Optimization of irrigation schemes in ‘Conference’ pear orchards using Worldview-2 multispectral imagery

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Abstract

Well considered drip irrigation increases pear fruit size in Belgian pear orchards. Irrigation scheduling, using soil moisture sensors, plant sensors or soil water balance models focus often on one specific location per orchard. However, significant heterogeneity in soil water content can be expected in orchards situated on variable soil profiles, planted on slopes with variation in planting regimes, tree age, irrigation efficiency and management strategies. To come to irrigation scheduling which accounts for this spatial variation Worldview-2 multispectral imagery was compared to soil water content, stem water potential (Ψ_{stem}) and fruit yield in an irrigated ‘Conference’ pear orchard. Correlation analysis revealed a relationship between soil texture and varying available water content (R^2=0.47). Soil water content correlated to Ψ_{stem} and reference evapotranspiration (ETo) in a linear multivariate regression in 2011, 2012 and 2013 (R^2=0.64, 0.52 and 0.59). Ψ_{stem} correlated to fruit size in 2011 (R^2=0.57) and fruit weight in 2013 (R^2=0.34). Ψ_{stem} correlated to the Red-edge Normalized Difference Vegetation Index (ReNDVI) derived from multispectral imagery (R^2=0.68) (Van Beek et al., 2014). These insights in the relationship between Ψ_{stem}, soil properties and irrigation contribute to a new approach for irrigation scheduling which accounts for the spatial variation in the orchard.

Keywords: stem water potential (Ψ_{stem}), soil water content, fruit yield *Pyrus communis* ‘Conference’, multispectral remote sensing

INTRODUCTION

In Belgium ‘Conference’ pear tree (*Pyrus communis* ‘Conference’) is often irrigated to maintain a high fruit yield in dry years (Janssens et al., 2011a). 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 is applied in orchards situated on soils with moderate or low available water content, where it is supplied by drip irrigation on a weed free strip under the canopy of the trees.

Irrigation scheduling is carried out through observations of Ψ_{soil} (Janssens et al., 2015) or based on a soil water balance (Janssens et al., 2011b). Despite the efforts made to optimize irrigation scheduling at the plot scale (e.g., Janssens et al., 2013) a significant optimization in irrigation scheduling can be expected at the orchard level by including the spatial variation in decision support systems. In Belgium, the majority of the orchards is situated on slopes or on fields with varying soil profiles which suggests a variation in soil water content evolution (Odeurs et al., 2014). Information from additional data sources, such as high spatial resolution remote sensing, can be used to optimize irrigation dosage in the orchards. Recently, thermal imagery has been observed to be highly correlated with plant water stress observations in vineyards and fruit orchards (e.g., Bellvert et al., 2015; Gonzalez-Dugo et al., 2013). Even so Struthers et al. (2015) showed how infrared

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measurements in 'Conference' pear conducted in a controlled environment are related to vapor pressure deficit (VPD) and stomatal conductance. Today's space-borne spatial resolutions for thermal imagery do not reach below 100 m, while spectral information from satellite platforms is available at spatial resolutions of up to 0.5 m. Spectral information has previously been proven to have possibilities for irrigation management (e.g., Suárez et al., 2010; Zarco-Tejada et al., 2013).

Van Beek et al. (2013) showed how high resolution Worldview-2 multispectral imagery was correlated with Ψ_{stem} observed in 'Conference' pear orchards. In the current work the research results achieved by Van Beek et al. (2013) are further elaborated. Van Beek et al. (2013) described the relationship between Ψ_{stem} and the ReNDVI (Roujean and Breon, 1995) derived from Worldview-2 multispectral imagery:

$$\mathrm{ReNDVI} = (R_{NIR1} - R_{red\ edge})/(R_{NIR1} + R_{red\ edge}) \qquad (1)$$

with R_{NIR1} reflectance at 770-895 nm and $R_{red\ edge}$ reflectance at 705-745 nm. In the current work the relationship between the observed Ψ_{stem} and the associated soil properties, evaporative demand and irrigation efficiency is investigated. These insights may contribute to a new approach for irrigation scheduling which implies the spatial variation in the orchard.

