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"Water fluxes in a South Tyrolean apple orchard estimated by different techniques"

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Water fluxes in a South Tyrolean apple orchard estimated by different techniques

1. Introduction

Water is essential for life. About 70% of the Earth surface is covered by water, roughly 97% of this water is saline water and 3% is fresh water. Of these 3% nearly 2/3 are stored in the icecaps and glaciers. Thus, the freshwater needs of the whole world are served by 1% of the total water present on planet Earth (Brahana, 2003). Water is the key component of the organisms on Earth. As such, it also plays an important role in agriculture. In fact, it represents the most important resource for agriculture activity, without water nothing can grow. To underline how significant water is for farming activity it is enough to look at its consume, 70% of the whole water used by human kind in the world goes to the branch of agriculture (Bacon, 2004). By seeing this high percentage it is obvious that this sector has a great responsibility in using water in the most efficient way. Water scarcity is a problem that we have to face in future in all parts of our life and especially in agriculture. Furthermore, it is important to increase the water use efficiency to achieve economical and local benefits (Conceceicao and Ferreira, 2009). By planting crops that have a high water requirement like apples, the water has to be used in an efficient way to satisfy the needs of the plants. To cope with this duty it is important to know how water behaves in an orchard and how much water a plant requires.

1.1 Water requirements of the apple tree

The apple is a crop class with high water requirements. In fact the estimated need of a single apple tree in South Tyrol, where the experiment took place, is about 1060 mm over an entire growing season (Friedrich and Fischer, 2000). In comparison, pears require 30% less water under similar conditions and plums require 15% more water than apples under comparable conditions. These requirements can vary in function of climatic (air temperature, precipitation, solar radiation and wind), site (soil type, soil texture and depth of ground water table), crop (age of the plant, cultivar, rootstock, phenological phases and additional crop) and management (growing system and soil maintenance) (Friedrich and Fischer, 2000). In order to grow apples under the best hydraulic conditions in South Tyrol, as well as in other apple growing regions, irrigation is needed, especially in the summer when transpiration and therefore water use of the crop reaches the maximum values. On average in South Tyrol during July and August transpiration rises up to 117.5 mm/month and precipitations are not high enough to satisfy this demand. Consequently there is a bottleneck of water supply that is commonly overcome only by irrigation. To satisfy the necessity of the trees without wasting precious water a good knowledge of the water cycle and the requirements in an orchard is essential.

Water is present in all different subparts of the orchard ecosystem. In the soil, in the tree and in the atmosphere. In every subpart, the water movement is driven by different forces. For instance, in the soil and the plant water is subject to forces as the adhesion, the cohesion and the capillarity (Plaster, 1997). In addition plants are subjected to a gradient in water potential (Ψ) existing from roots to air. From the roots the water goes through the vascular-system of the plant and reaches, driven by the gradient, the place of consumption, the leaves. Fruits, in terms of water consumption, are nearly negligible as compared with leaves; they are relevant in terms of stock, instead. The vascular system is composed of xylem and phloem (Green et al.,2003). Phloem is build up of soft walled tubular cells and transports organic nutrients from the leaves downwards to the storage organs. In contrast the xylem consists of hard walled tubular cells and transports water and nutrients to the upper part of the plant (Friedrich and Fischer, 2000). In the atmosphere water is primarily present as vapor. But the water vapor doesn't stay for long in the atmosphere. In the space of a few days or some weeks it condensates and returns back to earth as precipitation (Brahan, 2003).

The interplay of these different forces makes it possible that a hydrological cycle is built up, whose driving force is the solar radiation (Brahan, 2003).

1.2 Variables that influence the evapotranspiration

There exist many approaches to estimate the water requirements of an ecosystem. Most of them rely on the value for the evapotranspiration being the key linkage between water balance and vegetation dynamics (Gong et al. 2007). This value is composed on the one hand from the evaporation of water from the soil surface and on the other hand from the transpiration of water by plants, whose contributions to evapotranspiration varies during the growing season. This statement is based on the fact that solar radiation is the key factor that influences the evapotranspiration of a cropped soil (Allen et al., 2000). If the crop is still without foliage and solar radiation begins to rise in early winter the soil will lose more water thanks to evaporation. In the following months the leaves develop and shadow most of the soil. In this way solar radiation hits mainly the leaves of the crop. As a consequence losses of water by means of transpiration through the stomata of the crop predominate (Allen et al., 2000).
In the experimental site we should consider also the contribution of the alleys between the rows of apple trees, where is no bare soil but a 1.8 m broad grass strip. Therefore it is expected that the portion by which transpiration contributes to evapotranspiration is higher than in the case of bare soil. The evapotranspiration is affected by the climate, by the kind of vegetation that covers the soil and by the management of the soil and the vegetation. The main climatical factors affecting evapotranspiration are solar radiation, air temperature, humidity and the wind speed. The crop type, the variety and the development stage are the main crop-factors affecting the evapotranspiration. The management of the soil and the vegetation like the ground cover, the plant density and the soil water content can also influence the evapotranspiration (Allen et al., 2000).

1.3 Methods to estimate evapotranspiration

Various methods allow the determination of evapotranspiration. Firstly, there is the possibility to detect the evapotranspiration through micrometeorological methods. As evapotranspiration is governed by energy exchange at the vegetation surface, it requires relatively high amounts of energy in form of radiant energy (Allen et al., 2000). This exchange can be registered by different methods. Secondly, we can rely on the soil water balance. In this case the method operates with the in- and output water fluxes in the rooted zone of the soil (Bos et al., 2009). Thirdly, evapotranspiration can be derived from meteorological data through empirical and semi empirical formulas. In 1990, the FAO Penman - Monteith method was recommended as standard method for the computation of the reference evapotranspiration (ET_0). The crop specific evapotranspiration (ET_C) is then detected by the crop coefficient (K_C) (Allen, 1998). This formula calculates the ET_C under standard conditions (best water supply) which is not always the case. For that reason this is adjusted through a stress coefficient or by modifying the K_C. Computing the ET_C of the apple orchard was necessary because it represents the most important output water flux in the orchard. As such it reflects a great part of the water requirement of the ecosystem (Allen, 1998).
The water fluxes can be estimated by different methods. Two of them were already mentioned, micrometeorological methods and the water balance that monitor in- and outputs of water. These methods take into account the evapotranspiration and thus the water fluxes of the whole orchard.

As a micrometeorological method, the eddy covariance technique estimates the ET_C of the whole orchard. As a direct measurement approach, it reflects the crop evapotranspiration during a certain time period. The methodology was proposed by Montgomery (1948), Swinbank (1951) and Obukhov (1951) (Aubinet et al., 2012). The instruments used to detect micrometeorological data for this technique have changed over time due to the great and fast developments in the field of

technology. Nowadays several studies exist that utilize the eddy covariance method to estimate ET_c of different ecosystems. It is not just used to measure ET_c but also to evaluate the accuracy of empirical methods that estimate crop evapotranspiration. This is so thanks to its high reliability under standard conditions (more in chapter 2). In the study of Paco et al. (2011) the technique was applied to detect orchard evapotranspiration for a daily drip irrigated peach (*Prunus persica*) orchard under Mediterranean climate conditions (Paco et al., 2011). The results of eddy covariance measurements, since they reflect the effective ET_c of the site, were compared to the SIMDualKc, a water balance simulation system, to verify the reliability of this simulated value. Another study of Motisi et al. (2012) uses the eddy covariance measurement to detect mass exchange of woody crops in a Mediterranean environment (Motisi et al., 2012). This experiment was carried out on olives (Nocellara del Belice), on grapevines (Chardonnay) and on oranges (Tarocco). In addition to the eddy covariance method also a sap flow measurement technique using the heat pulse velocity (HPV) method has been proposed. Aggregation of the results of the two methods gave a valuable insight into the different mechanisms regulating water use in the orchards of the different crop classes (Motisi et al., 2012).
The water balance of an ecosystem represents a simple principle to estimate the evapotranspiration. Nevertheless the components of the water balance have to be gathered with a high accuracy, to ensure the best results (Gong et al., 2007). Because of that, input (precipitation and irrigation) and output (Drainage, Capillarity Run off and Changes in soil water content) of water from the ecosystem must be recorded constantly (Hess, 1996). By surveying these parameters, a balance can be established in order to detect the ET_c of the site of interest. To detect ET_c the water balance approach was used by Gong et al. (2007) in a field study on an apple (*Malus pumila*) orchard in Northwestern China. Additionally the water balance in the Gong et al. (2007) study gives references to the hydrological processes in an apple orchard.
Another highly accurate method to detect evapotranspiration (ET) is the lysimeter method. The measurements according to this method are carried out as follow: in order to get accurate data, the root zone of the crop is isolated from its environment. This is done by planting the crop into large pots. In the case of precision weighing lysimeter, the water loss is directly measured by the mass change of the pot. In contrast in non-weighing lysimeter, the ET is computed by subtracting the drainage water, collected at the bottom of the pot, from the total water input, after having considerated the change in soil water content (FAO, 2013).

In addition to these methods the water requirements of a single tree can also be studied by the Granier method and by the Heat Balance method. Based on heat dissipation through xylem mass flow, these two methods determine the amount of water passing the branch or the stem in a particular portion of time. Nevertheless the two methods differ in their application and their method of measuring (detailed description of application in chapter 2).
André Granier (1985) developed the method named after him, a technique to detect xylem mass sap flow in wooden plants that gives informations about the transpiration of the whole tree (Granier, 1987; Köstner et al., 1998). A study of Ferreira et al. (2009) evaluates the performance of sap flow methods. They focus on the heat dissipation method according to Granier. They found that this method is widely used because it is relatively simple, requires low costs and enables long term measurements (Ferreira et al., 2009). The results of the study show that the Granier method has still its warranty, but further improvements are needed to prevent under or over estimation of the flux, caused by difference in thermal conductivity of various wood kinds (Ferreira et al., 2009). Due to its positive properties the Granier method was used in different studies. By Conceicao and Ferreira, it was used in combination with the eddy covariance method to detect long term transpiration of a pear (*Pyrus communis* L. cv. Rocha) orchard in the Oeste region (central

Portugal) (Conceicao and Ferreira, 2009). In another study performed by Sugiura et al. (2009) the Granier method was used to measure daily transpiration of Japanese pear (*Pyrus pyrifolia*) (Sugiura et al., 2009). According to Smith and Allen (1996) the Granier method should be calibrated for every tree species. In the study of Sugiura et al. (2009) they calibrated the system for Japanese pear (Smith and Allen, 1996).

As already mentioned the second method that was used to measure the sap flow was the Heat Balance method. It represents one of the first trials to measure the stem water flow (Kucera and Urban, 2012). The revolutionary idea behind the Heat Balance method was the direct heating of the xylem by electric current (Kucera and Urban, 2012). In a study conducted by Weibel and Vos (1994) they tested the reliability of a sap flow meter which works with the stem Heat Balance method on apple plants (*Malus domestica* L. cv Red Elstar and Jonagold on M9 rootstock) (Weibel and Vos, 1994). The measurements of the sap flow were compared to the weight loss of the tree measured with an automatic balance, supposing that the loss in weight is equal to the amount of water transpired by the tree (Weibel and Vos, 1994). As result they found three major weaknesses of the sap flow method. Firstly, the contact to the bark was not always optimal. Secondly, the Heat Balance method did not account for the energy stored in the heated stem and thirdly continuos heat application could cause damage to the bark tissue. Considering these three problems they developed an improved sap flow meter (Weibel and Vos, 1994). The Heat Balance method was used by Lascon et al. (1992) to detect water use of 3 years old grapes (*Vitis vinifera*, L. cv. Chardonnay) in the city of New Deal, Texas (Lascon et al., 1992). Using the method over a 100-days period, they found out that it is accurate and suitable to measure daily values of sap flow. In addition, they were able to confirm that grapes are a crop with low water requirements (124.0 ± 11.8 mm over 100 day period) in contrast to the apple tree which requires ten times as much water (Lascon et al., 1992).

1.4 Objectives and experimental outline

This experiment was carried out in an orchard located in South Tyrol, where studies about gross primary production (GPP) and net ecosystem efficiency (NEE) were carried out since 2009 (Zanotelli, 2012). My measurements follow those of Marseiler (2012) who studied crop ET_C and the water balance of the site until summer 2012. Furthermore, this experiment is focused on the determination of water fluxes in the orchard with different techniques.
During my study, which lasted from September to December 2012, I used the eddy covariance method to detect ET_C of the whole orchard based on the data recorded from the eddy covariance tower. Moreover, I installed Heat Balance sensors and a Granier sensor on two trees. I placed the Heat Balance sensors on branches of the trees to detect their water use. The Granier sensor instead was mounted on the stem of an apple tree to detect water flux of a whole tree. Every 15 minutes data of both sensors were logged. In a second step, I surveyed meteorological data and soil water movements (water table depth and soil moisture content). Combined with the ET_C detected by the eddy covariance method I was able to draw up a water balance for the experimental site.
There exist publications where the water fluxes in different ecosystems were described by one method but only few studies use more approaches to record water fluxes. In the publication of Gong et al. (2007) a sap flow method and the water balance approach were used to detect the evapotranspiration in an apple orchard in northwest China (Gong et al.,2007). Such studies are primarily made to increase quality and quantity of fruit yields and have mostly a practical approach. Furthermore, the existing studies focus on the ET_C and the water fluxes during the spring and summer months. In my study I tried to provide information about the water fluxes in the late season (September - December).

- In particularly, water fluxes were studied on different scale levels: at branch level, by the Heat Balance method, at the tree level by the Granier sensor and at orchard level through the eddy covariance technique,

- eddy covariance data were combined with precipitation and irrigation measurement, and with soil water change values, to characterize the water balance of the orchard.

2. Materials and Methods

2.1 Site description

The experiment took place between September and the beginning of December in an apple orchard (*Malus domestica* cv. Fuji on M9 rootstock) in Kaltern (Caldaro), South Tyrol, Italy (46° 21‘ N, 11° 16‘ E). The area, where the experiment has been conducted is the Etsch river valley, at an altitude of 243 m.
The trees in this orchard were planted in the year 2000 and set at a constant spacing of 3 m · 1 m. Whereas 3 m is the distance between the rows which have an East to West orientation and 1 m is the distance between the single plants along the row (Zanotelli, 2012). By planting the trees in this way alleys were formed and the soil in these alleys was covered with grass (1.8 m broad grass strip between the rows).
The orchard is managed by the owner according to organic production guidelines. The training system on this intensively farmed orchard is the slender- spindle and the mean height of the plants is about 3.6 m. The yields on the orchard were in average around 61 t ha^{-1} ± 15 t ha^{-1} (Marseiler, 2012). The orchard is provided with generous amounts of water by the over-crown irrigation, water availability was not limiting.
Soil texture was 10.6% clay, 44.7% slit and 44.7% of sand. These findings refer to a soil depth of 0-60 cm (Marseiler, 2012). According to the soil texture calculator (USDA) this soil falls into the category of loamy soils. Moreover, the pH of the soil was measured in different depths. In the first 20 cm it was about 7.2 and it increased to 7.3 in 40 cm depth and finally in the layer from 40- 60 cm the pH reached 7.6 (Marseiler, 2012). During the study of Marseiler in 2012 on the same site the bulk density and the field capacity was determined. The soil density was 1.5 g cm^{-3} in the 0- 60 cm soil layer and the field capacity was 35% vol.. On the basis of these values describing the soil texture, the plant wilting point should be around 14% vol. (Saxton and Rawls, 2006).
During the last 30 years the mean temperature was 11.5 °C and the mean precipitation (without including irrigation) was 810 mm y^{-1}. During the year 2012 the annual mean temperature was 13.3 °C and the annual precipitation was 964.5 mm y^{-1}. Additionally to the precipitations, 144.5 mm y^{-1} were added through the over head sprinklers.
In this region of South Tyrol, the cultivation of apple plants is intensive and the experimental site is surrounded by fields with nearly the same characteristics in all directions (Zanotelli, 2012).

2.2 Instrumental set up

2.2.1 Meteorological data and soil moisture measurements

In order to measure all relevant meteorological data for the calculation of the ET_C and the water balance, different meteorological instruments were installed at the site. The solar radiation was measured by a CNR1 (Kipp & Zonen, Delft, Holland), the air temperature and the relative humidity by a CS215 (Campbell Scientific Incorporated, Logan, Utah, US). Furthermore, precipitation was measured by a professional rain gauge (RAIN-O-MATIC, Pronamic, Silkeborg, Denmark) installed at 8 m of height above ground to obviate the collection of irrigated water (Figure 2). In order to survey the amount of water given by irrigation, a plastic pluviometer was installed at the height of 2 m. This amount was recorded weekly. Irrigation was calculated by the difference between the amount of water detected from the plastic pluviometer and the one detected by the professional rain gouge. All these data of interest were recorded each half hour and logged by a CR 3000 data logger (Campbell Scientific Incorporated, Logan, Utah, US).
To develop the water balance, the knowledge of the soil water content is necessary. The soil water content (SWC) measurement was made using three TDRs (time- domain reflection sensors) (CS616, Campbell Scientific Incorporated, Logan, Utah, US). These probes were placed in the middle of the orchard at the southern side of the row with a distance of 40 cm from the trees, at different soil depths, 5, 30 and 60 cm.
The calibration for the TDRs, elaborated by Marseiler (2012), was made by using two additional TDRs installed vertically at a depth of 30 cm. By taking five soil samples at two different dates and determining their water content (% vol.) it was possible to compare the amount of water in the samples and the measurements recorded by the TDRs at the same time. Thanks to this record TDRs were calibrated according the linear regression equation (Figure 1) (Marseiler, 2012).

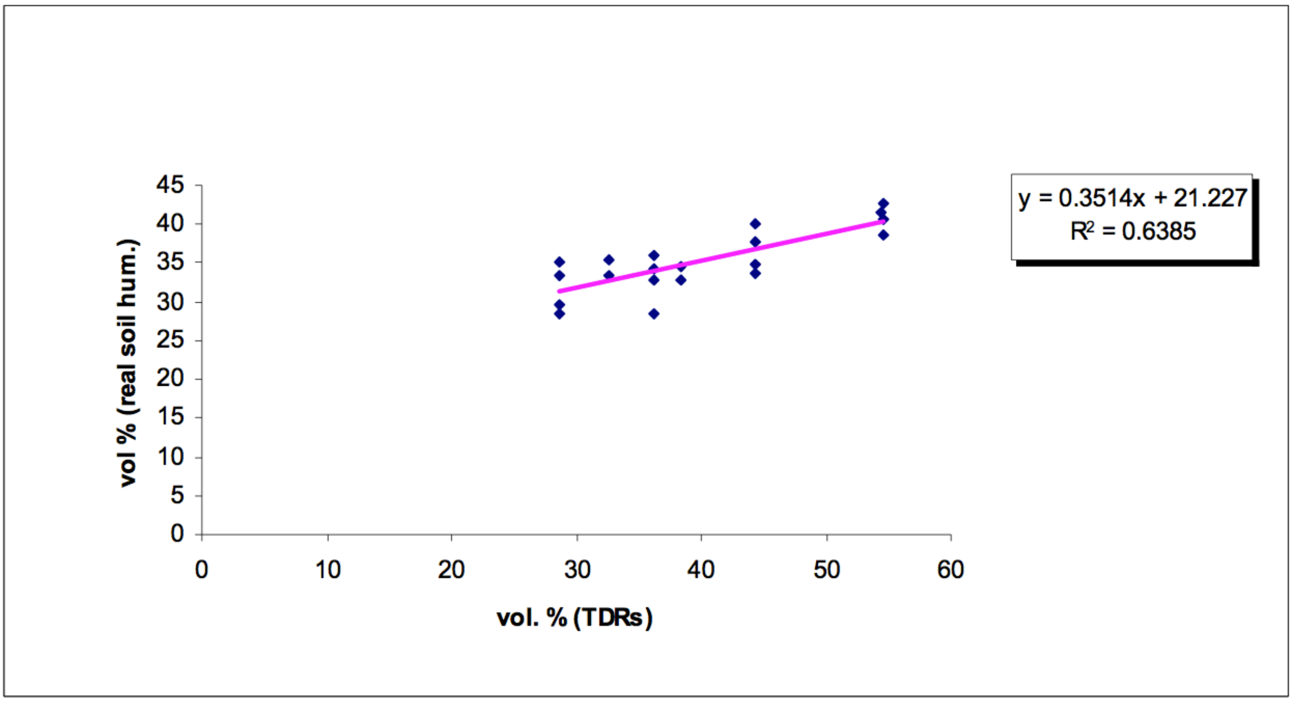


Figure 1: Regression line and regression equation for the calibration of TDRs (Marseiler, 2012)

In order to relate the ET_C calculations and the water flux measurements by the Granier method and the Heat Balance technique, they were represented in relation to temperature and Vapor Pressure Deficit (VPD). It was still necessary to determine the VPD. This was done by using the data of air temperature and relative humidity. VPD is known as the difference between the air, saturated at 100% with water vapor and the actual water pressure for a given time period (Allen et al., 1998).

