*Università degli Studi della Basilicata*

PhD in
Agricultural, Forest and Food Sciences

TITLE

# “Hazelnut (*Corylus avellana* L.) response to water management”

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Cycle XXXVI

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*To Greta*

**Abstract**

Hazelnut (*Corylus avellana* L.) is an important crop linked to direct consumption and used as a main ingredient in many agribusiness products. Due to demand from the hazelnut industry, the crop is expanding into new areas, thus new challenges related to climate change and sustainability goals arise. Therefore, new agronomic management techniques and research goals are needed.

A main consequence of global warming is a lower and more irregular availability of water for crops. Irrigation may become necessary even for species that are not traditionally irrigated, as is happening with hazelnut. Irrigation amounts and scheduling are still estimated empirically, so water excesses and shortages often occur. The physiological behavior of hazel toward water stress needs to be further characterized: in relation to vapor pressure deficit (VPD), it is considered to be a water-saving species, taking advantage of low VPD values to optimize stomatal activity and carbon uptake. Several authors consider *Corylus avellana* L. sensitive to water stress with low stomatal control capacity. Therefore, it is necessary to investigate fundamental aspects useful for identifying water stress signals.

Regarding applications for agronomic management of water and other inputs for orchard condition assessment, precision management technologies could help improve resource use efficiency and increase growers' income. However, hazelnut production techniques are far from the so-called Agriculture 4.0. Sensors for precision management include canopy characterization technologies and soil mapping devices. Among the former, unmanned aerial vehicle platforms are increasingly available to meet the demand for rapid real-time monitoring for orchard management at spatial, spectral and temporal resolutions, addressing the analysis of geometric traits such as canopy volume and area and vegetation indices. Research on remote sensing systems, particularly drone devices and soil mapping systems, for hazel is still limited and indices are needed for canopy characterization.

Research work presented in this Ph.D. thesis was conducted with the general objective of gaining insight into water relations and response to irrigation of *Corylus avellana* and techniques related to its management. Specific objectives were:

- to define a rapid procedure to calculate geometric parameters of the canopy, such as canopy area and height, by methods using NDVI and CHM values derived from UAV images;

- to identify physiological parameters useful for quantifying early signs of stress in *Corylus avellana* and to provide methodological indications for the measurements of such parameters and to identify physiological response of leaves to deficit water stress according to position on different sides of the canopy. This objective was conducted in cooperation with Oregon State University and its extension service through an internship of the doctoral candidate at the Department of Horticulture of Oregon state University Corvallis (Oregon -U.S.A.). During the internship a research scheme for agronomic and physiological characterization of the response of *Corylus avellana* L. to irrigation was applied at a commercial farmer's field;

- response of *Corylus avellana* cv. Tonda di Giffoni to different levels of irrigation, and evaluation of the effect of irrigation levels on physiological response, yield, production indices WUE, and quality;

- study of the relationships between LAI/Yield and LAI/NDVI in the production season.

Methods and results are presented in three chapters and summarized as follows:

1. **Establishment of relationships between remotely sensed parameters and hazelnut biometrics**

A new procedure was tested on young *Corylus avellana* trees with the aim to draw parameters for hazelnut orchard management in the early years of cultivation. The study area was a hazelnut orchard (6.68 ha), located in Bernalda, Italy. The survey was conducted in a six-year-old irrigated hazelnut orchard of Tonda di Giffoni and Nocchione varieties using multispectral UAV. We determined the Projected Ground Area and, on the *Corylus avellana* canopy trough, the vigor index NDVI (Normalized Difference Vegetation Index) and the CHM (Canopy Height Model), which were used to define the canopy and to calculate the tree crown area. The projection of the canopy area to the ground measured with NDVI values > 0.30 and NDVI values > 0.35 and compared with CHM measurements showed a statistically significant linear regression, $R^2 = 0.69$ and $R^2 = 0.70$, respectively. The ultra-high-resolution imagery collected with the UAV system helped identify and define each tree crown individually from the background (bare soil and grass cover).