MATERIALS AND METHODS

The experiment was conducted in an orchard situated in Bierbeek (50.826621°N; 4.794847°E), Belgium. The orchard perimeter is 6.5 ha. In the upper soil layer (0-30 cm) the soil texture was loam, the soil texture in the deeper soil layer (30-60 cm) was sandy loam. The orchard was planted in 2000 with pear tree 'Conference' on quince C, with a planting distance of 3.3×1 m. The trees are trained in an intensive V-system with four fruiting branches per tree on one central stem. The trees in the orchard were subjected to root pruning conducted at the end of winter, one month before bloom.

From 2011 to 2013, 16 'test' plots were installed in the orchard, which consisted of four successive trees where all measurements were concentrated. The test plots were situated in four neighboring tree rows alongside a slope in the orchard (Figure 1a). From these plots 8 plots were fully irrigated (100% ET_c) and 8 plots where deficit irrigated. The deficit irrigated plots received full irrigation (100% ET_c) during stage I of fruit growing, from bloom to the end of cell division, but were rainfed during stage II during shoot growth. Shoot growth in Belgium starts at the beginning of June and ends at the end of July. In stage III during rapid fruit growing, in the month of August, full irrigation was again applied (100% ET_c) in the deficit irrigated plots just as in the fully irrigated plots. In 2012 and 2013, 16 additional 'observation' plots were installed where irrigation was managed by the famer (Figure 1a). In 2011 there was a high rain deficit in spring, while in 2012 there was a moderate rain deficit in summer. In 2013 there was a moderate rain deficit in spring and summer (Figure 1b). Reference evapotranspiration (ET_o) was calculated after Allen et al. (1998) based on weather recordings on a nearby weather station (20 km), rainfall was measured on site. The crop coefficient (K_c) described by Girona et al. (2004) was used for the calculation ET_c.

In each plot soil water content (θ) and stem water potential (Ψ_{stem}) were monitored weekly. Gravimetric water content was measured by drying the soil samples at 105°C for 24 h. Soil samples were taken with a gauge auger of 30 cm in the soil layers 0-30 and 30-60 cm. One sample consisted of minimal 8 subsamples taken randomly in the weed free strip beneath the canopy. Stem water potential (Ψ_{stem}) was measured in every plot on sunny days without rainfall between 13:00 and 15:00 h. For each measurement three leaves were selected from the inner part of the canopy. Without detaching the leaves from the tree, these leaves were enveloped in a plastic bag covered with aluminum foil. After one hour, the leaves were detached and put immediately in a pressure chamber to determine Ψ_{stem} (Scholander et al., 1965).

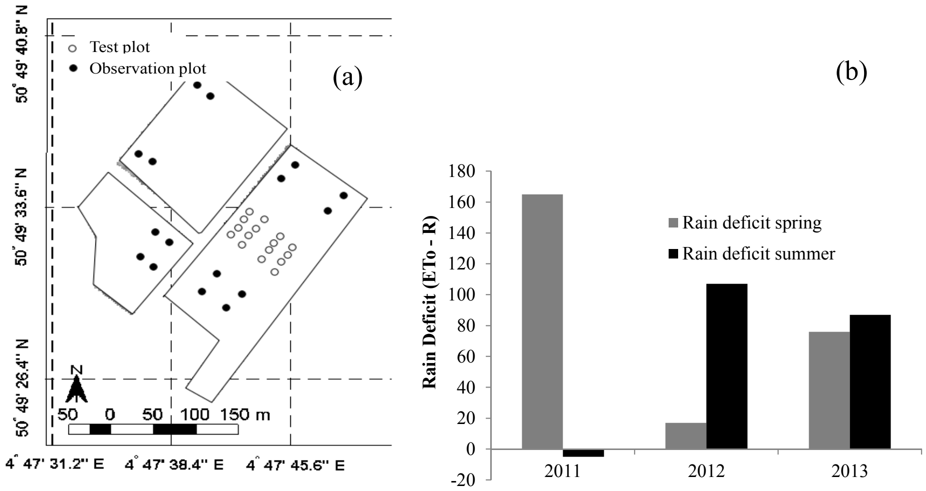

Figure 1. (a) Schematic of the location of the observation plots and the test plots. (b) Rain deficit (R-ET_o) in the three years in the experimental orchard. Rainfall was recorded on site, ET_o was calculated using data form a nearby weather station.