VPD was calculated using the following formulas:

$$SVP = 610 \cdot 10^{\frac{7.5\,T}{2373+T}} \qquad \text{Eq.(1)}$$

SVP	Saturated vapor pressure [Pa]
T	Temperature [°C]

$$VPD = \left(\frac{100 - RH}{100}\right) \cdot SVP \qquad \text{Eq.(2)}$$

VPD	Vapor pressure deficit [Pa]Temperature [°C]
RH	Relative humidity [%]

2.2.2 Measurements of water fluxes according to the eddy covariance method

Eddy covariance method is a technique to measure turbulent fluxes in the surface boundary layer of the atmosphere. This method is primarily used to estimate gas exchange of an ecosystem. The technique is used for researches about water, carbon dioxide, methane and other trace gases fluxes. Whereas fluxes describe how much of a certain material goes through a portion of air in a unit of time. In this study the data recorded through the eddy covariance method were used to determine the crop evapotranspiration (ET_C). This reliable method works best when the site where the experiment takes place is flat, the cover of vegetation is homogeneous and the atmospheric conditions are steady (Baldocchi, 2003), all requirements that were met in the study site in Kaltern. To understand how the eddy covariance method works it is important to know that the wind has a vertical component and a lot of eddies that flow in all different directions, but of interest is the component that goes down- and upward. To measure the exchange rate of water vapor and CO_2 between atmosphere and canopy an omni-directional sonic anemometer (Gill R3-50, Gill-Instruments, Lymington, UK) was necessary. This instrument is able to detect the wind velocity in different directions. In addition a closed path CO_2/H_2O gas analyzer (IRGA, LI-7000, Li-Cor Biosciences, Lincoln, Nebraska, USA) was installed which was sampling the air at 40 cm distance from the anemometer on the top of the tower to measure the concentration of water or CO_2 in the portions of air passing the sensor with a certain velocity. In fact the general principle of the eddy covariance method is the covariance between the concentration of molecules of interest and the vertical velocity of the eddy moving the particles. Furthermore, to calculate the ET_C, the eddy covariance method requires the latent heat exchange of the orchard that is estimated through the concentration of water vapor detected by the gas analyzer. In addition to the Li 7000 closed path gas analyzer in September 2012 a Li 7200 (IRGA, LI-7200, Li-Cor Biosciences,

Lincoln, Nebraska, USA) was installed. This was made with the purpose to improve the quality of measurements of the water fluxes. In contrast to the Li 7000 the Li 7200 system has a shorter sampling line. Due to its form the Li 7200 can be mounted directly on the tower, in contrast the Li 7000 must be placed on the ground connected to the sampling point with a 12 m long sampling line. This sampling line takes the air from the sampling point to the gas analyzer. The time of residence in the sampling line affects the concentration of air constituents in two main ways: (a) ambient fluctuations are partially damped (amplitude effect); (b) concentration time series are somewhat shifted (phase effect) in relation to the concerned wind speed measurements (Fratini et al. 2012). Having the shorter sampling line, these effects are reduced in the Li 7200 gas analyzer. As consequence, the data analyzed with the Li 7200 are more reliable (Fratini et al. 2012). From 11 September 2012 to the end of the experiment in December 2012 the two gas analyzer measured concurrently. For the values from the 1 to the 11 of September a correction factor was computed due to a regression equation. The values measured by the Li 7000 and those measured by the Li 7200 were plotted respectively on the x and the y axis of a graph (figure 9, chapter 3). Through the addition of a regression line the correction factor was computed.
The instruments used for the eddy covariance method were placed on the top of a tower at 8 m hight in order to be 4 m above the canopies of the apple orchard (Figure 2). It was located at the center of the orchard. The eddy covariance tower was installed in the 2009, from this time on data were recorded until December 2012.

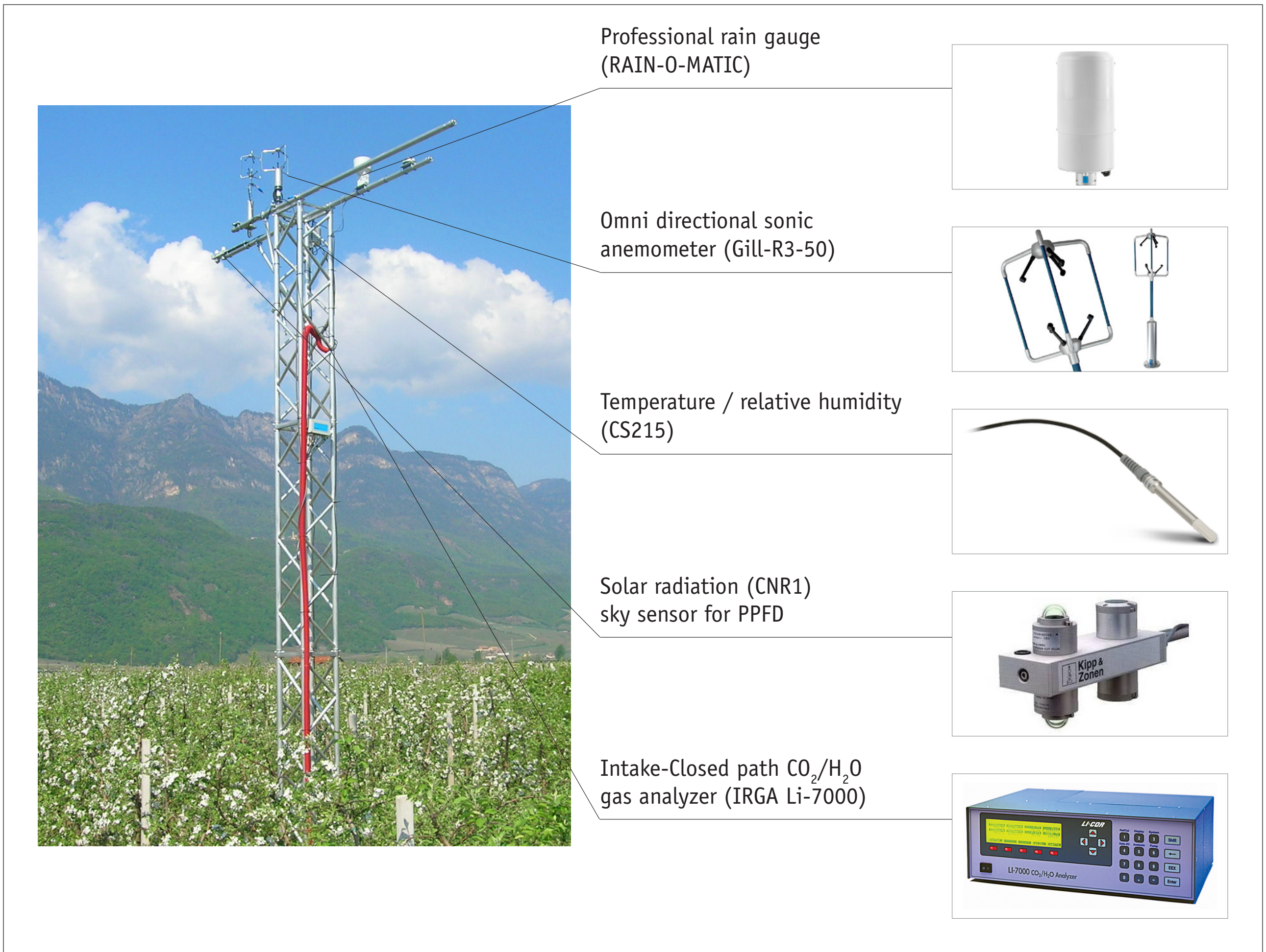


Figure 2: Eddy covariance tower in the study site at Kaltern, South Tyrol, Italy. And the instrument used in the study. (References Picture on Page 45)

For the collection and the computation of the data the Eddysoft software (Kolle and Rebmann, 2007) was used. The Foken and Wichura (1996) quality test was applied in order to exclude data with low quality. Additionally, to exclude data with an inaccurate water vapor concentration measurement, the quality test following the equation of Clapeyron-Clasius was applied. When measurements were missing for certain reasons, the gaps were filled with the average value under similar meteorological conditions (Reichstein et al., 2005).

By eddy covariance it was possible to measure the latent heat flux, and from this parameter it was possible to asses the orchard evapotranspiration. The following formulas use the latent heat (LE) measurements to compute the ET_C of the orchard (Aubinet et al., 2000):

$$\lambda = \left(3147.5 - 2.37\,T\right)\cdot 10^3 \qquad \text{Eq.(3)}$$

λ	Latent heat of vaporization of water
T	Temperature [K]

$$ET_C = \frac{(LE \cdot 1000)}{(Mw \cdot \lambda)} \qquad \text{Eq.(4)}$$

LE	Latent heat in [W m^{-2}]
Mw	Molar mass of water [0.0180153 kg mol^{-1}]
ET_C	Evapotranspiration of the crop [mmol m^{-2} s^{-1}]

In a second step from the ET_C in mmol m^{-2} s^{-1} was derived the ET_C in mm hh^{-1} (hh= half hour) using the following formula.

$$ET_{C\,(in\;mm\;hh^{-1})} = \frac{(ET_{C\,(in\;mmol\;m^{-2}s^{-1})} \cdot 1800)}{(55.5 \cdot 1000)} \qquad \text{Eq.(5)}$$

The ET_C was detected because it represents a key component of the water balance and it is site specific as well as crop specific and also climate specific. Through the measurements it was possible to obtain a highly accurate data for this site. So that it wasn't necessary to adopt the ET_C data from the literature. In a further step the discovered ET_C was used to compute the trend of the average day ET_C for the months of September, October, November and December.

2.2.3 Elaboration of a water balance for the study site

To develop a water balance for a certain area it is necessary to detect all the inputs and outputs of the ecosystem of interest. Therefore, the computation of the apple orchard water balance was carried out according to the following formula (Franco et al., 2000).

$$ET_C = I + P - D - \Delta SW + C\ (-R) \qquad \text{Eq.(6)}$$

I	Irrigation
P	Precipitation
$\triangle$SW	Difference in soil water
C	Capillarity
R	Run off
D	Drainage

In a given period, the difference in soil water content ($\triangle$SW) can be positive or negative. It will be positive if the amount of water in the root-zone rises and it will be negative if the amount of water in the root-zone declines during a certain time period. Drainage (D) and capillarity (C) were not measured but detected with the following formula:

$$D - C = I + P - ET_C - \Delta SW \qquad \text{Eq.(7)}$$

If the result of the right site of the equation is positive, drainage is higher than capillarity (If the result is negative it will be vice versa). It was assumed that if the value for D-C results positive all the water will contribute to drainage. All the calculations in the formulas were made in mm. The data for this part of the experiment were collected since the year 2011. The data until 15 July 2012 were taken from the master degree thesis of Marseiler (2012) and revised in this study. In addition, the data until December 2012 were collected in this study.

2.2.4 Thermal dissipation probe (TDP) according to Granier

The Granier method was used to determine the water consumption of a single apple plant. This tree was located in a row in the center of the orchard and represented the standard for all trees present in the field. Its identification number was E 123. The Granier method works with two 20 mm long probes with 2 mm diameter, in order to measure mass flow in the xylem these probes were inserted radially in the stem at a vertical distance of 20 cm (Figure 3). The nether probe was about 30 cm above ground. Each of the probes contained a thermocouple, but only the upper one was permanently heated at a constant power of 0.2 W (Lu et al., 2004; Kell et al., 2000). After wiring the probes, they were covered with a plastic film to protect them against external influences. Subsequently, the probes were connected to the data logger (CR10, Campbell Scientific Incorporated, Logan, Utah, US) and a power unit. Every 15 minutes data were logged. Whereat the blank sample was taken at 3 o'clock a.m. because sap flow at this time is expected to be equal to zero. Subsequently, the measurements over the whole day started at 6 o'clock in the morning and concluded at 8.45 in the evening. Thus, the measurements reflected the trend of transpiration of the whole day.

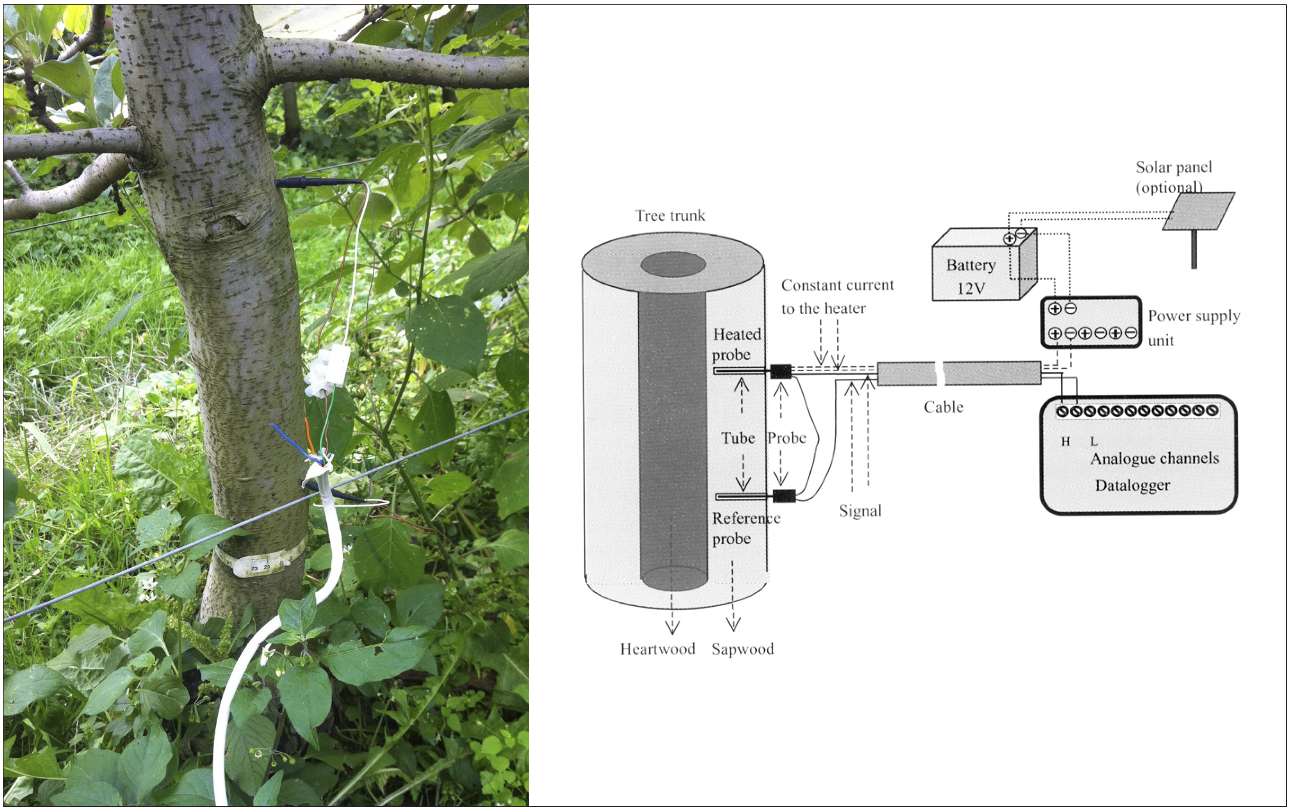


Figure 3: Setting of the Granier sensor on the apple tree E 123. and graphical representation of the experimental set- up of the Thermal Dissipation Probe (TDP) according to Granier (Lu et al., 2004).

The thermocouples of the Granier sensor were used to detect the temperature difference between the two probes. This difference in temperature is caused by the heat dissipation effect of sap flow in the vicinity of the probes. The temperature difference increases with decreasing flux (Ferreira et al., 2009). In the end, temperature differences between the two probes were used to calculate the flux density with the following formula (Lu et al., 2004):

$$F_d = 136.8356 \cdot 10^{-6} \left[\frac{(\Delta T_{\max} - \Delta T)}{\Delta T} \right] \cdot 1.299714 \qquad \text{Eq.(8)}$$

F_d	Flux density
$\triangle T_{max}$	Maximum temperature difference between the heated and non heated probe at a given F_d
$\triangle T$	Temperature difference between the heated and non heated probe at given F_d

As the Granier method measures only the flux density along a 20 mm · 3.14 · 1 mm² cylinder, these measurements were extrapolated to the whole area of sap wood present in the plant. This was made by the following formula (Lu et al., 2004):

$$F = F_d \cdot A_{SW} \qquad \text{Eq.(9)}$$

A_{SW}	Area of the cross-section of the sapwood at the level of the heated probe

To establish the area of sapwood, this study relied on information detected in the literature. Two different studies found two varying approaches. Atkinson et al. discovered that in *Malus pumila* the percentage of sap wood on the rootstock M9 is about 76.6 % ± 5.9 % (Atkinson et al., 2003). Another approach to estimate the sapwood area of a tree was traced by Huber (1956). In his studies Huber proved that the area of sapwood in trees of the northern temperated zone depends on the amount of green parts on the plant. More precisely, for every gram of green part (foliage) on the tree, the plant requires 0.5 mm^2 of vascular tissue (Huber, 1956).
Possible techniques to calibrate the Granier method have been published. According to Conceicao and Ferreira (2009) it is possible to calibrate the heat dissipation (HD) method, named after Andre Granier, through the ET measurements of the eddy covariance method (ET_{ec}) (Conceicao and Ferreira 2009). This should be possible by considering the soil evaporation and the understory transpiration (E_s) measured with mini-lysimeters (ML) (Conceicao and Ferreira 2009). If these components were combined in an simple equation $T_e = ET_{ec} - E_s$ the result is the transpiration of the crop (T_e) (Conceicao and Ferreira 2009). Finally the result T_e could be used to calibrate the value measured from the Granier method (Conceicao and Ferreira 2009). The calibration technique used by Conceicao and Ferreira (2009) could have been a way to calibrate the measurements of the Granier method of this study. Another method of calibration was followed by Sugiura et al. (2009). They used a balance to calibrate sap flow (transpiration) measurements by the Granier method. They proceeded as follow: a japanese pear (*Pyrus pyrifolia*) tree was planted in a pot and and placed on a balance, to suppress evaporation from the surface the pot was covered with a plastic film. The whole weight was recorded every five minutes (Sugiura et al. 2009). The weight loss was expected to be equal to the amount of water transpired by the tree, excluding the weight of the irrigation water (Sugiura et al. 2009). Previously, the same pear tree was used to detect sap flow with the Granier method. As consequence, the results were compared and the sap flow meter was calibrated according the values recorded with the balance (Sugiura et al. 2009). In a further step these considerations could be used to calibrate the Granier sensor and to detect the quantitative amount of sap flow (transpiration) for the trees.

2.2.5 Heat Balance method to estimate sap flow of single apple trees

The Heat Balance sensor is typically used to detect water flux in stems or branches of wooden and herbaceous plants. This sensor is made as follow:
The flexible, 2 cm wide heater is located in a cork band that is wrapped around the branch. Additionally, a pair of thermocouples is embedded in the cork to get a thermopile. Whereat one junction of each pair is placed on the inner surface of the cork while the other one is placed at the outer surface away from the heater (Smith and Allen, 1996). As a result the thermopile measures the radial temperature gradient away from the heater (Steinberg et al., 1989). In this study the heater band was wrapped around eight single branches (mean diameter 9,46 mm) of two different trees in various positions on the plant. These trees were located in the center of the orchard, one was the plant E 123 (where the Granier sensor was placed) and the other one was the plant E 124. The branches were selected in reason of their location in terms of height above the ground and their orientation (South or North). So that the whole tree was represented. Moreover, the number of leaves on the single branch was monitored 3 times during the whole experiment. This was necessary because the amount of transpiration depends on the leaf area. Particularly, the leaf area has a huge impact on the water requirements of different branches. An additional factor is the different position of the branches. Therefore, the sensors were applied on different branches in different positions with a comparable diameter. In figure 4 the position on the tree and the label of the different sensors were represented.

