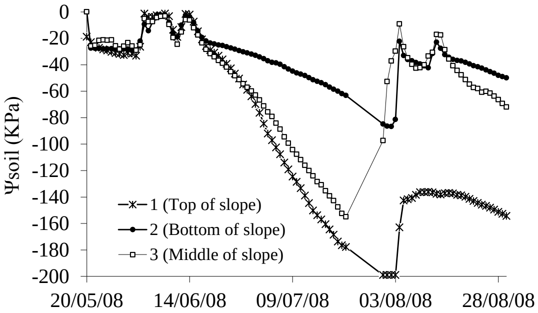


Fig. 8.1 Ψ_{soil} observed with Watermark sensors for the individual plots in the DI treatment in Bierbeek 2008 where location on the slope is indicated in the legend (similar to Fig. 2.3).

Information from additional data sources, such as remote sensing or non-invasive geophysical techniques, which generate data with high spatial resolution can be used to optimize irrigation dosage in the orchards. The adapted soil water balance, as presented in this PhD dissertation, can be used to derive an irrigation advice at the appropriate temporal scale in a reference plot in the orchard. The information generated in the reference plot can be translated to an irrigation advice with optimal spatial coverage using the additional data sources.

The capability of non-invasive geophysical techniques, such as ground-penetrating radar (GPR) and electromagnetic induction (EMI) has been tested by Andre et al. (2011) in a vineyard. Especially EMI correlated with the expected variation in soil characteristics such as soil compaction. Non-invasive techniques reveal additional information about soil characteristics which allows improvement of soil water balance models. Furthermore, Andre et al. (2011) observed an agreement with geophysical techniques and the normalized difference vegetation index (NDVI) derived from airborne imagery. Airborne imagery has been related to vegetation stress in citrus orchards by Suarez et al. (2010) and more recently Van Beek et al. (2014) showed how satellite Worldview 2 imagery can be related to the variation in Ψ_{stem} in ‘Conference’ pear orchards.

Future research could lead to an integrated approach whereby soil water balances, or numerical simulations of soil water content in orchards are fed with information from geophysical techniques, which identify spatial variation in soil characteristics, to come to a 3D description of soil water content in the orchard. This could generate an irrigation advice for fruit growers which is specified for each homogeneous zone in the orchard. Remote sensing, identifying variation in Ψ_{stem}, can additionally be used to verify the effectiveness of the spatial adapted irrigation management.

8.2.4 Focus on fruit quality

As stated in the last chapter of the PhD the focus on fruit quality could be strengthened in irrigation and fertilization research in ‘Conference’ pear. Uniform fruit quality improves consumers’ preference (Pinto et al., 2008). Research on non-destructive post-harvest monitoring techniques to evaluate fruit quality is essential to initiate objective quality monitoring. Nicolaï et al. (2008) showed how continuous wave and time-resolved near infrared reflectance measurements were carried out on ‘Conference’ pear fruit to predict total concentration of solids (TSS). In chapter 6 it was shown how drought stress influences mineral constitution for the fruits with consequences for TSS. Fertigation seemed to interfere with fruit color. In a first phase consumer research should be conducted to identify which TSS and fruit color is preferred. Once reference zones for TSS and fruit color are known it should be further investigated how these parameters are related to soil and vegetation characteristics which can be monitored in early stages of the growing season. In the last chapter the difficulty of such an approach was shown however when successful it would permit an update of existing crop models to simulate and predict fruit quality

8.3 Recommendations to fruit growers

Based on the PhD research the following practical recommendations are made for fruit growers:

- During shoot growth a Ψ_{soil} of -60 kPa is suggested as a threshold to prevent yield decline.
- Our observations indicate that irrigation is necessary in a temperate climate in order to consistently achieve maximal fruit size and yield. However the sensitivity to water stress varies largely between the orchards. In one of the three orchards where the experiment was conducted, Ψ_{soil} dropped below -60 kPa every year in the rainfed plot while in the other orchards this was only one year out of three.
- Root pruning increases drought susceptibility of the trees and may induce a biannual bearing tendency.
- Spatial variation in Ψ_{soil} in the orchard can be significant; in that case multiple zone's in the orchard should be monitored.
- Irrigation can be scheduled with soil sensors, such as the Watermark sensor although multiple sensors, at least three, need to be used to have a reliable measurement of Ψ_{soil} in the root zone. Other tools, such as a soil water balance or plant based measurements, are promising for irrigation management but are more time consuming and need to be managed by experts to be effective.
- When Watermark sensors are used to measure Ψ_{soil} in the root zone positioning sensors close to the irrigation drippers should be avoided to prevent overestimation of Ψ_{soil} and inaccurate irrigation scheduling.
- Fertigation can be used to apply a fractionated nitrogen fertilization in 'Conference' pear tree. When basic nitrogen fertilization applied before bloom is 30 kg/ha, the optimal nitrogen fertigation dose ranges between 25 kg/ha and 50 kg/ha but is orchard dependent.
- Water stress alters mineral constitution of the fruits and was related to a higher TSS. Nitrogen fertigation was observed to be related to a more green color of the fruit. These observations may be useful by the determination of the optimal picking date or for the selection of storage or packaging facilities.

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