In all 32 plots, water retention characteristics were measured using undisturbed soil samples (Kopecki cylinders). Water content was measured at 0, -10, -50 and -1600 kPa using pressure plates. Total available water (TAW) content is considered as the fraction between -10 and -1600 kPa, readily available water content (RAW) is considered as the fraction between -10 and -50 kPa. In each plot fraction of sand, clay and silt was measured trough sieving and sedimentation (Day, 1969). In September 2013 the emitter discharge of the orchards drip installation was measured in the observation plots.

In the 16 'test' plots fruit yield was determined by harvesting the 4 trees of each plot. From each plot the total fruit yield was obtained and distinction was made between the high fruit size classes (larger than 60 mm and larger than 65 mm). Fruit yield results in relation to Ψ_{stem} in 2011 and 2012 were previously presented by Odeurs et al. (2014).

Acquisition of the satellite images is described by Van Beek et al. (2013). WorldView-2 multispectral images were acquired under different off-nadir viewing angles, with a resampled ground sampling distance of 2.0 m and a spectral resolution complying eight bands between 450 and 1040 nm. Images were collected on 03/08/2011, 28/05/2012, 20/08/2012, 09/07/2013 and 03/08/2013. Soil samples and Ψ_{stem} observations were assembled at the same days.

RESULTS

In every year there was a significant relationship between volumetric water content (θ_v), reference evapotranspiration (ET_o), day since bloom and Ψ_{stem} (Table 1). The correlation coefficient was highest in 2011 probably due to the higher rain deficit in spring. In all years high soil water content was associated with high Ψ_{stem} values. In 2012 a higher ET_o was related to higher Ψ_{stem} in contradiction to 2011 and 2013. A likely explanation was the lower ET_o during the growing season in 2012 than 2011 and 2013.

As expected, total available water content (TAW) was correlated to the clay content in the soil (Figure 2a). In plots with a higher clay content, TAW was lower because water content was higher at wilting point (-1600 kPa).

Table 1. Linear regression between Ψ_{stem}, ET_o, θ_v, and DAB (Ψ_{stem} [MPa]= a θ_v (%) + b ET_o[mm d^{-1}] + c DAB + d) observed at the 'test' plots.

Year	a		b		c		d		R^2	
2011	0.02	**	-0.20	**	-0.01	**	-0.58	*	0.64	**
2012	0.02	**	0.18	**	-0.01	**	-1.80	**	0.52	**
2013	0.16	**	-1.80	**	-0.06	**	-4.68	**	0.59	**

*p<0.05; **p<0.01.

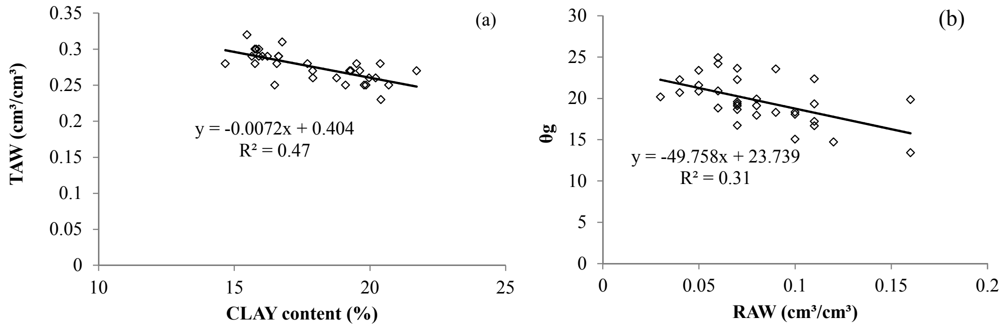

Figure 2. Relationship between TAW (total available water) content and clay content (a) and relationship between average gravimetric water content (θ_g) in 2013 and readily available water (RAW) content (b).

Despite an important variation in emitter discharge (Table 2) and despite varying irrigation regimes a significant correlation was observed between readily available water content (RAW) and average gravimetric water content (θ_g). Soils with lower RAW were associated with lower soil water content (Figure 2b).

Table 2. Discharge rates measured September 2013 in the 'observation plots'. Emitter discharge as indicated by manufacture was 1.6 L h^{-1}.