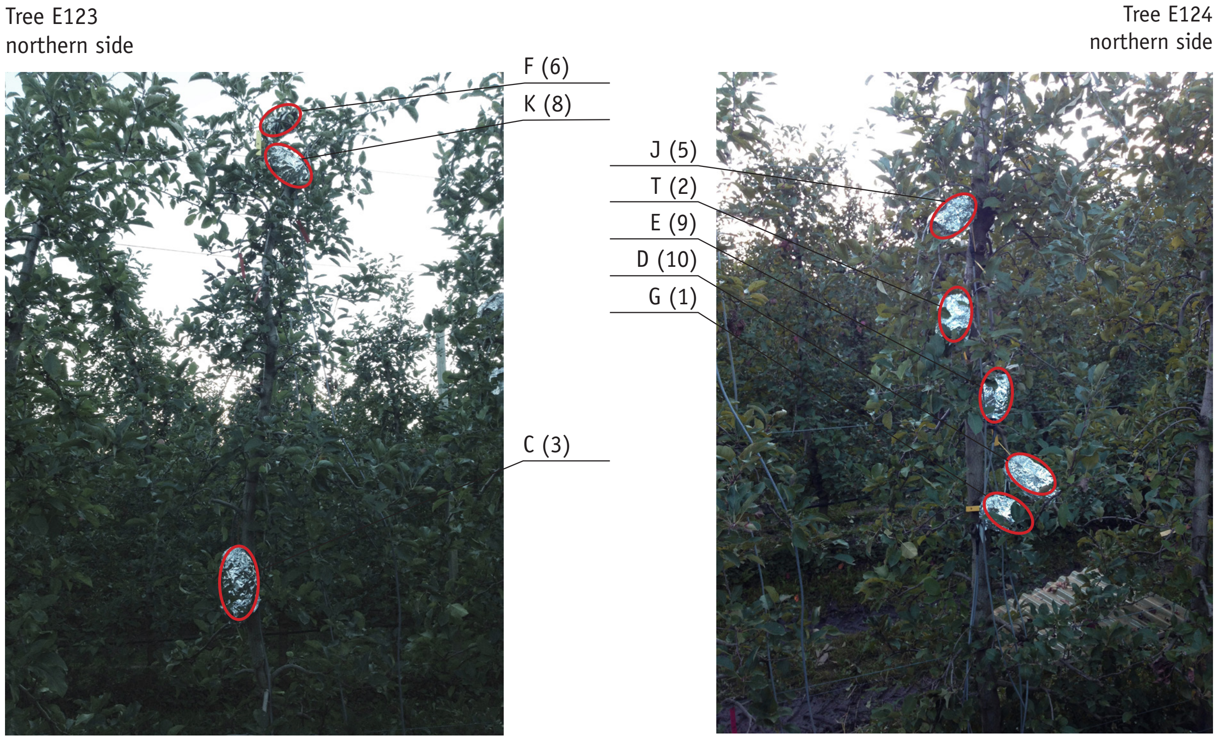


Figure 4: Setting of the Heat Balance sensor on the trees. On the left tree E 123 and on the right tree E 124

In order to protect the heating element from external influences, like solar radiation, wind or precipitation, it was isolated with a foam rubber band, that was wrapped around the sensor. On top of the rubber band a waterproof aluminum film was placed to reflect the solar radiation, and offered an additional protection from precipitation.
After the positioning of the sensors they were connected to the power unit and the data logger (CR10, Campbell Scientific Incorporated, Logan, Utah, US). The measurements during the day started at 3 o'clock in the morning. This measurement was the control measurement because sap flow at this daytime is expected to be equal to zero. Thereupon the measurements over the day started at 6 o'clock in the morning and were concluded at 8:45 in the evening. In this manner the measurements reflected the trend of the transpiration of single branches during the whole day.
According to the theory of operation of the Heat Balance method, the heat energy is applied through a heater band wrapped around the entire circumference of the branch. This heat energy input is limited to the power given to the heater (P). Starting point of the calculation is the heat balance of the branch (stem).

$$P = q_v + q_r + q_f \qquad \text{Eq.(10)}$$

P	Power given through heater
q_v	Vertical heat loss by conduction
q_r	Radial heat loss by conduction
q_f	Heat uptake by the moving sap stream

The value q_f is calculated by subtracting q_v and q_r from P, which can all be measured. P could be calculated from the electrical resistance and voltage across the heater, while q_v and q_r were determined from measurements of temperature differences ($\triangle T_a$ $\triangle T_b$ and $\triangle T_r$). In the end p_f was converted to the mass flow of sap (Smith and Allen, 1996).
To determine q_v and q_r specific formulas exist. For q_v the Fourier's Law for one-dimensional heat flow was used.

$$q_v = A_{ST} \cdot K_{ST} \left[\frac{\Delta T_b - \Delta T_a}{x} \right] \qquad \text{Eq.(11)}$$

A_{ST}	Cross-section area of the heated section of stem
K_{ST}	Thermal conductivity of the stem (in general 0.42 W m^{-1} K^{-1}) (Steinberg et al., 1989)
x	Distance between the two thermocouples

In order to calculate the radial component of the stem heat balance q_r the $\triangle T_r$ was used. The applied formula is the following one.

$$q_r = K_{SH} \cdot \Delta T_r \qquad \text{Eq.(12)}$$

K_{SH}	Effective thermal conductance of materials surrounding the heater (depends on thermal conductivity of materials) (Smith and Allen, 1996)

The last step was to calculate the value q_f by difference and the mass flow rate of sap (F_m) was calculated using the following equation.(Sakuratani, 1981; Baker and van Bavel, 1987; Steinberg et al, 1990).

$$F_m = \left[\frac{2 \cdot q_f}{c_S(\Delta T_a + \Delta T_b)} \right] \qquad \text{Eq.(13)}$$

F_m	Mass flow rate of sap
c_S	Specific heat capacity of sap
$\frac{(\Delta T_a + \Delta T_b)}{2}$	Increase in sap temperature across the heater, assuming that heating of the sap is radially uniform

3. Results

3.1 Water vapor fluxes from Eddy covariance method and meteorological data

The Evapotranspiration (ET_C) measured through the eddy covariance method is basis of most calculations in this experiment. Furthermore, it was applied as reference measurement for the sap flow methods (Granier and Heat Balance). The ET_C in this orchard was recorded in the years 2010, 2011 and in 2012. The table 1 summarizes the results obtained during my study, by showing the average daily crop evapotranspiration and the cumulative evapotranspiration along September, October, November, and December.

Month	Daily ET_C averages 2012 [mm d^{-1}]	Cumulate ET_C [mm]
September	1.93 ± 0.61	57,9
October	1.18 ± 0.49	36,58
November	0.35 ± 0.17	10,5
December	0.17± 0.10	5,27

Table 1.: Average daily ETC from September to December 2012 and cumulative ETC for every month

In the figure 5 the ET_C from 12 September 2012 until December was represented. From the beginning of the experiments until the 11 of September 2012 measurements were taken only with the Li 7000 (closed path gas analyzer). This gas analyzer tends to underestimate the water fluxes due to problems indicated in chapter 2. As a consequence from 12 September on, measurements were recorded simultaneously by Li 7000 and Li 7200, shown respectively in blue and red colored bars (figure 5). In addition to the ET_C, the figures 6, 7, and 8 display the Photosynthetically active Photon Flux Density (PPFD), the air temperature and the Vapor Pressure Deficit (VPD) for the period of interest.

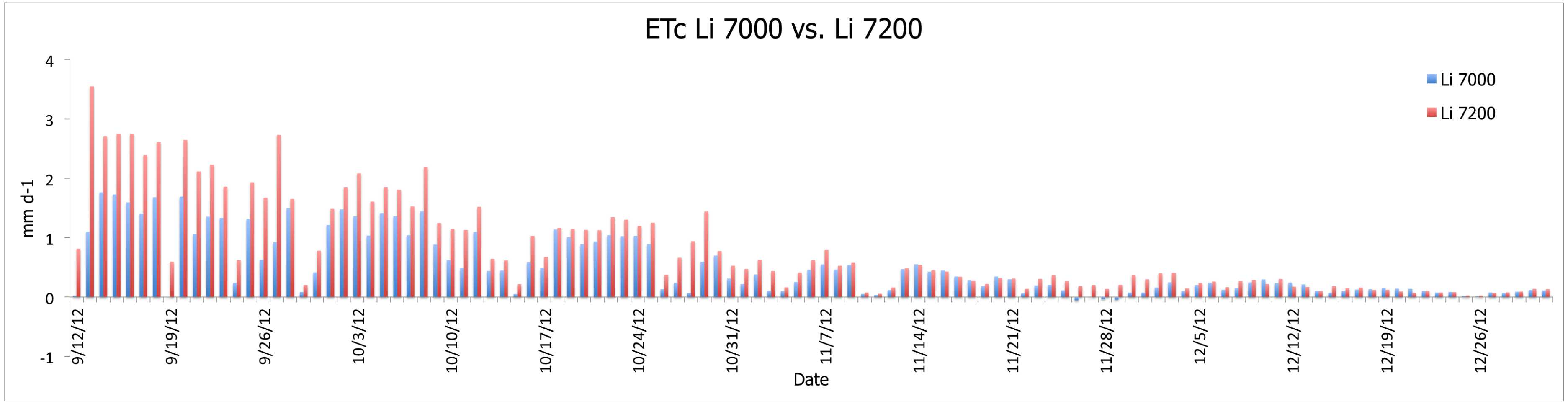


Figure 5.: Daily crop evapotranspiration over the period from 12 September to December in mm day $^{-1}$. Comparison of the data collected with the Li 7000 (blue bars) and the Li 7200 (red bars).

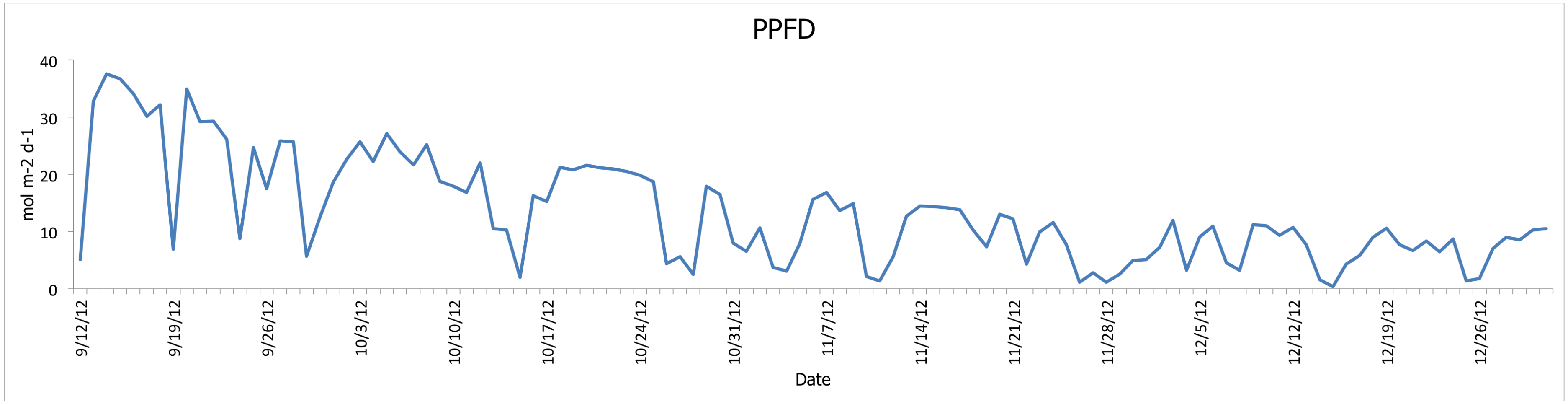


Figure 6.: Daily PPFD (Photosynthetically active Photon Flux Density) over the period from 12 September to December in µmol m^{-2} s^{-1}.

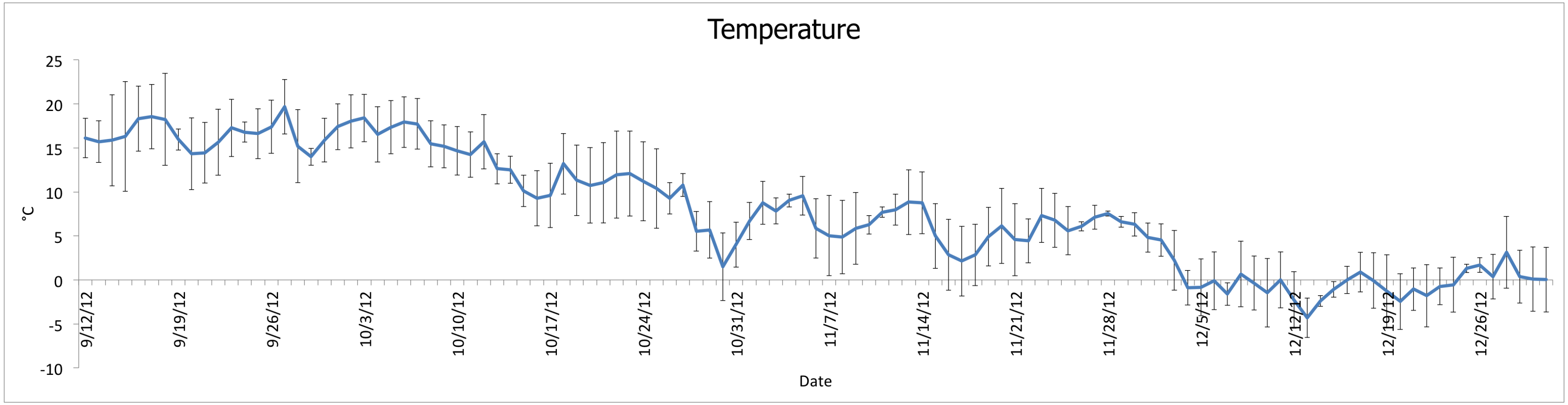


Figure 7.: Mean daily air temperature during the period from 12 September to December in °C. Error bars = Standard deviation.

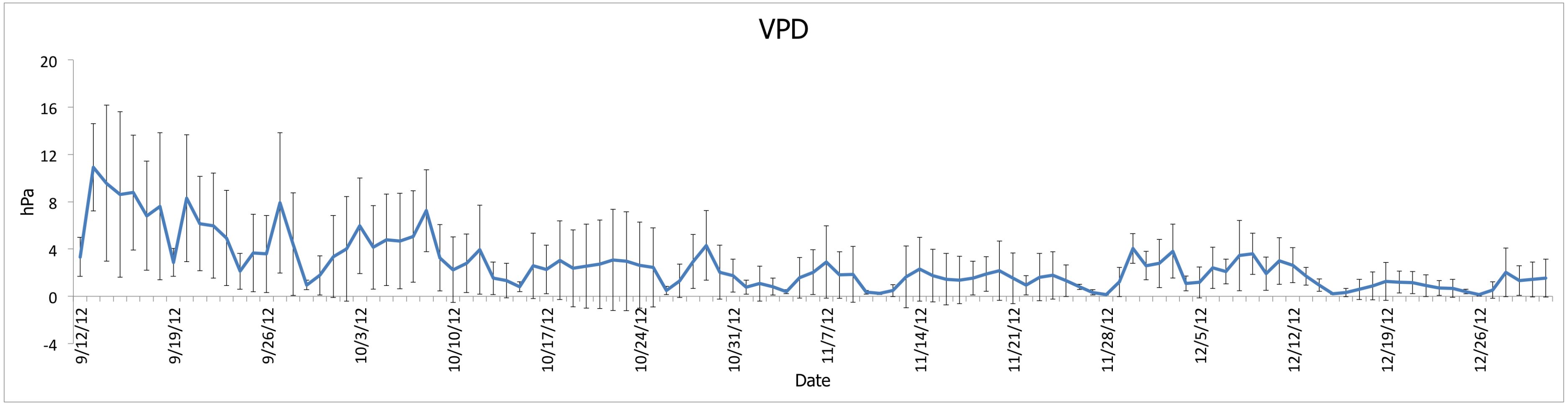


Figure 8.: Mean daily VPD (vapor pressure deficit) for the period form 12 September to December in hPa. Error bars = standard deviation.

In figure 5 it is possible to observe that the values recorded from the Li 7000 underestimate the values of the effective daily ET_c. The values recorded by the Li 7200 are probably closer to the real crop evapotranspiration. The crop evapotranspiration during late season, as depicted in the figure 5, had its maximum value in September. From September on, the crop evapotranspiration declined until it reached values close to zero in December. It can be observed that after the last week of October the daily ET_c decreased. This was because until that time, the trees still had some leaves that transpired, afterwards for the months of November and December, ET_c declined slightly but steadily toward the end of the year. When daily ET_c was high also the daily cumulated PPFD (Photosynthetically active Photon Flux Density) reached the maximum values, as it is depicted in figure 6. This observation confirmed the strong linkage between radiation and the crop evapotranspiration. Also the mean daily air temperature (represented in figure 7) was highest in September and reached the minimum at the beginning of December. The pattern of the mean daily VPD had a similar behavior as the air temperature. This was due to their high correlation. The pattern of air temperature and VPD, as the other two variables, reached their maximum during the month of September. After the beginning of October, the mean daily air temperature began to decline, reaching the minimum in the second week of December. VPD during the whole late season (September - December) displayed low values. The trend of these values followed in general the curve of the air temperature.

The values of the Li 7000 and the Li 7200 were compared in the following figure (figure 9) and a regression line was inserted in the chart to obtain the regression equation and the R^2 (correlation coefficient) value. This equation in a further step was used to correct the values of the first days of September to obtain the cumulative amount of the monthly ET_c.