## 2. Assessment of leaf water potential and stomatal conductance to define early signs of stress in young hazelnut in Willamette valley

An experiment was set up in a 5-year-old *Corylus avellana* L. var. 'McDonald' orchard. A split-treatment design was applied with two levels of irrigation: irrigated and rainfed and aspect of canopy sections with regards to cardinal points at different times of the day. Results show that hazelnut trees rapidly reduced leaf stomatal conductance when the vapor pressure deficit was between 2 and 2.5 kPa in both irrigated and non-irrigated trees, even with good water availability. This suggests leaf stomatal conductance can be an efficient and effective early indicator of stress. In addition, results suggest measuring stomatal conductance of leaves on the west and north aspects of the canopy, where they showed lowest and highest values respectively. Leaf and stem water potential values increased during the measurement period and show a strong correlation, but their mean values do not show statistically significant differences between treatments. In our experimental conditions, stomatal conductance provided earlier indication of stress than water potential. The results obtained are of methodological importance for the future design of experimental plans.

## 3. Irrigation effects on hazelnut (*Corylus avellana* L.) yield and quality

This study was conducted in a traditional area for hazelnut cultivation in Italy, specifically in Montoro (Avellino)to explore the impact of different irrigation levels (0, 40, and 100 % ETc daily restitution) on the physiological response, yield, and quality of hazelnuts, focusing on the Tonda di Giffoni cultivar in a non-irrigated farmer’s field. The research also contributes novel insights through the construction of NDVI-LAI and NDVI-Yield relationships.

Yield showed no significant differences among the treatments, indicating that different levels of irrigation did not have a significant impact on overall hazelnut production.

In the qualitative analysis of hazelnuts, the dryland treatment showed the lowest total discard, differing significantly from the full ETc daily restitution treatment.

Specifically, the treatment with 100% ETc daily restitution (T1) showed a high percentage of hidden bug damage, suggesting potential quality compromises with higher irrigation levels.

Relationships between NDVI and crop biometrics showed that in the dryland orchard it is possible to estimate LAI using NDVI values. Linear relationships were significant and positive in June ($R^2$ = 0.79) and negative in July ($R^2$ = 0.66). While linear relationship NDVI-Yield showed the treatment with 40% ETc daily restitution (T2), significative and negative from June to September, suggesting that T2 treatment, may have achieved good trade-off between vegetative renewal and production. In addition, T2 treatment showed the highest efficiency in terms of amount of seed produced per leaf area.

The dryland and T2 treatments showed the best overall performance.

Treatment T2, with 63% water savings compared to the treatment T1, emerges as a promising compromise for sustainable hazelnut management.

The results suggest that careful water management, with a daily replacement of 40 % ETc, could achieve a balance between reducing water inputs, improving quality, thus, sustainable practices for the hazelnut orchard.

## 1. *Corylus*: botany and morphology

The genus *Corylus* belongs to the order Fagales and the family Corylaceae (ex-Betulaceae) and consists of 25 species. The genus name "Corylus" originates from the classical Greek word "corys," meaning "helmet," referring to the envelope-shaped bracts surrounding the fruit (Chen et al., 1999; Yoo and Wen 2002; Baratta et al., 2016).

The most recognized species include, in Europe, *C. avellana* multi-stemmed shrubs 3–10 m tall, *C. colurna* single trunk, pyramidal trees, 20-40 m tall and *C. maxima* with bushy bearing; *C. americana* and *C. cornuta* in North America which are characterized by small multi-stemmed shrubs, 1–3 m tall, that spread by abundant suckers; and in Asia *C. ferox with single trunk trees, C. heterophylla and C. sieboldiana,with* multi-stemmed shrubs *and C. chinensis* single-trunk trees, 20-40 m tall (Molnar, 2011).

For *Corylus*, China is a center of diversity. Eight species are native to China but only one species *C. heterophylla* Fisch. (named Ping hazelnut in Chinese), is well developed in terms of commercial cultivations. Ping'ou hybrid hazelnuts have been improved through the interspecific hybridization between *C. heterophylla* × *C. avellana*. About 14 cultivars of Ping'ou hybrids have been released, divided into three groups according to their level of cold – hardiness (Liang et al., 2012; Wang et al., 2018).