Plot nr	Emitter discharge (L h^{-1})	Plot nr	Emitter discharge (L h^{-1})
O1	0.70	O9	0.08
O2	0.00	O10	0.65
O3	0.00	O11	0.35
O4	1.00	O12	0.23
O5	1.40	O13	1.50
O6	1.13	O14	1.55
O7	1.80	O15	1.45
O8	1.25	O16	1.50

As presented by Odeurs et al. (2014), in 2011 lower fruit yield in the high fruit size classes was associated with lower Ψ_{stem}. In 2012 no such relationship was observed, probably due to the lower rain deficit in spring, during stage I of fruit growing. In 2013 lower Ψ_{stem} was related to a lower average fruit weight (Figure 3).

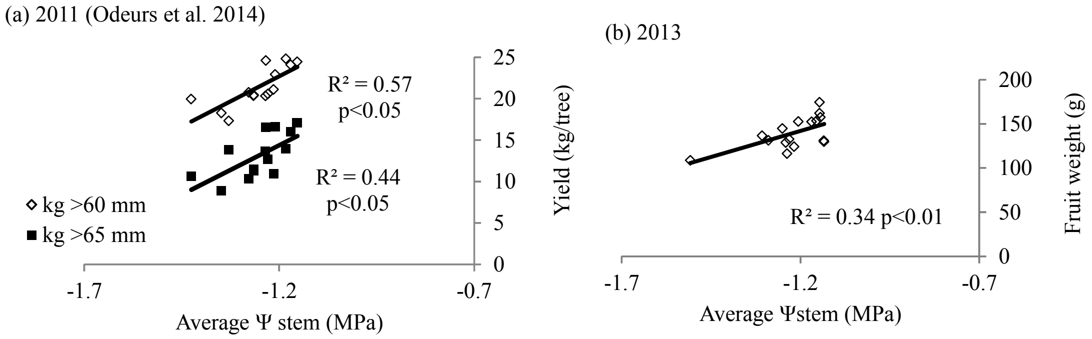

Figure 3. Relationship between average observed Ψ_{stem} and fruit yield in 2011 (a) and fruit weight in 2013 (b).

The variation in Ψ_{stem} in the orchard was correlated to the variation in ReNDVI as presented by Van Beek et al. (2013) (Figure 4). Lower Ψ_{stem} values corresponded with a higher ReNDVI values. In water stressed trees, ReNVI values were lower because reflectance in the Red Edge, between 705 and 745 nm, band was higher. Based on the regression between Ψ_{stem} and ReNDVI a map could be derived which estimates the variation in Ψ_{stem} on 02/08/2015 (Figure 5a). At same date there was a positive correlation between gravimetric water content and Ψ_{stem} (Figure 5b).

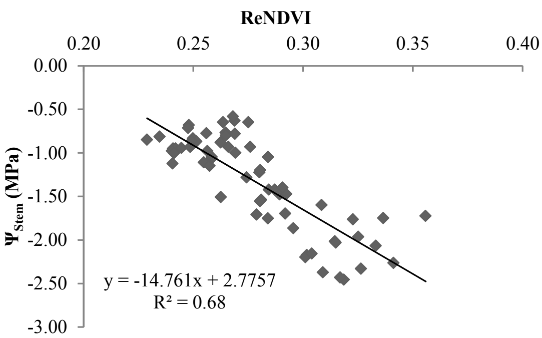

Figure 4. Relationship between average observed Ψ_{stem} and ReNDVI derived from Worldview II multispectral imagery (derived from Van Beek et al., 2013).