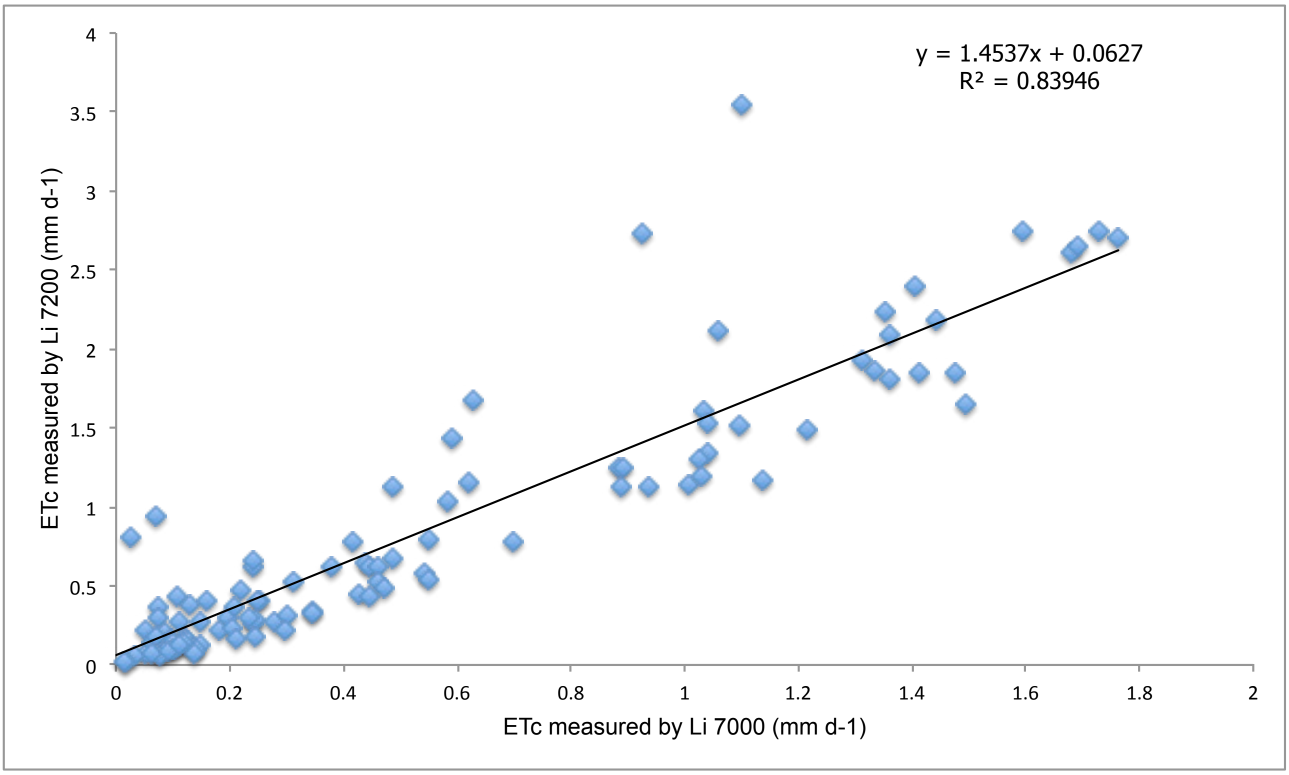
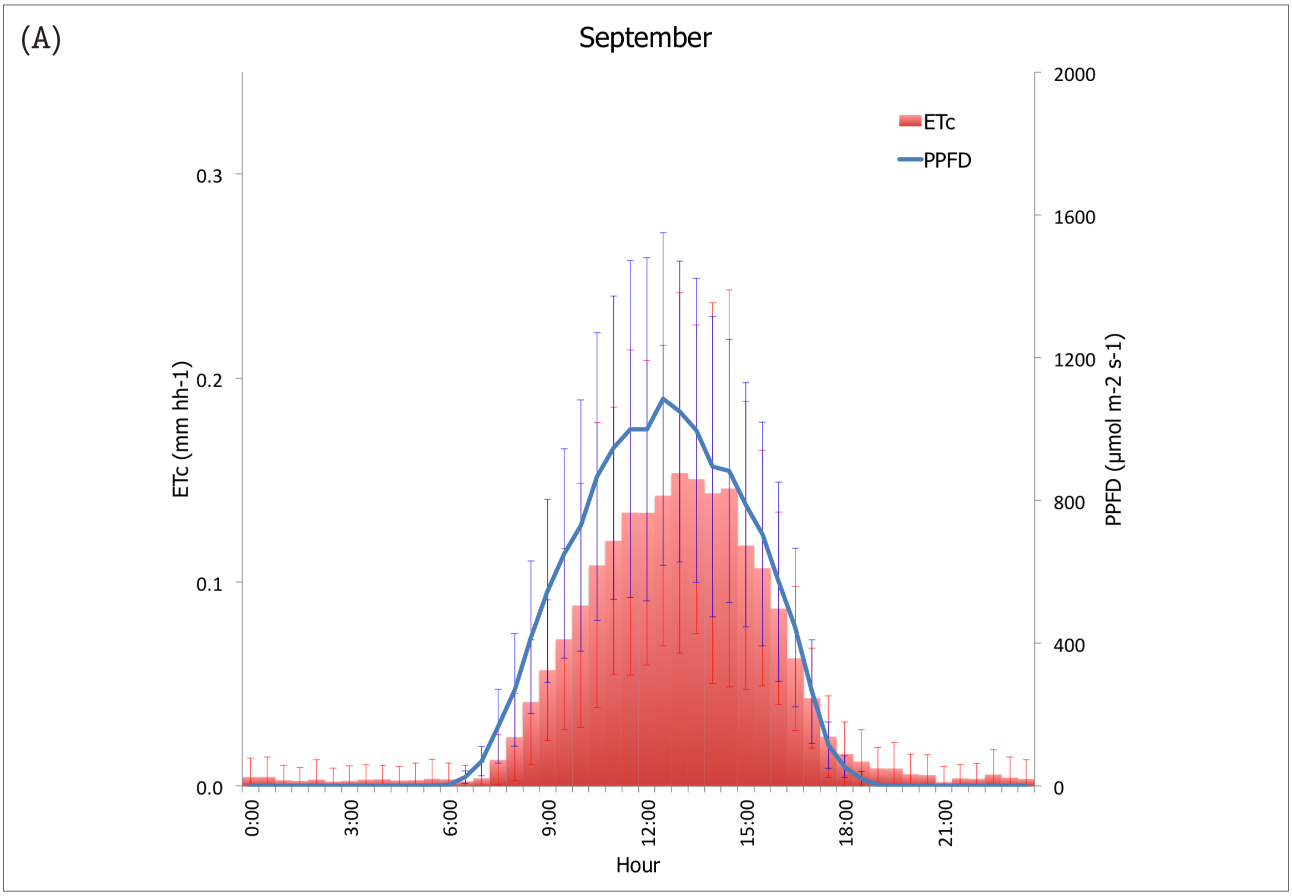


Figure 9.: Data measured from the Li 7000 on the x-axis and the values of the Li 7200 on the y-axis. Regression equation and the R^2 value were displayed in the figure.

The average pattern of ET_c along the day was calculated for each month from September to December and depicted in separate figures. In addition, for every month Photosynthetically active Photon Flux Density (PPFD), Vapor Pressure Deficit (VPD) and air temperature were summarized to a daily average. These three variables have the largest influence on the ET_c, therefore they are also shown.

The following paragraph describes the daily pattern of ET_c, PPFD, VPD and air temperature along the experimental period. The data reported in the figures 10, 11, 12 and 13 refer to the average daily pattern for each month. During the whole period of measurements air temperature and VPD reached the maximum at 3:30 p.m.. Only in November the peak was anticipated by half an hour. Furthermore, it was possible to observe that the VPD pattern followed the trend of the air temperature: this is an evidence of their close connection. The air temperature, and therefore also the VPD, decreased along the season, reaching their minimum as expected in December. The main peak of air temperature was reached in September (20.4 °C). Like the air temperature also the VPD achieved the maximum value in September with 11.9 hPa. In September the first slight upward trend of the air temperature during the averaged day around 6:30 a.m. while in December it was recorded at 10:00 a.m.. In the same way the VPD pattern was shifted during the time interval from September to December.
The maximum values of ET_c along the day were normally recorded in correspondence of the highest levels of PPFD, only in November, the PPFD pattern peak anticipated that of the ET_c of 90 minutes. The peaks of ET_c and PPFD in every month anticipated the peaks of VPD and air temperature by two hours in average. The PPFD and the ET_c are highly correlated in time, responses of evapotranspiration to PPFD fluctuations were immediate. This was especially striking during the months were the trees still had their leaves (until mid of November). It was possible to see that the starting and the ending points of the ET_c coincided with that of PPFD. The time interval between starting point (sun rise) and the ending point (sun set) of the records got shorter passing from September to December. From 11.5 hours in September to 8.5 hours in December. After the leaf fall the correlation of the ET_c and the PPFD decline. From then on, evaporation from the soil and the plant surface predominates. During this time the VPD can have a positive influence on the ET_c. Moreover, it was possible to observe that from September to December, ET_c was decreasing. In consequence also the peaks of the ET_c and the PPFD occurred later on the day. If in September highest values for both variables were recorded at 12:30 p.m., in December the highest values shifted by half an hour (1:00 p.m.). Further, it was possible to observe that in the average day of September and October the PPFD declined faster then the ET_c. Therefore the PPFD reached the zero point in average two hours before it was reached for the ET_c.



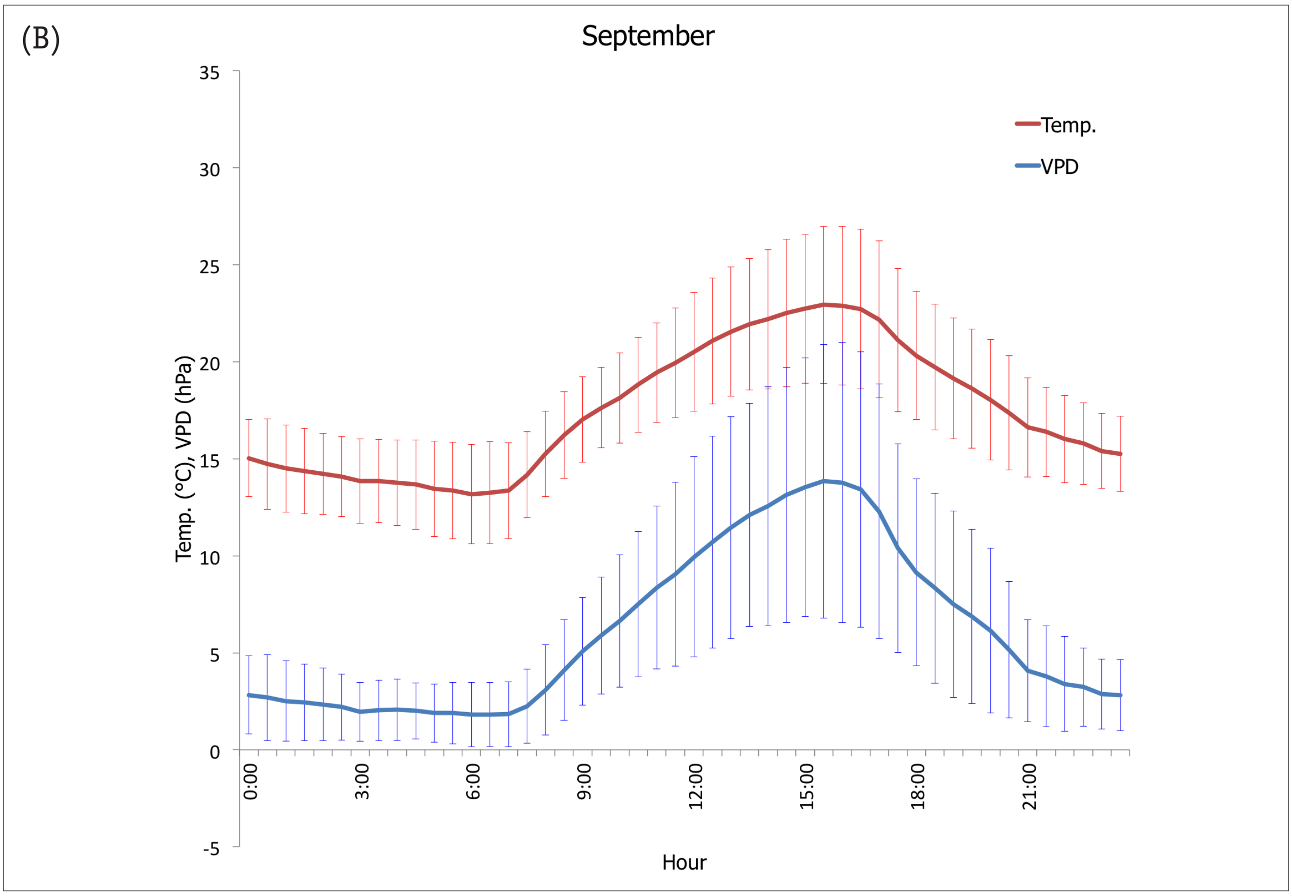
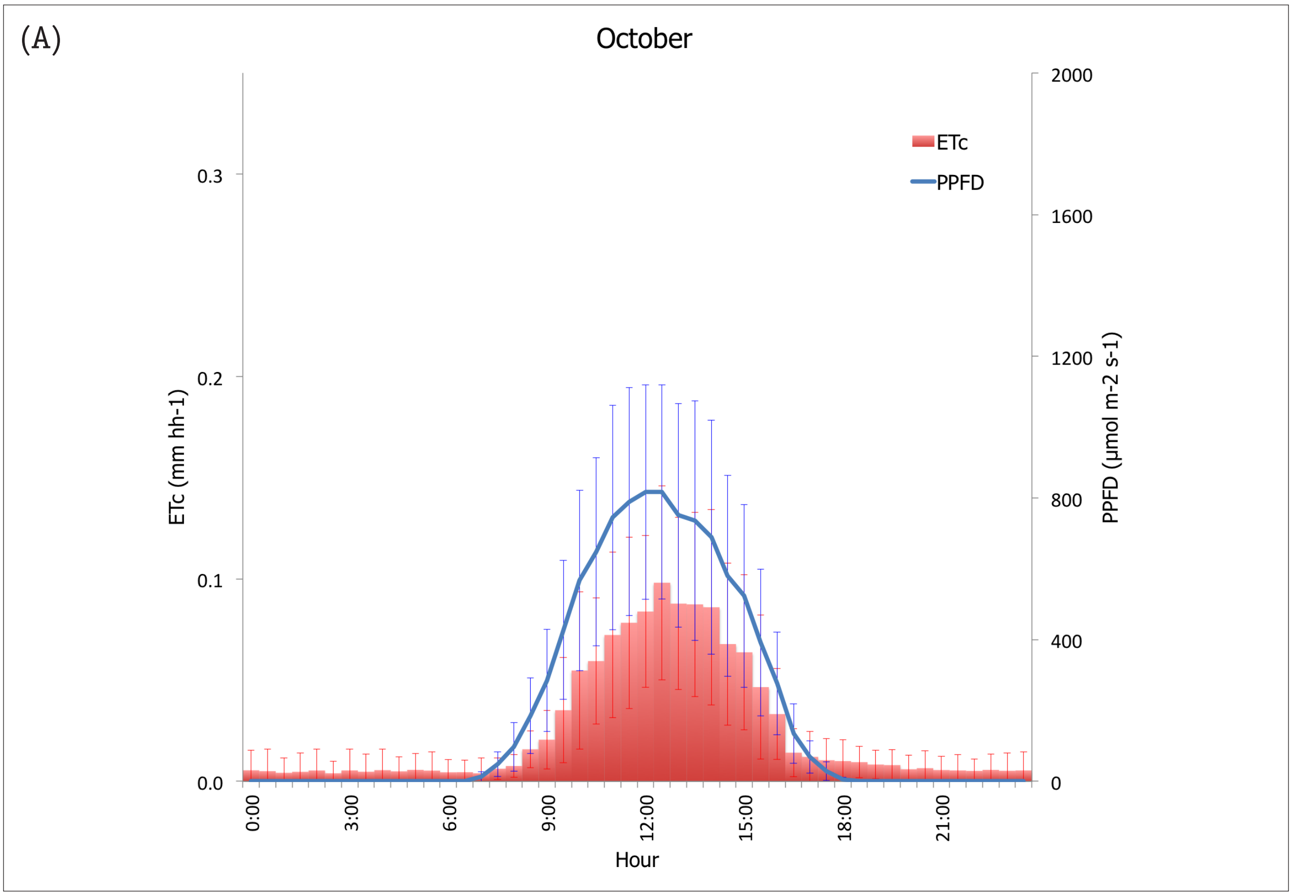


Figure 10.: (A) Average daily ET_c (Li 7200) in comparison with the PPFD for the month September. (B) Average daily air temperature and the VPD for the month. Error bars = standard deviation.



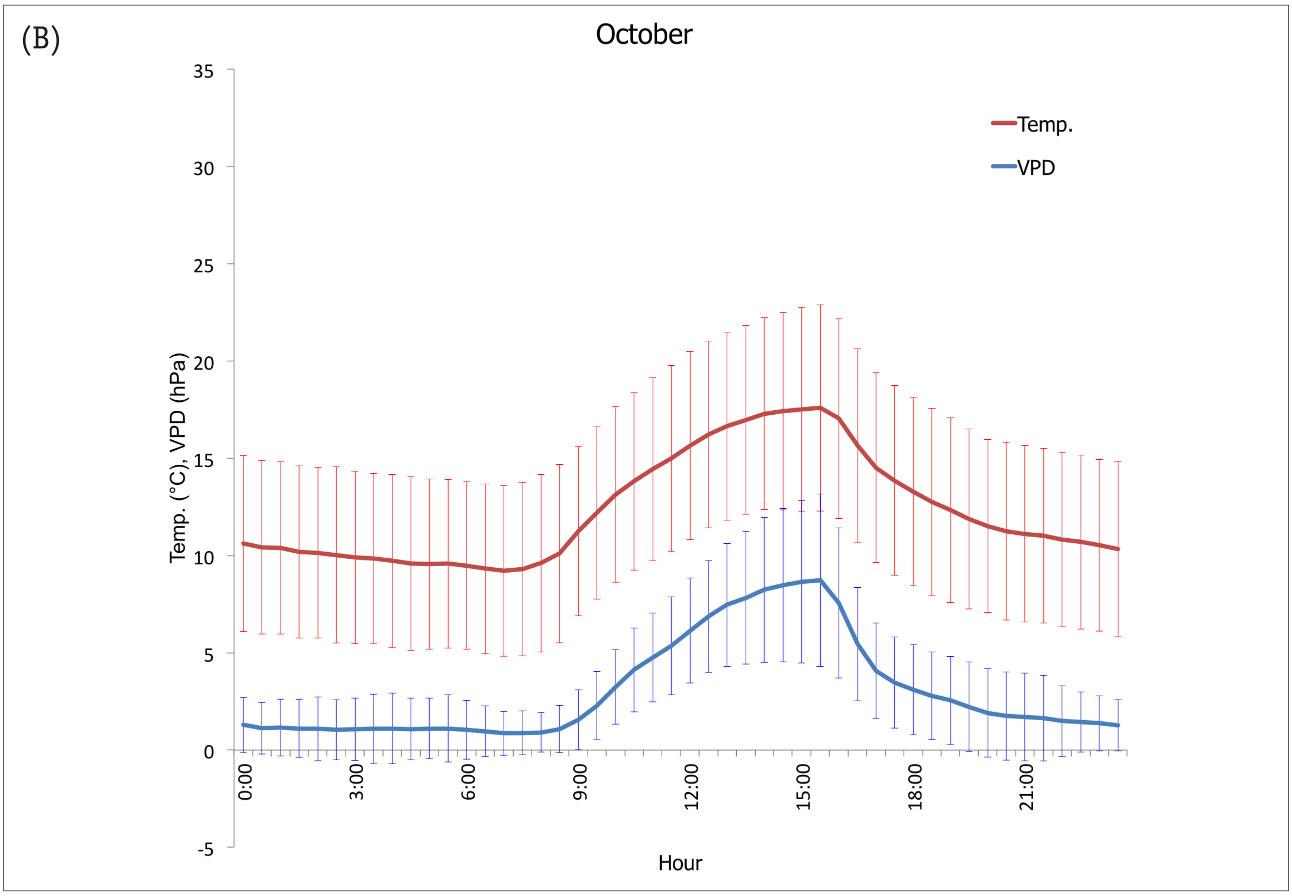
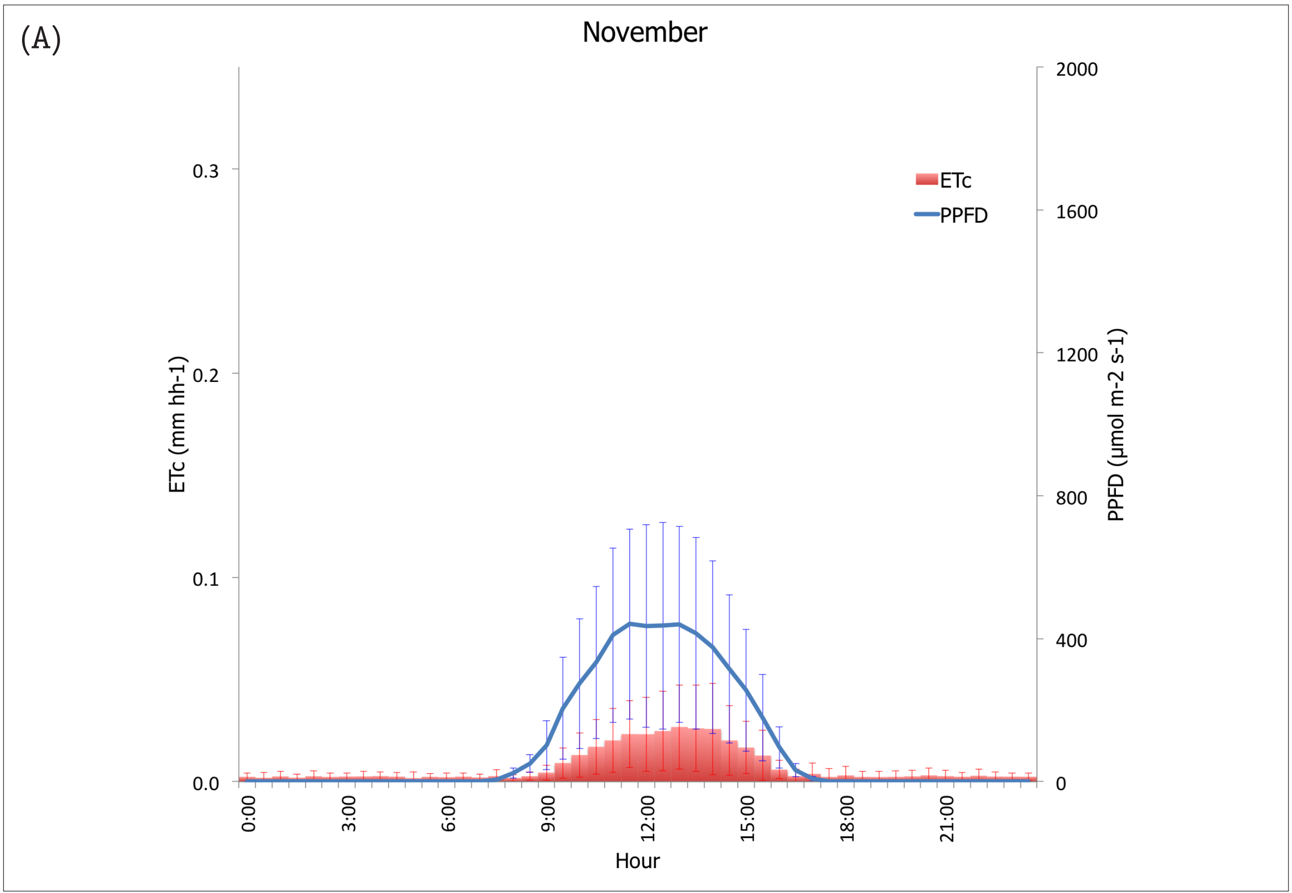


Figure 11.: (A) Average daily ET_c (Li 7200) in comparison with the PPFD for the month October. (B) Average daily air temperature and the VPD for the month. Error bars = standard deviation.