For cultivation purposes, *C. avellana, C. maxima* and hybrids between the two species, are of particular interest for direct use as varieties. With reference to the latter, it is known (Trotter, 1951) that several valuable Italian cultivars such as: the " Tonda di Giffoni," " Mortarella," "San Giovanni," Riccia di Talanico," " Camponica," and " Santa Maria del Gesù" are hybrids between *C. avellana* and *C. maxima*. With regard to obtaining non-polloniferous rootstocks, the tree species *C. colurna, C. chinensis* and also *C. vilmorini*, which is a hybrid between *C. avellana* and C. chinensis (Lagerstedt, 1975) are of particular importance. All hazelnut species produce edible fruits, but *Corylus avellana*, is the most cultivated species for commercial production due to the favorable plant characteristics and high quality of its fruits (Botta & Valentini, 2018). *Corylus avellana* is also the most widespread species in the wild in Europe, from Scandinavia to the Iberian Peninsula and up to the Urals (Russia), Turkey and Asia Minor (Lebanon, Syria, Iran) (Baratta et al., 2016). The etymology of the term "*avellana*," which identifies this species, presumably originates from the ancient city of Abella, now known as Avella, located in Campania, in the province of Avellino (Baratta et al., 2016). Finally, all species that are widespread in the world are, depending on the objectives to be pursued, worthy of attention with regard to genetic improvement; for example: *C. avellana* for the characters of its fruits, C. maxima for resistance to erophytes (Pbytoptus avellanae, Nal), C. americana and C. cornuta for resistance to low temperatures and diseases (Romisondo, 1977).

*Corylus avellana* trees, varying in height from five to seven meters, have a shrub morphology with a natural bushy habit. These plants are characterized by the presence of a variable number of stems, originating from their continuous emission from the rootstock of shoots called "suckers," which develop from adventitious buds located on the root zone (Tombesi, 1985).

The root system of hazel plants tends to be shallow, developing mainly in the top fifty centimeters of the soil. However, it can extend to depths well over two meters to absorb water, extending beyond the projection of the canopy to the soil (Eynard and Paglietta, 1962).

The hazelnut is a monoecious species, with male and female flowers borne on the same plant, but with a dichogamy involving male and female flowering at distinct periods (Tombesi, 1991). Male flowers are grouped in cylindrical inflorescences called catkins. The catkins are already visible during the summer and remain in a state of hibernation during the first part of the winter season, reaching full flowering between January and February (Botta & Valentini, 2018).

The female flower is called the glomerulus and is grouped in inflorescences containing from 7 to 12 flowers, inserted within mixed buds. Each female flower consists of a bicarpellar ovary, crowned by two short styles with evidents red stigmas. The stigmas emerge from the mixed buds during flowering and are subject to pollination. The mixed buds result mostly grouped at the base of the catkins, or isolated. The latter are inserted directly on the branches or on a short branch and have the appearance of lamburds (Pisani, 1968).

Ovary formation begins after flowering, during stigma desiccation in March, and is completed several months later, in late May and early June, when fertilization occurs. Four to five months occur between pollination and fertilization, during which the male germinative cells persist at the base of the styles in the ovarian tissue, where the female gametophyte develops (Botta & Valentini, 2018).

Starting in June, hazelnut growth proceeds rapidly.

Hazelnuts are dry, indehiscent fruits consisting of a single loggia, enclosed in a leaf envelope known as a " cupule," which tends to dry out completely at maturity. In most cultivars, the hazelnut spontaneously separates from the cupule and falls to the ground, with the exception of Turkish cultivars, in which the cupole remains wrapped and requires a manual separation. Hazelnut ripening occurs in late summer or early autumn, typically between August and September, and occurs gradually (Botta & Valentini, 2018).

Ripe fruits naturally drop from the shell and, depending on cultivar and cultural conditions, are composed of about 50-60% shell and 40-50% seed (Tombesi, 1991).

## 2. State of the art

### *2.1 Eco-physiological hazelnut responses and water stress in hazelnut*

Climate-exposed sectors such as agriculture, forestry, fisheries, energy and tourism were highlighted among the sectors most affected economically by climate change (IPCC, 2023). The last nine years, from 2015 to 2023, have been the warmest on record compared to the average temperature of 1850-1900. In particular, during the winter months, the central and southern parts of Italy experienced an increase in evapotranspiration and temperature of nearly 1°C (WMO, 2023). A recent study on hazelnut conducted in central Italy revealed that increasing temperatures and increased water consumption had resulted to a decrease in chilling accumulation (Vinci et al., 2023) and that hazelnut prefers cool and moist conditions (Di Lena et al., 2022). The mean air temperature and evapotranspiration will increase (Pan et al., 2014) with an increase in the frequency of extreme climatic events (heat waves and frosts). This increase is expected to be associated with more frequent high temperature events and heat waves, droughts and floods. Drought, excessive thermal load and high daily irradiation are considered limiting factors for agricultural production with consequences on plant growth which translate into low productivity and fruit quality.