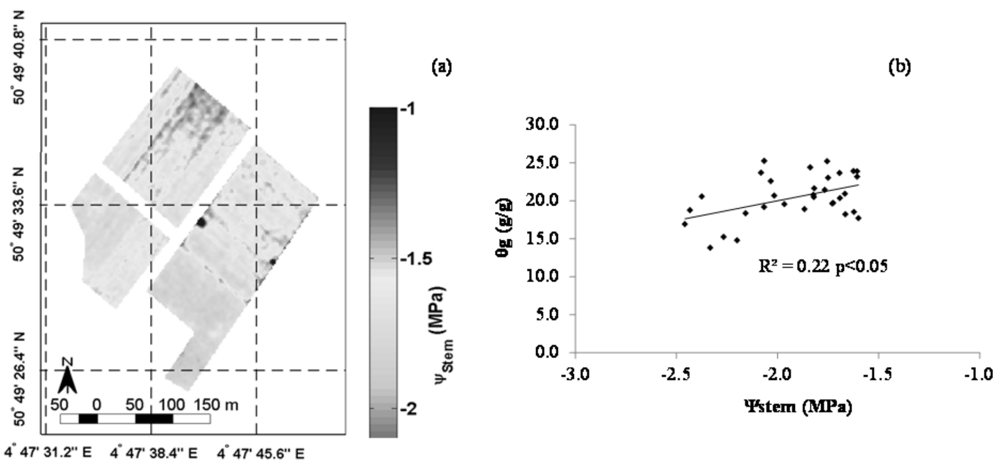

Figure 5. (a) Image of the Ψ_{stem} distribution on 02/08/2014 derived from the relationship between ReNDVI and Ψ_{stem} shown in Figure 4 (Van Beek et al., 2013); (b) Relationship between Ψ_{stem} and gravimetric water content (θ_g) on 02/08/2014.

The results show how the variation in Ψ_{stem} can be explained by a variation in soil water content throughout the orchard. This variation was caused by a variation in emitter discharge and a variation in soil properties. The variation in water availability for the pear trees led to a variation in fruit yield throughout the orchard.

DISCUSSION

The objective of this study was to see whether multispectral imagery can be used for an optimization of irrigation management in 'Conference' pear orchards. Van Beek et al. (2013) showed how ReNDVI values could be related to Ψ_{stem}, which was related to fruit yield in 2011 and 2013. The relations between fruit yield and Ψ_{stem} and the relationship with ReNDVI highlight the added value of multispectral imagery in the detection of water stress in 'Conference' pear orchards.

A drawback of the use of high spatial resolution multispectral satellite imagery is that images are not available on a daily basis. Competition between the different end users who solicit images of the same satellite and interference of clouds permit only a limited amount of images per growing season. In every year there was a significant relation between Ψ_{stem}, ET_o and soil water content confirming previous work (Odeurs et al., 2014; Janssens et al., 2011a). Since Ψ_{stem} is dependent on ET_o and soil water content, a soil water balance model or soil water sensors, which supply information on a daily basis, can be used to manage irrigation at a few reference plots per orchard. This information can be combined with high spatial resolution multispectral imagery to reveal water stress elsewhere in the orchard.

The variation in soil water content throughout the orchard was caused by a variation in emitter discharge and by a variation in soil hydraulic properties. Once a variation in Ψ_{stem} derived from ReNDVI values is revealed, fruit growers should inspect the irrigation system to detect possible failure due to clogging or pressure loss. In a second step, the irrigation system can be adapted to the variation in soil properties. In this orchard, average soil water content was related to the readily available water content and to the clay content in the soil. This indicated an interest in adjusting the irrigation system to the soil properties. Locations with higher clay content and lower readily available water content can be equipped with a higher emitter discharge or longer irrigation events.

The relationship between Ψ_{stem} and ReNDVI values described by Van Beek et al. (2013) was achieved after 5 image acquisitions over three years in an orchard in which Ψ_{stem} was observed on 32 locations. This resulted in a solid relationship independent of management, phenology, environmental conditions, off-nadir viewing angle and viewing geometry. The question remains how reliable the relationship is in an operational service where only a limited amount of images is available. Zarco-Tejada et al. (2013) showed a similar relationship in vineyards between ReNDVI values and leaf water potential Ψ_{leaf} based only one UAV image which was compared to 9 Ψ_{leaf} observations. This indicates that also from 1 image per growing season useful information can be derived.

Furthermore, in a commercial orchard Ψ_{stem} is only rarely used to schedule irrigation. Mostly soil moisture sensors, or equivalent, are preferred by farmers. In this way the image information needs to be compared with soil moisture which is less correlated with biophysical processes in the plant, fruit yield and possible vegetation indices derived from satellite imagery (e.g., Intrigliolo and Castel, 2004; Janssens et al., 2011a; Naor et al., 2006). The current study shows how Ψ_{stem} was related to soil moisture and soil hydraulic properties which suggests that it should be possible to use Worldview-2 imagery in operational irrigation scheduling.

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