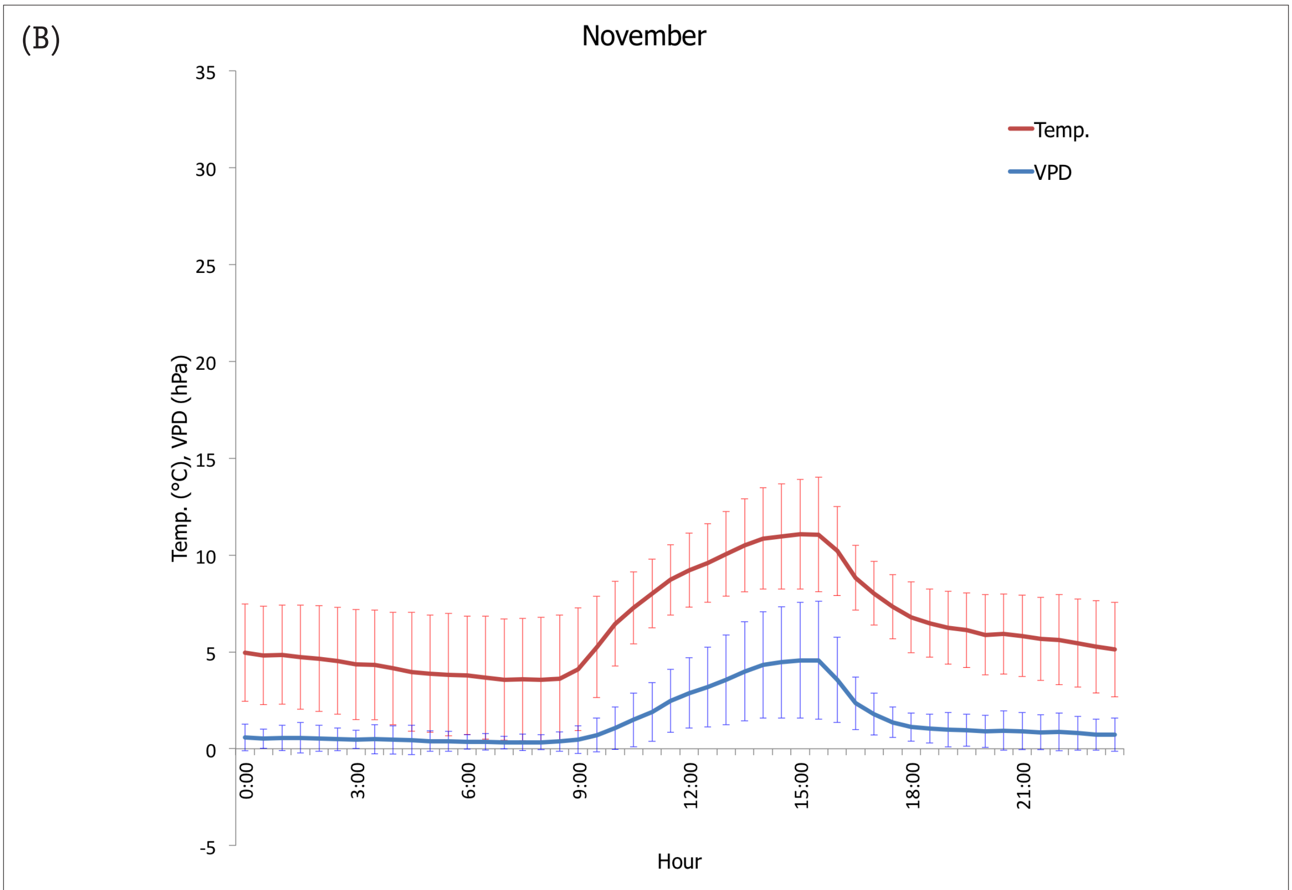
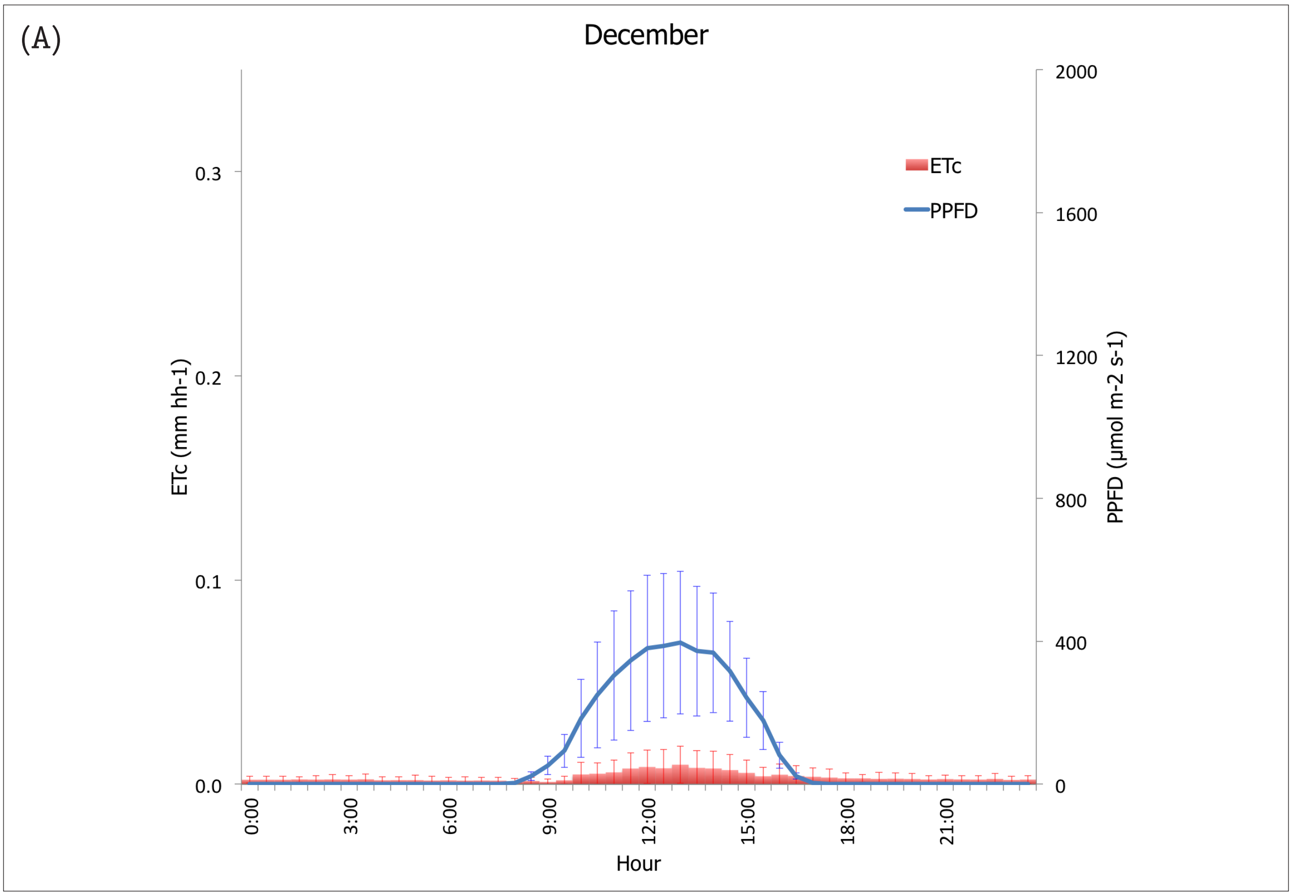


Figure 12.: (A) Average daily ET_c (Li 7200) in comparison with the PPFD for the month November. (B) Average daily air temperature and the VPD for the month. Error bars = standard deviation.



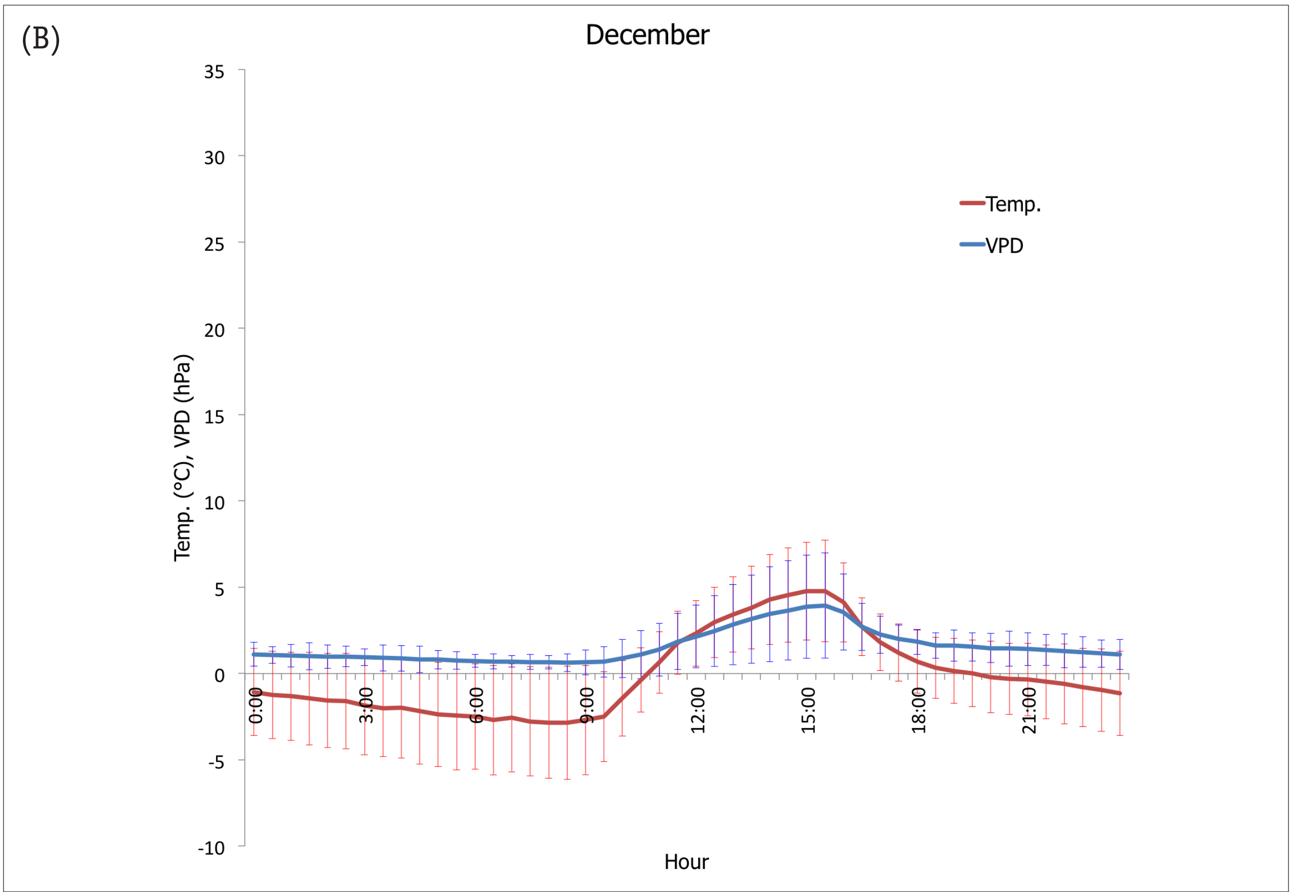


Figure 13.: (A) Average daily ET_c (Li 7200) in comparison with the PPFD for the month December. (B) Average daily air temperature and the VPD for the month. Error bars = standard deviation.

In table 2 the values for the figures 10 - 13 are summarized. The peaks of every variable, ET_C, PPFD air temperature and VPD, during the average day are represented.

	PPFD [µmol m^{-2} s^{-1}]	sd ±	ET_C [mm hh^{-1}]	sd ±	Temp. [°C]	sd ±	VPD [hPa]	sd ±
September	1084,5	466	0,15	0,06	20,39	5,43	11,98	6,92
October	816,7	301	0,09	0,04	17,57	5,31	8,72	4,42
November	440,8	96	0,02	0,02	11,05	2,82	4,57	2,98
December	396,3	199	0,009	0,009	4,77	3,07	3,93	2,32

Table 2.: Maximum values of ET_C, PPFD, air temperature and VPD along the averaged day for each month.

PPFD was highest during the average day in September (1084.5 µmol m^{-2} s^{-1}). After that it decreased during the following months to a minimum of 396.3 µmol m^{-2} s^{-1} in December. In the average day of September even the highest values for the ET_C were recorded (0.13 mm hh^{-1}). In the following month the maximal value decreased to 0.009 mm hh^{-1}. The maximum values of air temperature decreased continuously from September to December from 20.39 °C to 4.77 °C. The VPD followed the trend of the air temperature.

3.2 Water balance

To create the water balance for the orchard all data about inputs (precipitation, irrigation, and the change in soil water content - only if it is positive) and outputs (ET_c and the soil water content - if it is negative) were collected. This was done over an eight month period from the beginning of May to the end of December in the year 2012.

In the following figure the daily precipitation, irrigation and the daily average soil moisture content are described in three different depths under the soil. This was made to draw inferences about the influence of the two water inputs on the soil moisture content.

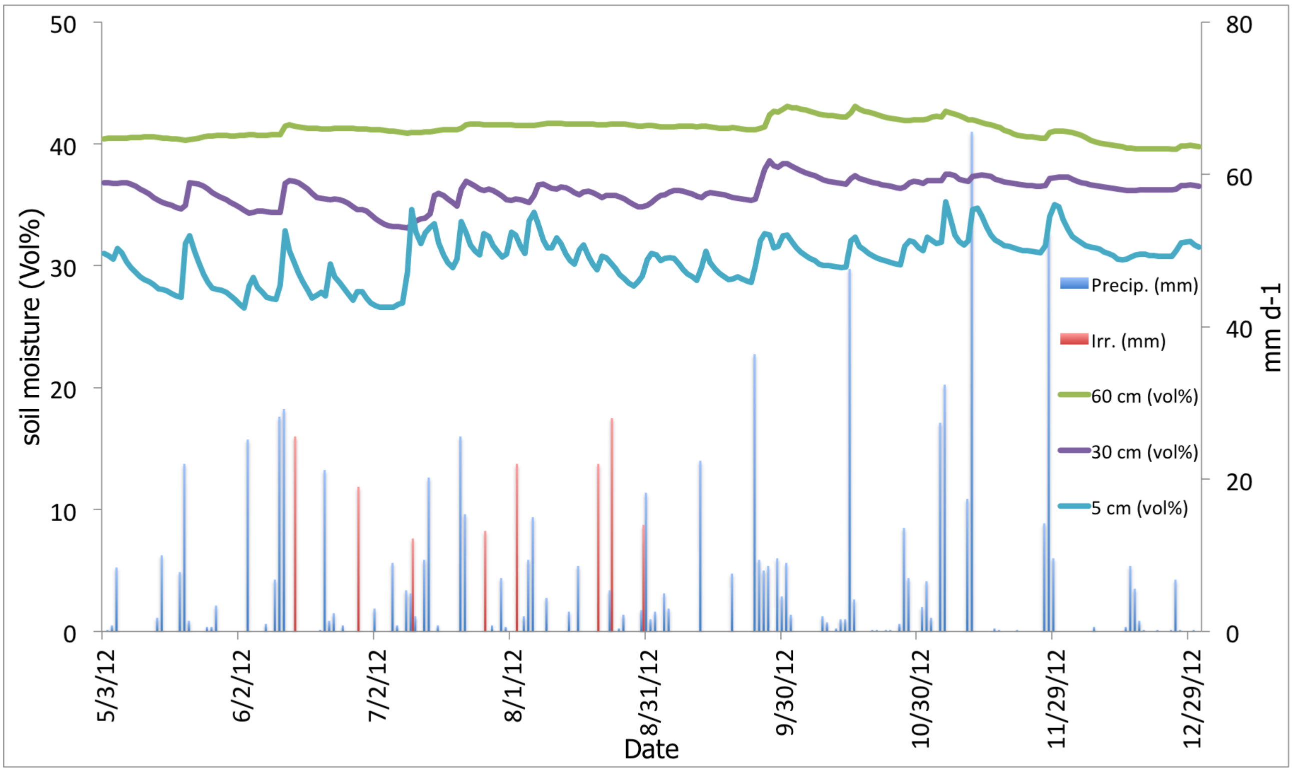


Figure 14.: Daily precipitation and irrigation. Daily average soil moisture content at different depths 5 cm, 30 cm and 60 cm, over the period from May to December 2012. Data until July 15 were taken from Marseiler (2012) and revised.

In Figure 14 it is possible to observe that the moisture content in a depth of 5 cm had strong variations, and was affected immediately from the water supply in form of irrigation or precipitation. Soil moisture content at 5 cm depth varied from 26.52% vol. to 35.22% vol.. At 30 cm depth, the soil moisture was subjected to smaller variations (33.10% vol. - 38.60% vol.). The soil moisture content in a depth of 60 cm was almost constant and subjected only to minimal variations during the growing season. Only slight variations were evident from May to September. After the 23 September for a period of 55 days stronger fluctuations were recorded. This could be triggered by the abundant rainfall over this period: During these days the maximum of soil water content at a depth of 60 cm was observed (43.11% vol.).

In addition to the soil moisture content measurements, also the water table depth was monitored weekly. Over the entire growing period the water table depth was subjected to quite large variations. This was due to the different supply of water in form of precipitation and irrigation. Furthermore, the water height in the Etsch river and in the channels in the vicinity of the orchard affected the water table. The soil water table depth during October rose up to 0.84 m and the maximal depth, due to the end of the measurable range, was observed 6 times (1.87 m).