The research activities on the intensity of physiological processes carried out on *C. avellana* demonstrate that the linear regressions resulting between the intensity of physiological processes (photosynthesis and transpiration) and active photosynthetic radiation, leaf temperature and stomatal conductance show a positive correlation, with specific variations and therefore higher values in mature leaves, compared to young leaves. (Ion et al., 2016).

There is therefore a conflict between the need for water conservation and the need for $CO_2$ assimilation aggravated in the hazelnut plant due to poor stomatal regulation control.

The factors influencing the development of hazelnuts were analyzed through a simulation model. The sensitivity of the model varies slightly between environments, however presenting a good reliability. The processes involved in leaf area development and plant architecture are the main factors contributing to the forecast variability, followed by the photosynthetic process, the impact of water stress, the partitioning of photosynthate to fruits and then the initialization of the carbon pool (Bregaglio et al., 2020). However, adopting water restriction regimes during leaf development of hazel saplings induces morphological, anatomical and physiological adaptations, improving the performance of the plant when transplanting in the open field, resulting in better ability to cope with water stress (Catoni et al., 2017).

Hazelnut trees under conditions of thermal stress associated with low relative humidity of the air do not seem to have the ability to control and regulate the stomatal opening during periods of maximum stress (Tombesi, 1992; Girona et al., 1994; Cristofori et al., 2014). Native to temperate regions, hazelnut does not tolerate temperatures between 35 and 40 °C for several days and relative humidity below 70%. These conditions strongly inhibit stomatal activity (Fideghelli and De Salvador 2009, Cincera et al. 2019), which reduces yield and vegetative growth and is linked to decreased kernel filling (An et al., 2020; Jha et al., 2021). It is particularly sensitive to Vapor Pressure Deficit (VPD) when this exceeds 1 kPa (Pasqualotto et al., 2021) and 2.3 kPa (Altieri et al., 2024), reducing its stomatal activity.

However, recent studies have shown that there are potential means to help the plant mitigate stresses from extreme weather events. These include the use of kaolin, which reduces leaf temperature from 2.9 °C to 6.9 °C, and thus the resulting heat stress (Luciani et al., 2020); Cabo et al., 2019 observed a greater tolerance to drought and heat stress in hazelnut trees following summer treatment, for two consecutive years, with kaolin and Ascophyllum nodosum, alone or in combination with irrigation. In both treatments the relative water content of the leaves was higher in the treated thesis than in the control. The effects were more pronounced in the second year, suggesting that the use of kaolin and Ascophyllum nodosum should be considered in the long term; the application of *Glomus iranicum tenuihypharum sp. nova* mycorrhiza improved the physiological function of leaves, promoted recovery, increased the amount of chlorophyll in summer, when fruit growth and vegetative activity occur simultaneously, and improved the yield and oil content of kernels (Luciani et al., 2019); compared with own-rooted hazelnuts, grafted plants showed root development that allowed deeper water uptake, higher stomatal reactivity and higher accumulation of carbohydrate reserves in root tissues (Portarena et al., 2022).

Adopting water restriction regimes during leaf development of hazel saplings induces morphological, anatomical and physiological adaptations, improving the performance of the plant when transplanting in the open field, resulting in better ability to cope with water stress (Catoni et al., 2017).

Traditional hazelnut production areas require average annual rainfall of between 800-1000 mm, distributed evenly throughout the year (Cristofori et al., 2014).

The hazelnut cycle presents the overlap in the period June-August (fig. 1) of different processes of development/growth of the plant and of the fruit, this requires an adequate level of water availability, an essential factor to mitigate the competition between the various organs of the plant and to limit the effects of stress both on growth in the early years of the plant and on production entry times and productivity (Tombesi and Rosati 1997). Tonda di Giffoni begins hazelnut growth in mid-June, reaching more than 30 % of final volume on June 23 and more than 70 % in early July, after which kernel, development start and continue for about 5-6 weeks until full size was reached (Valentini et al., 2015)