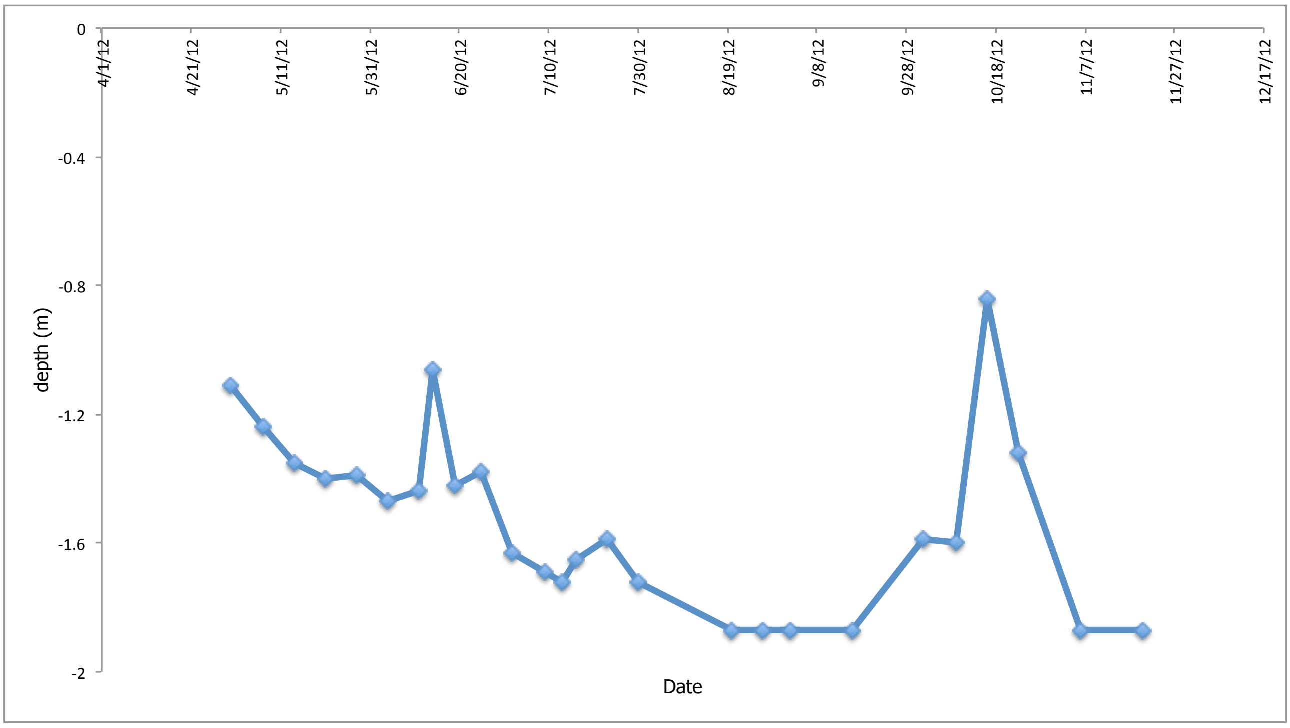


Figure 15.: Soil water table depth in the orchard measured weekly from May to December. 1.87 m was the end of the scale. Data until July 15 were taken from Marseiler (2012) and revised.

Table 3 reports weekly and total values for the different variables of interest (ET_c, Precipitation, Irrigation, △SW - difference in soil water content as respect to the previous date of measurement and D - drainage and C- capillarity).

Week	Date	Precipitation [mm]	Irrigation [mm]	ET_C [mm]	△ SW [mm]	D-C [mm]
1	07.05- 14.05	0	0	32,89	-8,68	-24,21
2	15.05- 21.05	34,8	0	20,71	10,7	3,39
3	22.05- 28.05	12,8	0	26,68	-10,26	-3,62
4	29.05- 04.06	25,2	0	21,13	-1,66	5,73
5	05.06- 11.06	14,8	0	19,48	-3,43	-1,25
6	12.06- 18.06	50,4	25,6	50,61	5,43	19,96
7	19.06- 25.06	25,2	0	36,37	-0,76	-10,41
8	26.06.-02.07	2	19	53,85	-6,76	-26,1

Week	Date	Precipitation [mm]	Irrigation [mm]	ET_C [mm]	△ SW [mm]	D-C [mm]
9	03.07- 09.07	11,6	0	32,83	-1,7	-19,5
10	10.07-16.07	42,8	12,2	23,11	4,63	27,26
11	17.07.-23.07.	41	0	21,76	0,82	18,42
12	24.07.-30.07.	7,8	13,2	11,73	-4,41	13,68
13	31.07.-06.08.	27	0	11,8	7,93	7,27
14	07.08.-13.08.	4,4	11	10,92	-5,55	10,03
15	14.08.-20.08.	11,2	13,4	12,92	-3,84	15,52
16	21.08.-27.08.	8	22,5	12,52	-3,12	21,1
17	28.08.-03.09.	25,2	13,8	8,55	4,53	25,92
18	04.09.-10.09.	8	13,8	19,87	-1,91	3,84
19	11.09.-17.09.	22,4	0	17,43	0,3	4,68
20	18.09.-24.09.	44	0	12,68	6,82	24,49
21	25.09.-01.10.	49,2	0	10,46	7,62	31,12
22	02.10.-08.10.	2,2	0	12,92	-7,21	-3,51
23	09.10.-15.10.	54,4	0	6,53	6,27	41,6
24	16.10.-22.10.	4,6	0	7,62	-7,43	4,41
25	23.10.-29.10.	22	0	7,17	2,39	12,43
26	30.10.-05.11.	71,4	0	3,41	7,9	60,09
27	06.11.-12.11.	83	0	2,82	-2,28	82,46
28	13.11.-19.11.	0,6	0	2,74	-7,85	5,72
29	20.11.-26.11.	0,2	0	1,9	-2,15	0,45
30	27.11.-03.12.	76,2	0	2,03	3,88	70,29
31	04.12.-10.12.	0,6	0	1,58	-4,78	3,8
32	11.12.-17.12.	14,8	0	1,24	-1,49	15,05
33	18.12.-24.12.	1,8	0	0,67	-0,34	1,48
Σ		**799,6**	**144,5**	**518,91**	**-3,72**	**429**

Table 3.: Water balance: Out- and inputs of water were listed as well as the difference in soil water content and the difference of capillarity and drainage. All this values were recorded weekly. The values in gray were reported from Marseiler's (2012) study and revised. The black ones refer to this study.

In table 3, starting from the week 07.05- 14.05 the 33 weeks were labeled. In all weeks except the first one there was a water input by irrigation or precipitation. The highest water input due to precipitation was in week 27 and reached an amount of 83 mm. Highest amount of irrigation was observed in week 6 with 25.6 mm. The ET_C had its maximum in week 8 with an amount of 53.85 mm. From this week on, the ET_C decreased continuously, with some slight increments in some weeks and reached the minimum in week 33 with an amount of 0.67 mm. The difference in soil water content varied strongly during the period from May to December. Highest change in soil water content during this period was detected in week 2, where soil water increased by 10.7 mm. In week 7 the biggest decrease in soil water content was recorded with 10.26 mm. To sum up, over the entire period of the experiment (May - December) the total input was 944.1 mm (799.6 from precipitation and 144.5 from irrigation). Overall, the ET_C in this period reached 518.91 mm. Along the measurement period the difference in soil water content decreased by 3.72 mm and the drainage exceeded capillarity by 429 mm.

To facilitate the comprehension of table 3, the figure 16 depicts the water balance with all their inputs (Irrigation, Precipitation, if positive change in soil water content) and outputs (ET_C and if negative the change in soil water content). Furthermore, it shows the difference between drainage (D) and capillarity (C).

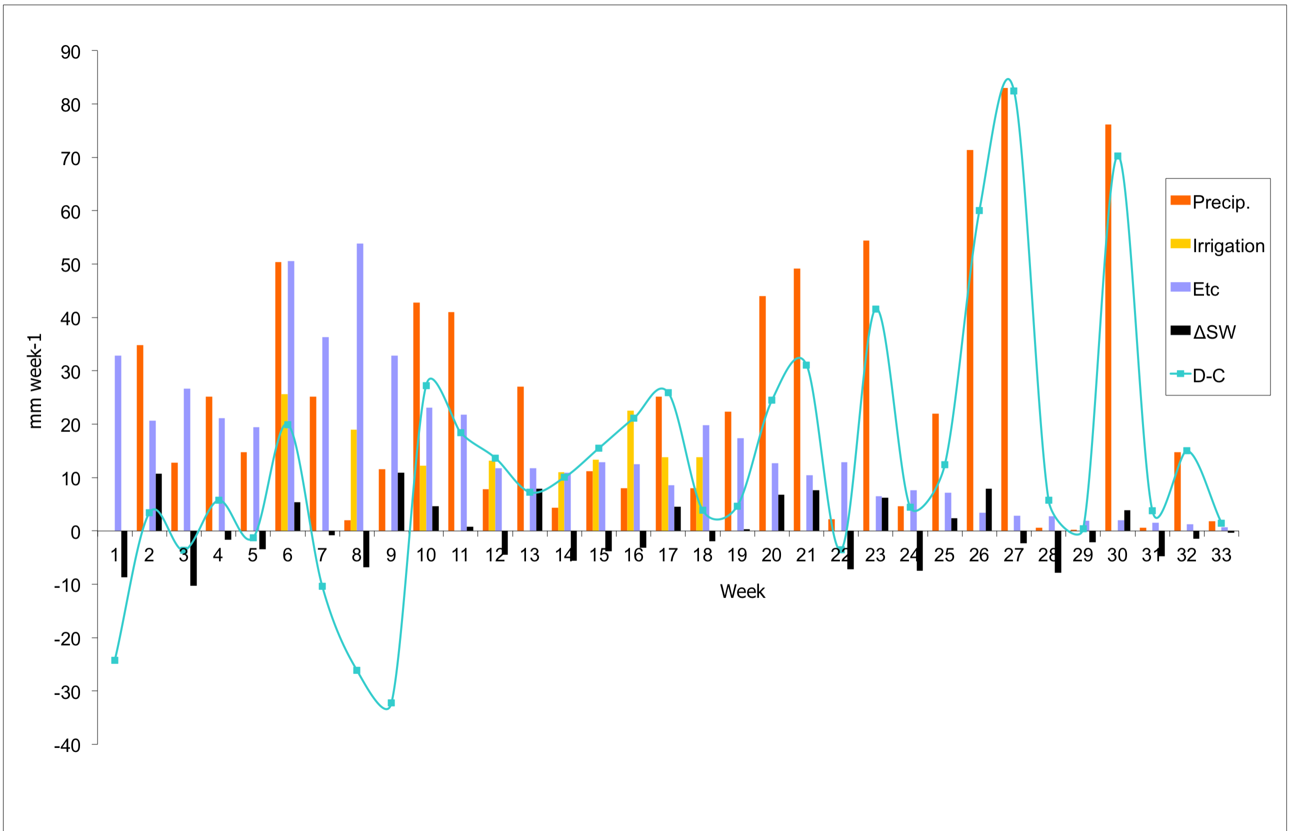


Figure 16.: Water balance of the orchard for 33 weeks from May to December. Irrigation, Precipitation, crop evapotranspiration (ET_C), change in soil water storage (△SW)and the difference of drainage and capillarity (D-C). Data until July 15 were taken from Marseiler (2012) and revised.

To understand the fluxes in the orchard the following flowcharts (Sankey diagrams) were elaborated, using the "e!sankey 3.0" software (ifu Hamburg GmbH, Hamburg, Germany). They represent the fluxes of water during a week. The four charts depict output and input flows in the ecosystem as arrows, the width of the arrows in the figures are proportional to their effective contribution to the water cycle. The selected weeks were the week 9 (03.07 - 09.07), the week 10 (10.07 - 16.07), the week 15 (14.08 - 20.08) and the week 21 (25.09 - 01.10). If D – C (drainage – capillarity) was positive, I have assumed that the whole water amount represents drainage flux, whilst I attributed the whole amount to capillarity, if the difference was negative.

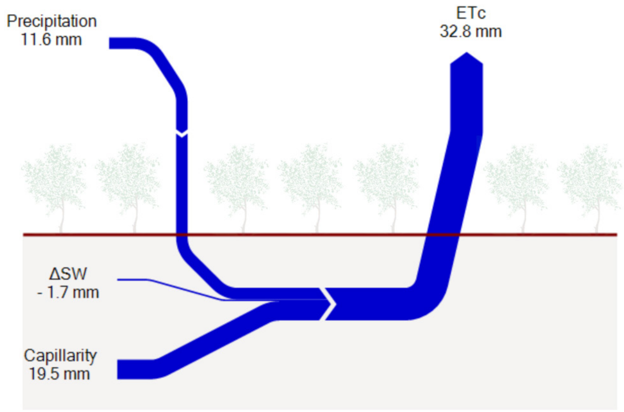


Figure 17.: (Week 9) 03.07. - 09.07.
(Reference Picture on Page 45)

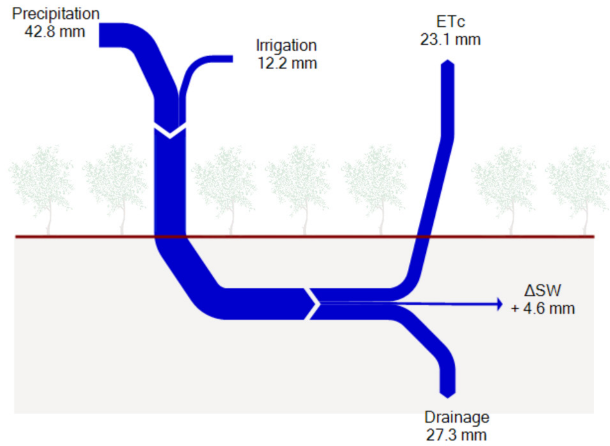


Figure 18.: (Week 10) 10.07. - 16.07.
(Reference Picture on Page 45)

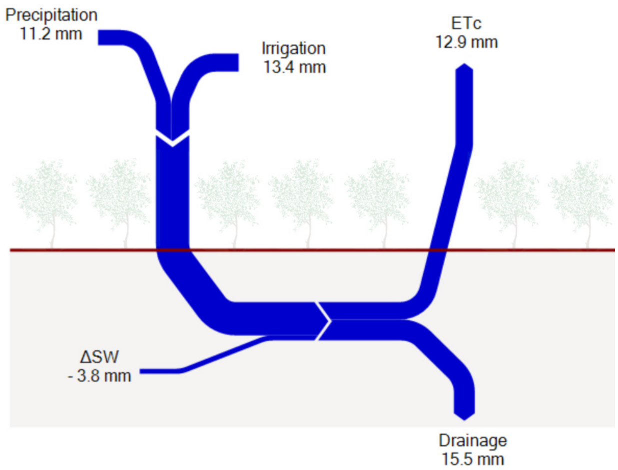


Figure 19.: (Week 15) 14.08. - 20.08.
(Reference Picture on Page 45)

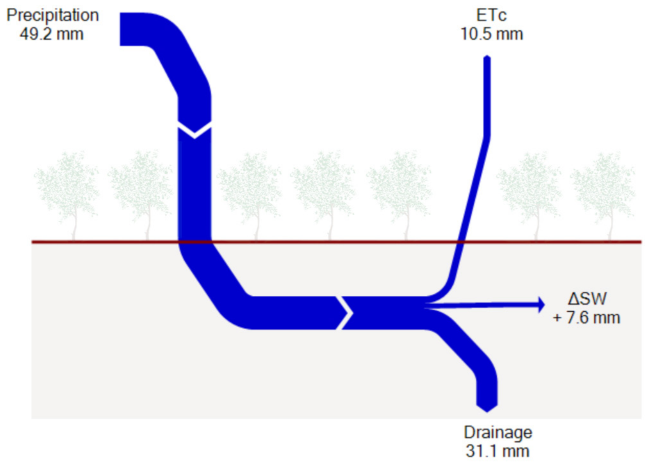


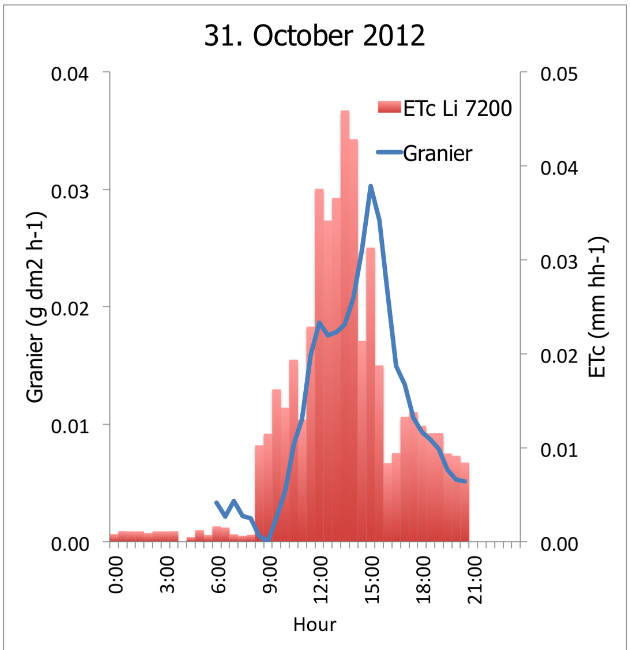
Figure 20.: (Week 21) 25.09. - 01.10.
(Reference Picture on Page 45)

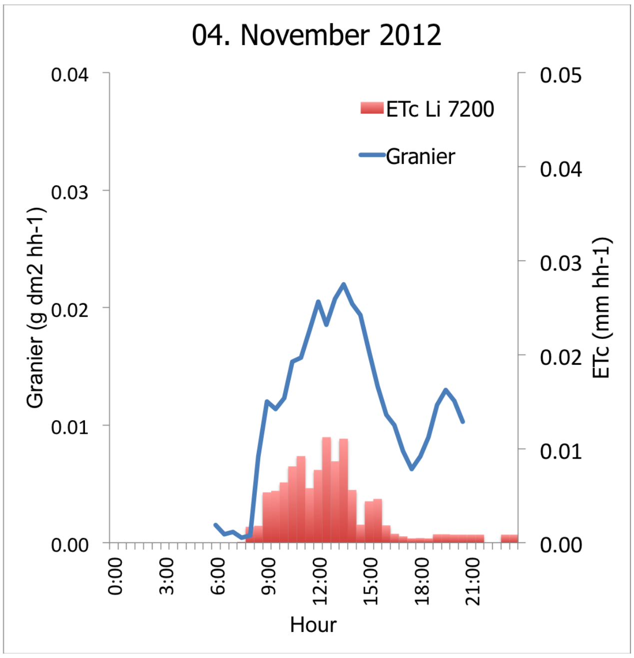
In figure 17 and 19 it is possible to observe that the difference in soil water content (△SW) during these weeks contributes to the inputs of the system. In other words the soil losts moisture due to the ET_C. These variations in soil water content in all four weeks were low. In the weeks 9 and 15 the soil had enough moisture and could provide the plants with water, stored in the pores of the soil. Another important observation was made during week 10 and week 21. It is assumed that as consequence of the high water inputs during both weeks, the saturation point of the soil was reached. This is the point where all soil pores were filled with water. The water that could not be captured in the pores percolated and contributed to drainage flux in both weeks. When the

water exceeding field capacity percolated, the field capacity was reached (large pores are filled with water and air while small pores are still filled with water) (FAO, 2013).
Further in figure 17 the capillarity (C) (19.5 mm) contributed as main input to the system. In contrast it is also possible to observe, that drainage (D) along the weeks 10, 15 and 21 was always the main output of the system. The high amount of drainage was mainly due to the abundant precipitation (P) and irrigation (I) along these weeks. The weeks (10, 15 and 21) where the drainage was the main output, the ET_c was low. Only in week 9 (figure 17), due to the low precipitation and the high amount of capillarity the ET_c was the main and only output recorded. It is also possible to observe that during the week 9 (03.07.2012 - 09.07.2012) the ET_c was high because in the month of July where solar radiation and air temperature were also high. In contrast, during the week 21 (25.09.2012 - 01.10.2012) the amount of water lost through ET_c was small and the drainage was high. These results are in agreement with the figure 16, depicting that high amounts of water inputs during the late season contributed mainly to drainage. Overall, these figures (17 - 20) gave an insight on how the inputs and the outputs in the water cycle of the orchard can vary during different weeks along the season.

3.3 Sap flow density measured by the Granier method

Through the Granier method it was possible to detect the water mass flow in the xylem of the whole apple tree. These measurements allowed to draw inferences about the water use and as consequence about transpiration of a tree. The measurements were made from September to December. Because of problems with the weather, during this time period only some measurements were reliable. The results and figures of this part of the study should be seen from a qualitative point of view. To detect a potential relationship between the water passing the plant and the amount of ET_c of the whole orchard (as detected by eddy covariance), in the following figures, the values of Granier measurements and the ET_c for the different days were depicted. In addition PPFD, VPD and air temperature were displayed to show the meteorological conditions during the measurements.





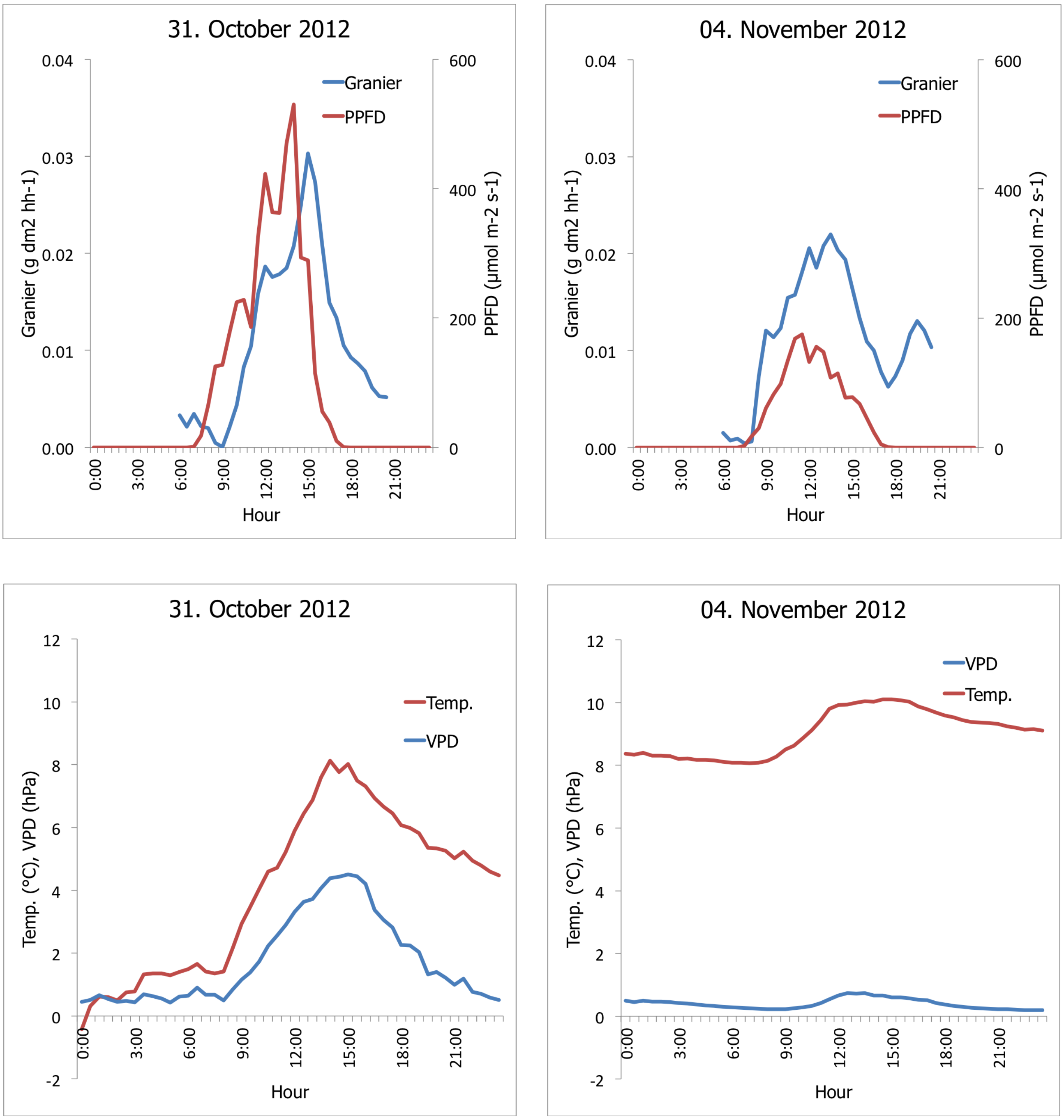
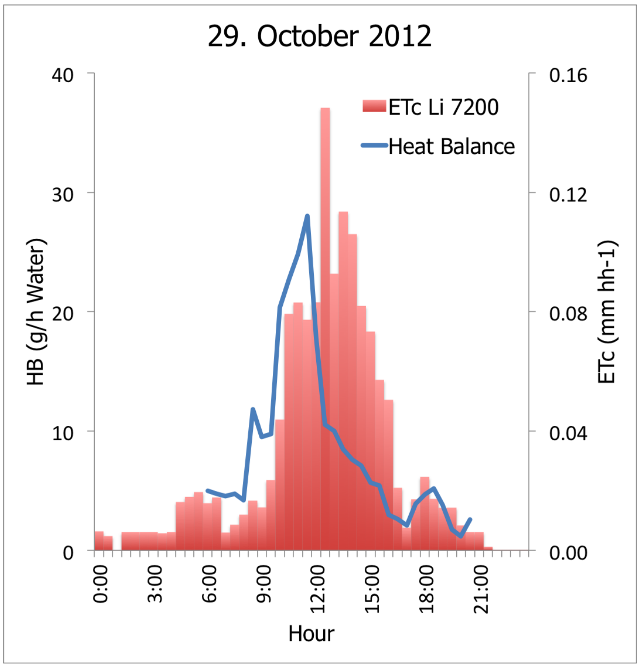


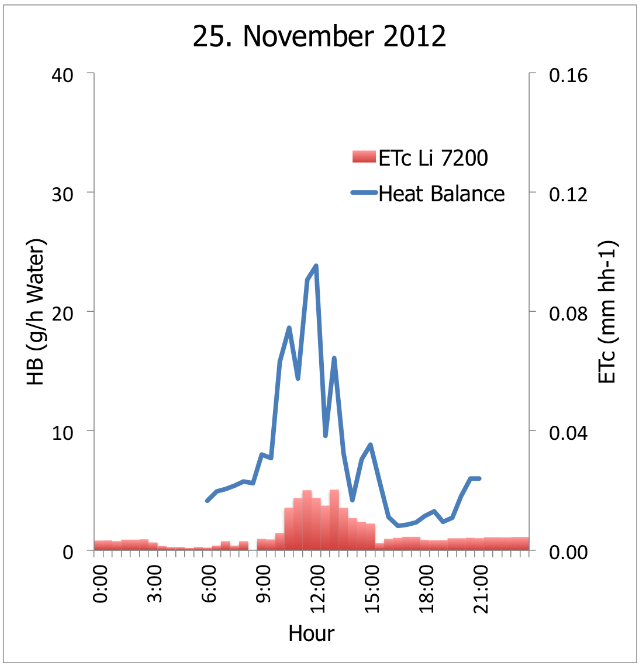
Figure 21.: Measurement of the sap flow density through Granier method for two specific days, in comparison with daily ET_c trend. In addition meteorological measurements PPFD (Photosynthetically active Photon Flux Density), air temperature and VPD (Vapor Pressure Deficit) are shown.

Measurements of the sap flow density were made on the plant E 123 (detailed description in chapter 2). Values depicted on these figures were recorded on October 31 and on November 04 2012. The figures show that the ET_c rose in the same period of time as the sap flow density did. In the figure of the 31 October the sap flow density measurements reached their maximum at 3:00 p.m., while previously the ET_c, measured by the eddy covariance method, reached its maximum value at 1:30 p.m.. Also in the figure of the fourth November the trends were similar. An interpretation of these measurements is not easy because, according to the literature, the Granier method should display an increase in sap flow density before the growth of the ET_c value. Beside this, the figures that depict the sap flow density in relation to the PPFD indicated a strong relationship between radiation and the water movement in the tree. The daily pattern of sap flow density and the PPFD showed the same peaks. The meteorological data during these two days were similar (comparable) and only the values for the VPD on November 4 were much lower than on October 31.

3.4 Sap flow measurement by Heat Balance method

The Heat Balance sensor detects the mass flow rate of xylem sap flow (measured in g/h). Overall eight sap flow meters on two different plants were placed, to detect the water fluxes in the tree. On tree E 124 the sensor J (5) (Figure 4 in chapter 2) gave the best results. Trends of this Heat Balance sensor were plotted for two different days. To have a point of reference as well as in the figures of the Granier sensor, the flow rate was shown in connection to the ET_c of the whole orchard for the same day. Also the results of this part of the experiment should be seen from a qualitative point of view, because the weather during the late season from September to December 2012 was not ideal for the measurements. The days selected were October 29 and November 25. The trends of the ET_c and the flow rate were depicted in the following figures. Furthermore for these days the meteorological variables PPFD, air temperature and the VPD were represented in the charts.





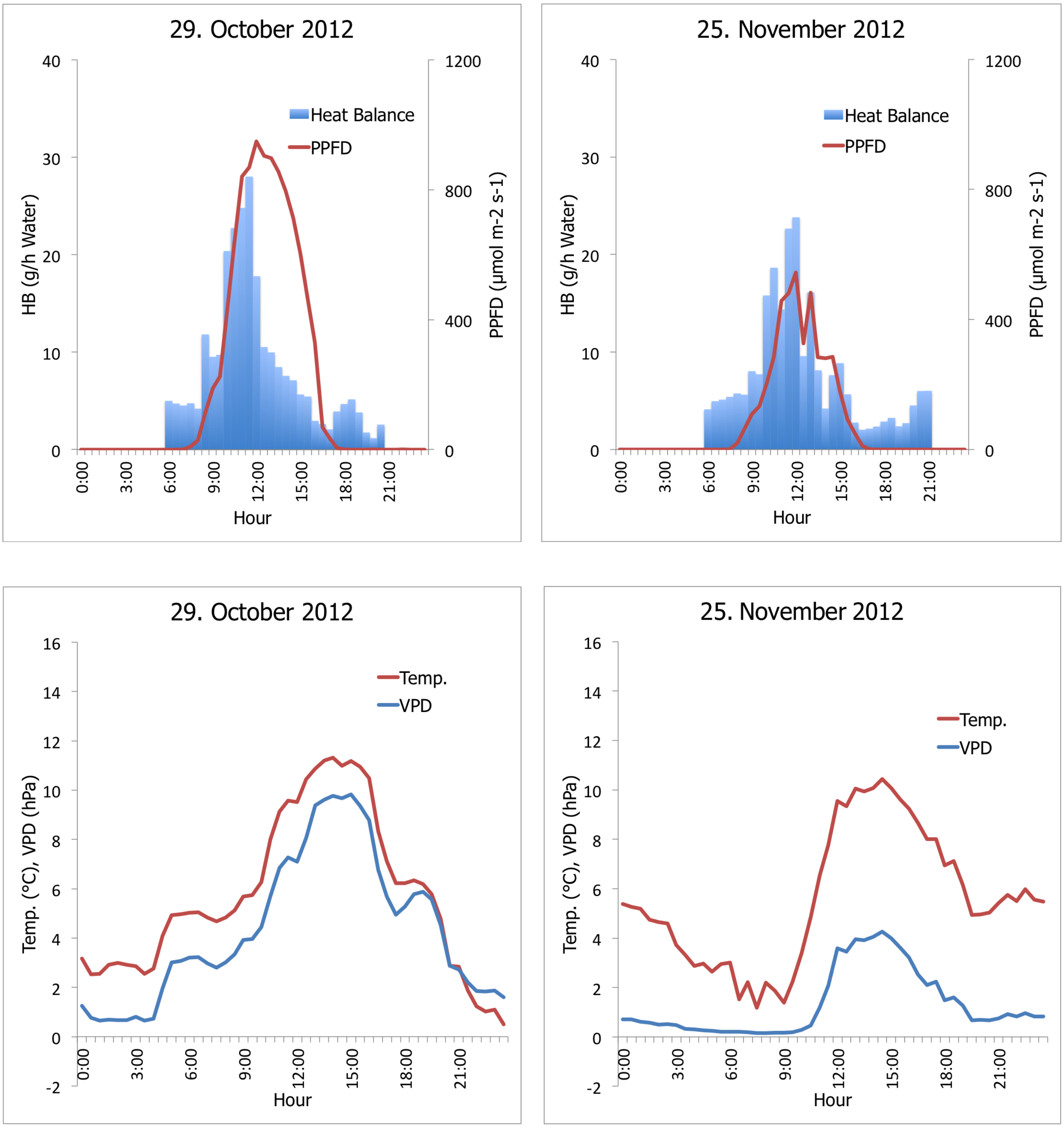


Figure 22.: Measurements of the sap flow rate through Heat Balance sensor on a single branch in comparison with the ET_c of the whole orchard. The measurements of the flow rate are in g/h. In addition PPFD the air temperature and the VDP for the same day are represented in the figures.

The measurements of the sap flow rate were made on a single branch of a plant. The branch was located 2 m above ground and had a diameter of 5.25 mm. Altogether, the plant E 124 where the sensor was placed had 2804 leaves and on the single branch of interest it counted 52 leaves. This fact is important because it is known that the number of leaves or the total leaf area (m^2) has a great influence on the water flux in the tree or the branch.
In the Figure 22 it was depicted the trend of the flow rate in the single branch together with the ET_c of the whole orchard (by eddy covariance). The maximum of flow rate on October 29 and on November 25 anticipated the maximum of the ET_c pattern. In both cases the peak of the flow rate anticipated that of the ET_c by one hour in average. On October 29 the peak of the heat balance

measurements was at 11:30 a.m. while the maximum of the ET_c records was on 12:30 p.m.. A similar pattern was observed on November 25 on 12:00 p.m. when the daily pattern of sap flow rate reached the maximum. An explanation could be that the plant respond immediately on the rising of the PPFD, being the variable with the greatest effect on the transpiration. As reaction on a high PPFD value, the plant mobilized water that reached the gas analyzer used for ET_c computation only an hour later. This affirmation was based on the representation of PPFD and the sap flow rate pattern in the same figure. Both of the daily patterns reached their maximum value nearly at the same time.
Furthermore, for the two days the air temperature and the VPD were represented. The daily pattern of the air temperature on both days followed a similar trend. The maximum of air temperature on October 29 was 11.2 °C and the maximum on November 25 was 10.5 °C. Minimum temperature for October 29 was 0.5 °C and for November 25 it was 1.28 °C. In contrast VPD was smaller on November 25 and the peak value reached only 4.26 hPa while on October 29 it reached a maximum of 9.82 hPa.

4. Discussion

4.1 Partitioning of the ET_c in evaporation and transpiration

Many researches about ET_c in agricultural ecosystems are present, at only few refer to apple orchards, especially if autumn and winter months are considered. ET_c is affected by the crop type, the rootstock, the phenological stage, the soil conditions, the soil cover, the climatical factors, the training system and the managing strategy of the orchard (Allen et al. 1998).
As already mentioned in the introduction ET_c is composed of two parts. On the one hand there is the evaporation from soil and plant surface and on the other hand there is transpiration through the stomata of the plants (Allen et al. 2000). Both components can vary during the growing season. In this study the partitioning of evapotranspiration in the amount produced by the soil and the ground cover and the one produced by the crop was not possible, because the Granier sensors were not calibrated. In addition rain periods made it difficult to obtain reliable data for the Heat Balance sensors. In a study of Testi et al. (2004) they proved that in an olive orchard in southern Spain the ET was largely composed of soil evaporation (Testi et al., 2004). This was the case especially after rain periods and irrigation events, where the orchard evapotranspiration rose up to more than three times the value it had before water supply (Testi et al., 2004). In this study by comparing the figure 5 (daily ET_c during period from September to December) and the figure 16 (water balance) it was found that effectively after longer rain periods or irrigation events the ET of the whole orchard rises but in a smaller magnitude as observed in Testi et al. (2004) study. These observations refers to timeframes of two to three days around September 24. Considering the affirmations of Testi et al. (2004) and the value discovered in this study, it is assumed that the ground cover has not a high impact on the values of orchard transpiration. Allen et al. (1998) affirmed that the ground cover have influence on transpiration but it confirms also that the ground cover affects mainly the amount of evaporation from the soil. In addition, Allen et al. (1998) affirmed that the percent contribution of evaporation from soil, to the ET_c varies through the year. During late season (end of October to December), when trees are without foliage, the contribution of transpiration to the total ET_c is small. The main component of the ET_c during this period is certainly the evaporation from soil or plant surface. In contrast, during September and the beginning of October the influence of the leaf transpiration is still perceptible: on one hand, because of the higher amount of daily ET_c, as it can be observed in figure 5 (Chapter 3), on the other hand, because until mid - October the Heat Balance sensors detected higher sap flow rates than in the following months.
In another study of Er - Raki et al. (2009) in an olive (*Olea europaea*) orchard in thecenter of Morocco, they used Heat Balance sensors and the eddy covariance method for ET partitioning. The amount of transpiration measured by the Heat Balance sensors were corrected using the reference evapotranspiration (ET_0) calculated with the Penman - Monteith equation (Allen et al., 1998; Er-Raki et al., 2009). To partition the orchard evapotranspiration into soil evaporation (ES) and plant transpiration (T), they calculated the ratio of transpiration to the total ET_c (Er-Raki et al., 2009). They discovered that this ratio under dry conditions, with no ground cover, was about 1 while under wet conditions the value was in the range between 0.65 and 0.85 (Er-Raki et al., 2009). The results of the study by Er - Raki et al. (2009) confirm the findings of Testi et al. (2004) showing that after irrigation event, the contribution of soil evaporation to ET_c rises. Furthermore, the study conduced by Er - Raki et al. (2009) indicates again that the contribution of evaporation to the total orchard ET_c fluctuates during the season. Particularly during the dormant season the amount of evaporation from the soil is higher than the one of transpiration (Er-Raki et al., 2009).

4.2 Assessment of ET_C

Considering the eddy covariance method and the computation of all data that are necessary to implement this technique, the measurements of the gas analyzer Li 7000 were not considered, because of high underestimation of the actual values (Fratini et al.,2012). Therefore the Li 7200 gas analyzer is recommended, particularly if water fluxes has to be measured over an orchard. This is because of its structural improvements, discussed in the chapter 2 and examined in the paper of Fratini et al. (2012).
Bryla et al. (2005) performed a study on the influences of the irrigation methods in relation to the yield and fruit quality in a peach (*Prunus persica*) orchard in California. They computed the monthly ET_C for the orchard for all months of the years in 2002 - 2004. Averaged ET_C over the three years for the month September, October, November and December were respectively 154 mm, 95 mm, 13 mm and 2 mm. My data on apple trees indicated lower values for ET_C than the pear orchard in California, as it can be observed in table 2 (chapter 3). The apple orchard in Kaltern (South Tyrol, Italy) had a cumulate ET_C of 60 mm in September, 37 mm in October, 11 mm November and 5 mm in December. On the study site of Bryla et al. (2005) the soil was loamy as in my study. The main factor responsible for the high ET_C values in the study of Bryla et al. (2005) were likely the climatical conditions. Another possible explanation is the high application of irrigation reported in Bryla et al. (2005) study, 987 mm water on average. Rainfalls respectively in California are rare and precipitation amounts 210 mm in average of three years (Bryla et al. 2005). Consequently, the total water input of the peach orchard in Bryla et al. (2005) study reaches 1197 mm in average of the three years (Bryla et al. 2005). In my, study a total water input of 944.1 mm (through irrigation and precipitation) was measured.

4.3 Water balance and soil water fluxes

In my study, a water balance was elaborated for a timeframe of 33 weeks, considering all inputs and outputs of the agricultural ecosystem. Burt (1999) affirmed that a water balance is essential for making wise decisions about water management. He also recommended to make a multi year water balance to make right assumptions about the hydrological properties of the site of interest (Burt, 1999). In contrast Ridder and Boonstra (1994) suggest to make water balances for specific seasons (for example: growing seasons) (Ridder and Boonstra, 1994).
Beginning from the second week of May, the precipitation, the irrigation, the ET_C and the change in soil water content were logged until the end of the year. The soil water content reflects the water storage in the soil. The differences in soil water storage were calculated for every week. In addition, the difference between drainage (D) and the capillarity (C) was computed to understand which one of the two variables prevails.
Abrisqueta et al. (2001) studying in an apricot (*Prunus armeniaca*) orchard in Murcia (Spain) discovered that after rain periods and irrigation actions the ET_C of the orchard rose. This was observed also in this study, after heavy water intakes the ET_C rose especially in months (June - August) of high water demand (Abrisqueta et al., 2001). In months of low demand, instead, ET_C is not affected by precipitation. If heavy rainfalls or irrigation occur in late season and in months with low water demand, most of these water inputs contribute to drainage (D). This is represented in table 3 and in figure 16 (Chapter 3). Where it can be observed that nearly all the water inputs in late season contribute to drainage. In fact this circumstance was also observed by Palomo et al. (2002) studying an olive orchard in Coria del Rio (Spain) (Palomo et al., 2002). Actually the real value of drainage can not be given in this study because only the difference of drainage (D) and capillarity (C) is detected. Consequently, as already mentioned, it is only possible to know which

one of the two variables prevails. Capillarity exceeds drainage only in the months of high water demand even if rainfalls occurs and irrigation is applied. This can be observed by comparing figure 15 (soil water table depth) with figure 16 (water balance) in chapter 3. Ridder and Boonstra (1994) in their study, linked this effect to the shifting of the capillary fringe due to the up and downward movement of the soil water table. In their study they explained that capillarity force can rise the water only over a certain height in the soil, depending on the soil texture. This soil layer above the soil water table, where capillary force fills the pores with water, is called capillary fringe. This fringe shifts in relation to the water table depth (Ridder and Boonstra, 1994). In this study the soil water table rose two times reaching it's highest level with 0.84 m below ground. In the study of Battilani et al. (2004), conduced on the effects of the water table depth on capillary rise in a pear orchard, they figured out that the depth of 1.5 m below ground is ideal for the crop. As stated by them, the optimal range for the soil water table depth to ensure adequate water supply for the crop through capillary rise, is between 1.5 m and 2 m below ground (Battilani et al. 2004). If the soil water table reaches this range, irrigation has to be reduced. In the orchard of this study the water table depth vary from 0.84 m - 1.87 m below ground and is therefore within the limits proposed by Battiliani et al. (2004). Because of that, it is expected that also in the apple orchard capillarity could play a crucial role as input of water. In 12 weeks, out of the 33 recorded for the water balance, ET_C exceeded water inputs by irrigation and precipitation (Marseiler, 2012). This surplus of water comes from capillary rise (133.95 mm). The flowcharts (Sankey diagrams), elaborated using the e!sankey 3.0 software (ifuHamburg GmbH Hamburg Germany), can provide a clear insight in this process of water movements in the orchard. By looking at these figures (17 - 20 chapter 3) it is possible to understand the overall water cycle.

4.4 Comparison among different methodologies to measure water fluxes

In the last part of this study the orchard evapotranspiration was compared to sap flow methods. This type of studies is often made to detect the amount by which the transpiration and evaporation contribute to the ET_C. In this study the Heat Balance and the Granier method was used, to detect the sap flow in the xylem vessels.

In a study of Rana et al. (2005), conduced in a citrus (Clementine) orchard they used the eddy covariance method and the Heat Balance sensors to detect ET_C of the orchard (Rana et al., 2005). They figured out that the maxima of the ET_C measured by the eddy covariance method do not correspond to the maxima of the Heat Balance measurements. The maximum of the transpiration measured through the Heat Balance method is shifted towards afternoon in comparison with the ET_C pattern (Rana et al., 2005). Rana et al. (2005) traced this effect back to the fact that the sap flow method, unlike the eddy covariance method, takes into account water fluxes in the tree storage (Rana et al., 2005). They affirmed that water is stored in the branches and in the trunk of the trees during the night and affect thus the sap flow method measurements (up to 10 mm storage) (Rana et al., 2005). In this study no quantitative values were detected, but in the figure 21 and 22, the pattern of the daily trend of the sap flow, can be compered to the daily ET_C pattern. Figure number 22 depicts the sap flow density measured by the Heat Balance method in comparison with the daily ET_C. Altough only few data are provided in this thesis, my evidences are not in line with the statement of Rana et al. (2005), because the sap flow reaches the maximum value half an hour before the ET_C. The time lag between the two maxima is expected to be the time range that the water needs to reach the leaves and vaporize. On the contrary looking at the figure 21 representing the Granier sensor measurements, the sap flow maximum follows the maximum of the ET_C in average by an hour. These observations, based on the discoveries of Rana et al. (2005), leads to the assumption that water in apple tree is manly stored in the trunk and contributes in the short term to ET_c. Only if the water stored near the drafting point is exhausted the Granier sensor records sap flow. Therefore, the Granier method unlike the Heat Balance sensors is affected by the processes of water storage in the trunk. This is due to the fact that the Granier method measures the sap flow in the stem of the tree while the Heat Balance method is applied for the measurements on single branches. Also Motisi et al. (2012) found this variations in plant transpiration and total orchard evapotranspiration, during their studies on olive, (*Olea europaea*) grapevine and orange orchards (Motisi et al., 2012). They interpreted this differences by the tree capacity of water storing and thus confirm the observations of Rana et al. (2005) (Motisi et al., 2012).

During this experiment eight Heat Balance sensors were placed on the trees. Three of them on plant E 123 and five of them on plant E 124 (figure 4, chapter 2). The reason this was done since the branches were expected to have varying values for transpiration in function of there position on the tree. Results in agreement with these expectations were found by Nicolas et al. (2009). They conduced a study on apricot (*Prunus armeniaca* cv. Bulida, Real Fino apricot rootstock) trees looking at the transpiration of single branches (Nicolas et al.,2009). Taking into account the diameter and the respective leaf aria index (LAI) of every branch, they found differences in transpiration attributable to the micro-climatical changes in the orchard (Nicolas et al.,2009). De Lorenzi et al. (2009) in their study in a olive (*Olea europaea*) orchard found that VPD (vapor pressure deficit) of the air is not very different inside the tree canopy. In contrast the diurnal variation of the radiation affecting the different parts of the trees is noticeable (De Lorenzi et al., 2009; Morandi et al., 2012). In this study it was not possible to compute the amount of transpiration for the single branches because results, due to the inclement weather condition were only available for one of the eight Heat Balance sensors used. The Granier method, unlike the Heat Balance method, which is a direct measurement method, requires a calibration. In this study this was omitted.

In any case for further experimental activity considering the Heat Balance sensors and the Granier sensor the insulation of both sensors have to be improved, because they were affected by the bad weather conditions.

5. Conclusions

This study aimed to shed light on the hydraulic dynamics in a South Tyrolean apple orchard by evaluating inputs and outputs of the water cycle with different techniques.

As it can be observed in the results, the driving force of the water cycle is the solar radiation, affecting one of the main outputs, the crop evapotranspiration (ET_c). The values for ET_c during these months were low, the maximum value was reached in September (0.17 mm d-1). It was confirmed, that the Photosynthetically active Photon Flux Density (PPFD) and the ET_c were highly correlated among time. This was especially striking during the months where the trees had still their leaves (until mid November) and transpiration contributed mainly to ET_c. After leaf abscission the relationship between the two variables declined. In this period the evaporation from soil and plant surface was the main component of ET_c. Furthermore, the VPD and the air temperature during this period (mid November- December) showed the highest influence on ET_c values.

Computing the water balance for the orchard under study, other factors affecting the ET_c were found. ET_c during September and October rose owing to the high soil or plant surface evaporation, after heavy rain or irrigation events. In contrast during the later season (November - December) most of the water input contributed to drainage (D). From September to December the total water percolated, amounted to 384 mm.

Such high amount of drainage could determine a significant leaching effect on the soil nutrients. Especially the nitrogen (in form of nitrate NO_3^-) is prone to leaching. This affirmation requires further examination in order to detect the amount of nitrogen lost through drainage fluxes.

Furthermore, it had become apparent that during weeks of water scarcity (summer), capillarity (C) played an important role for the water supply of the orchard. This was due to the shallow water table in the study site which came up to 0.84 m. Considering such a high water table it may not be necessary to irrigate the orchard for some periods, depending on the water requirements of the apple tree. Irrigation is anyway justified since the quality of apples is enhanced by generous water supply.

To give a complete picture of the water cycle of the orchard the water movements in the trees were also considered. This was enabled through the measurements of two sap flow methods, the Granier heat dissipation method and the Heat Balance method. According to the results of these measurements, it was possible to hypotesize that apple trees store water especially in the trunk.

Thanks to all these techniques it was possible to obtain a holistic outlook on the water movements in an apple orchard in South Tyrol. Furthermore, the results of this study evidence how important it is, to have knowledge of the water fluxes in the orchard, to manage irrigation in an efficient way.

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Summary

Water fluxes in a South Tyrolean apple orchard estimated by different techniques

For a sustainable management of water resources in agriculture a good knowledge of hydrological processes is necessary. This study gives an insight on water fluxes on different scale levels in an orchard near Kaltern (South Tyrol, Italy), considering the last part of the 2012 growing season (September - December). Additionally, it provides a water balance for 33 weeks for the same site. The water fluxes were studied using three different methods. The Heat Balance sensors, fixed on branches in different locations of the tree, a Granier sensor was mounted on the trunk of a representative apple tree; the eddy covariance method was used to detect the fluxes at orchard level. Moreover meteorological data, such as Photosynthetically active Photon Flux Density (PPFD) and air temperature were recorded. The vapor pressure deficit (VPD) was computed through relative humidity measurements. This was made to show possible relations between the meteorological variables and the water fluxes in the orchard. To establish the water balance, precipitation (P) and irrigation (I) were also measured. Further, three TDRs (time - domain reflection sensor) were used to detect soil moisture at three different depths (5 cm, 30 cm and 60 cm), to detect the change in soil water content ($\triangle$SW) over a given period (one week). Beside this, the water table depth was recorded weekly.

The results indicated that the crop evapotranspiration (ET_c) during the end of the growing season was relatively low, as expected. For the whole month of September a value of 58 mm was found and until December the ET_c declined steadily to 5 mm/month. But the strong linkage between PPFD and the ET_c was still striking. Diminishing sap flow rates, detected by the sap flow methods indicated that ET_c was mainly due to evaporation from the soil and the plant surfaces. Another peculiarity that was observed was that the peaks of the sap flow and the ET_c, during the day did not coincided. The peak of ET_c anticipated the values measured by the Granier method. This could be an indicator for water storage in the stem of the apple trees in the evening-night. It was expected that this water storage in the short term contributes to ET_c. This confirms that the simultaneous measurements were necessary because the eddy covariance method could not consider the processes inside the tree. Considering the measurements of the Heat Balance sensors, the results showed that the peak occurred an hour before the peak of ET_c as measured by eddy covariance. These results were expected, because of the time interval necessary for the water to go through the branch and reach (as water vapor) the gas analyzer (eddy covariance method). The results of the water balance revealed that ET_c was influenced by the amount of water input. After strong rainfalls or irrigation event the ET_c rose, probably mainly due to soil evaporation. It was also proved that during late season (November - December) most of the inputs of water were lost in drainage (D). In contrast during periods of high demand and low inputs (precipitation - irrigation), water was also provided by capillarity (C). In other words capillarity played an important role in the water supply of the orchard. This fact was mainly due to the shallow water table coming up to 0.84 m under ground level.

One conclusion was that irrigation in the site could be reduced, due to the fact that the plants could satisfy their water requirements also through the capillarity (C), as a consequence of the shallow water table. But the additional water administration had its justification, because of positive effects on qualitative parameters of the yield. In addition, it was proved that the crop water requirements were low during the end of the season (September - December) and that the main losses were due to evaporation from the soil and plant surface and by the drainage (D).

Zusammenfassung

Wasserflüsse in einer Südtiroler Apfelplantage, gemessen durch verschiedene Techniken

Für einen verantwortungsvollen Umgang mit den Wasserressourcen in der Landwirtschaft, ist es notwendig genau über die hydrologischen Prozesse in der Obstanlage Bescheid zu wissen. Diese Studie bietet Einblicke in die Wasserflüsse einer Apfelplantage in Kaltern (Südtirol, Italien). Während des Experiments wurden die Wasserflüsse in den Ästen durch die Heat Balance Sensoren, im ganzen Baum durch den Granier Sensor und für die gesamte Anlage durch die Eddy - Covariance Methode ermittelt. Außerdem wurde für dieselbe Anlage über einen Zeitraum von 33 Wochen der Wasserhaushalt erstellt. Diese Studie konzentriert sich dabei auf das Ende der Wachstumsperiode (September - Dezember).

Im Zuge dieser Arbeit wurden die meteorologischen Daten am Standort erhoben. Es wurde die photosynthetisch aktive Photonenstromdichte (PPFD) und die Lufttemperatur gemessen. Um das Dampfdruckdefizit (VPD) zu errechnen wurde weiters die relative Luftfeuchtigkeit am Standort ermittelt. Dies wurde durchgeführt, um eventuelle Zusammenhänge zwischen diesen Variablen und den Wasserflüssen in der Anlage zu errechnen. Für die Erstellung des Wasserhaushalts der Anlage wurde die Bodenfeuchte in drei Tiefen (5 cm, 30 cm und 60 cm) und anhand von drei verschiedenen TDRs (time - domain reflection sensor) gemessen. Durch diese Messungen war es möglich die Unterschiede im Wassergehalt des Bodens ($\triangle$SW) für den Zeitraum einer Woche festzustellen. Dazu kam noch die wöchentliche Erhebung des Grundwasserspiegels.

Wie vermutet zeigten die Resultate, dass die Evapotranspiration (ET_c) während den letzten Monaten dieses Jahres niedrig war. Im Laufe des gesamten Monats September wurden 58 mm ET_c registriert und bis Dezember sank dieser Wert stetig bis zu 5 mm. Trotz dieser niedrigen Werte war die starke Abhängigkeit der ET_c vom Wert der PPFD ersichtlich. Anhand der Aufzeichnungen der Sensoren, die den Saftstrom im Xylem gemessen haben (Granier Sensor und Heat Balance sensoren) war es möglich zu beobachten, dass der Saftfluss zu dieser Jahreszeit gering war und von September an, bis Dezember abnahm. Diese Entwicklungen wiesen darauf hin, dass während des Zeitraumes, in dem die Studie durchgeführt wurde, die ET_c vor allem aus Evaporation von der Boden und Pflanzenoberfläche bestand. Weiters wurde erkannt, dass die Tageshöchstwerte von ET_c nicht zur gleichen Zeit auftraten, wie jene der Saftfluss - Messungen des Granier Sensors. Der Höchstwert der ET_c ging dem der Messungen des Granier Sensors voraus. Dies könnte auf einem Wasserspeicher im Stamm des Apfelbaumes zurückzuführen sein, der kurzfristig zur ET_c beiträgt. Die Werte des Heat Balance Sensors hingegen erreichten ihre Höchstwerte eine Stunde vor der ET_c. Dieser Zeitunterschied wurde auf die Zeitspanne zurückgeführt, die das Wasser vom Ast durch die Blätter bis hin zum Gasanalysenmessgerät (Eddy - Covariance methode) benötigt. Die Ergebnisse des Wasserhaushaltes ergaben, dass ET_c unter anderem auch von der Menge des Wassereintrages in das System beeinflusst wird. Insbesondere nach starken Regenfällen und nach dem Einsatz der Oberkronenberegnung stieg ET_c vor allem wegen der Evaporation an. Es wurde außerdem festgestellt, dass der Großteil des Wassereintrages während November und Dezember durch Abfluss (D) verloren geht. Im Gegensatz dazu spielt der kapillare Aufstieg (C) während den Zeiträumen mit hohem Wasseranspruch und wenig Wassereintrag eine wichtige Rolle. Dies wurde auf den hohen Grundwasserspiegel zurückgeführt ,der in dieser Apfelanlage, bis zu 0.84 m unterhalb des Boden liegt. Daraus folgt, dass die Apfelanlage auch ohne zusätzlichen Wassereintrag über Beregnung ausreichend durch den kapillaren Aufstieg (C) versorgt werden könnte. Allerdings ist bewiesen, dass der zusätzliche Wassereintrag seine Berechtigung hat, da er positive Auswirkungen auf die Qualität der Ernte mit sich bringt. Weiters sind die Wasserbedürfnisse des Apfels während September - Dezember niedrig und der größte Anteil des Wassers geht durch Abfluss (D) verloren. Abschließend, ist die wichtigste Erkenntnis die aus dieser Studie hervorgeht, dass ein gutes Wissen über die hydrologischen Prozesse in einer Apfelanlage unabdingbar ist, um das zur Verfügung stehende Wasser möglichst verantwortungsbewusst und effizient zu nutzen.

Riassunto

I flussi idrici in un meleto altoatesino, misurati attraverso differenti tecniche

Per un utilizzo responsabile delle risorse idriche nell'agricoltura è necessario acquisire buone conoscenze sui processi idrologici in campo. Questo studio fornisce delucidazioni sui flussi d'acqua in un appezzamento di meli a Caldaro (Alto Adige, Italia). I flussi sono stati studiati su diversi livelli di scala; a livello di branca, attraverso il sensore Heat Balance, a livello di albero attraverso il sensore Granier e a livello di ecosistema è stato usato il metodo eddy covariance. Inoltre, per il meleto in questione è stato elaborato il bilancio idrico considerando 33 settimane da maggio a dicembre. Questa ricerca si riferisce alla fine del ciclo vegeto-produttivo (settembre - dicembre).
Nel corso di questo studio sono stati eseguiti rilievi sui dati meteorologici nel campo. È stata individuata la densità di flusso fotonico fotosinteticamente attivo (PPFD) e la temperatura dell'aria. Per individuare il deficit di vapore acqueo (VPD) è stata anche misurata l'umidità relativa dell'aria. Lo scopo di queste misurazioni era quello di individuare eventuali collegamenti delle variabili meteorologiche con i flussi di acqua nel campo. Per poter realizzare il bilancio idrico del campo, l'umidità del suolo è stata misurata in tre profondità diverse (5 cm, 30 cm e 60 cm) utilizzando tre TDRs (time - domain reflection sensor). Attraverso queste misurazioni è stato possibile determinare la differenza del contenuto idrico del suolo ($\triangle$SW) durante un periodo di tempo stabilito (una settimana). Oltre a questo sono stati eseguiti rilievi settimanali della profondità della falda freatica.
Come supposto, i risultati affermano che durante gli ultimi mesi i valori dell'evapotraspirazione (ET_c) erano relativamente bassi. Nel corso del mese di settembre sono stati misurati 58 mm di ET_c e fino a dicembre l'ET_c calava continuamente fino a raggiungere i 5 mm. Nonostante i bassi valori è stato possibile osservare la forte dipendenza di ET_c dalla PPFD. Purtroppo solo pochi valori eseguiti con i sensori di flusso di linfa (sensore Granier e sensori heat balance) sono risultati utili allo studio per problemi di tipo metodologico; essi hanno confermato tuttavia che anche il flusso di linfa calava da settembre a dicembre. Inoltre, è stato osservato che i massimi giornalieri della densità di flusso di linfa e i massimi dell'ET_c non coincidevano. Il picco dell'ET_c anticipava quello delle misure fatte dal sensore Granier. Questo poteva essere riconducibile allo stoccaggio di acqua nel fusto del melo durante la notte. Quest'acqua, nel breve termine, può contribuire all'ET_c, ma non viene rilevata dal sensore Granier. Attraverso le misure eseguite con il Heat Balance sensor, si osserva che il picco dei valori misurati anticipava, seppure di poco, il massimo dell'ET_c. Osservando i risultati del bilancio idrico è risultato evidente che l'ET_c viene influenzata da alti valori input. Soprattutto dopo forti piogge o interventi di irrigazione l'ET_c aumentava rapidamente, dovuto particolarmente all'incremento dell'evaporazione delle superfici, del suolo e delle piante. Inoltre, l'elaborazione del bilancio idrico ha rilevato che gran parte delle piogge durante novembre e dicembre ha causato drenaggio idrico (D). Contrariamente, durante periodi di alte richieste idriche e poca immissione di acqua (pioggia e irrigazione) la capillarità (C) ha un ruolo importante nel rifornimento dell'acqua. Il fatto appena spiegato è stato attribuito all'alto livello della falda freatica nel meleto, che arrivava a 0.84 m sotto il livello del suolo.
In conclusione, si nota come il meleto almeno in settembre, con la falda superficiale, beneficia della risalita capillare (C) e può essere irrigato con minori quantità di acqua. Tuttavia, è riconosciuto che le irrigazioni hanno un effetto positivo sulla qualità dei frutti e quindi risultano giustificate. Inoltre, è stato confermato che le esigenze del melo durante i mesi di novembre e dicembre sono assi basse per cui gran parte dell'acqua contribuisce al drenaggio (D).

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