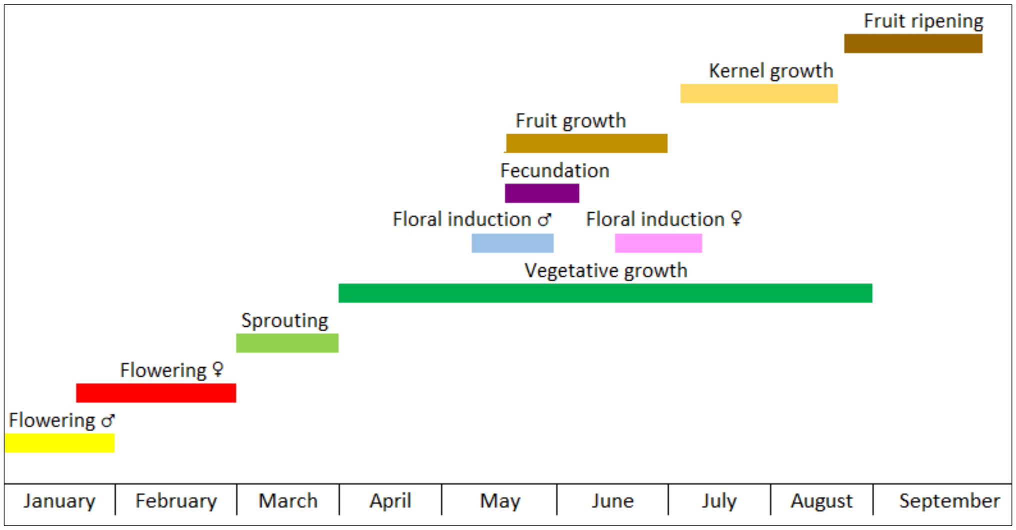


**Figure 1**. Calendar of the phenological phases of the hazelnut tree (Botta and Valentini, 2018)

Also, studies conducted by Tombesi and Rosati (1997) have demonstrated that reduced water volumes, water stress, compared to cultivation needs, have determined negative effects on production and on some technological characteristics of the fruit, such as the increase in the "blank" and the decrease in shelled yield. The authors found that in June, a soil water content higher than 60-65% of the total available water induces a greater degree of transpiration without an increase in photosynthetic activity but with an increase in fruit size, demonstrating that the period of rapid growth in fruit diameter, which occurs in the same period, appears to be particularly sensitive to water availability.

Summer water stress can be reduced with irrigation, particularly during hazelnut growth given the great influence on physiological parameters and probably also on fruit quality (Dias et al., 2005). Water stresses applied toward the end of kernel filling and during ripening affected time of harvest, early fruit drop and tree growth was compromise on July (Mingeau et al., 1992).

Water deficit affects leaf gas exchanges, therefore net assimilation of $CO_2$ and stomatal conductance. The xylem water potential, measured via pressure chamber, is highly sensitive to water variations and can therefore be used efficiently and at low cost in irrigation programming. Controlled water stress did not lead to a significant reduction in yields per kg of plant, saving up to 15% of maximum water demand. However, it must be ensured that the water potential value is between -0.8 and -1.1 MPa. Values lower than -1.1 MPa (severe stress) would cause a significant reduction in fruit and seed weight (University of Talca, 2017-2018). Instead, Ortega and Farias et al. (2020) showed that the effect of irrigation cutting strategies improved water productivity but reduced yield, gas exchange, and weight of nuts and fruits.

Interesting developments for the evaluation of the variability of water flows among hazelnut plants come from the recent use of probes that measure the sap flow (known as sap flow) which is assumed to be equivalent to the water transpired by the leaves (Pasqualotto et al., 2019). The measurement of the sap-flow is obtained with the thermal dissipation method (TDP) proposed by Granier in 1985. This method is the most used as it is simple, the probes are easy to install, cheap and with low energy consumption.

Therefore, gaps of knowledge for hazelnut crowing include all aspects of responses to water and management guidelines.

The physiological behavior of hazelnut with regards to water stress needs further characterization: in relation to early signs of water stress.

### *2.2 Remote sensing by UAV and soil mapping*

Over the past decade, geophysical sensors based on no-destructive measurement of the conductivity soil electrical conductivity (or its inverse resistivity) have been widely used in precision agriculture (PA), either alone or in combination with information of soil characteristics to delineate management zones uniform (Amato et al., 2008; Basso et al., 2010).

Using geophysical instruments, it is possible to study the variability of soil parameters and with the drone that of the topsoil. Soil parameters, electrical conductivity mapping, and plant measurements must be combined in order to obtain irrigation homogeneity for individual areas (Szabò et al. 2021). This approach in hazelnut orchard has not yet been pursued.

The resulting information can be integrated with each other by considering the measurements deriving from a series of proximal sensors.

Regarding applications for agronomic management of water and other inputs and evaluation of orchard status, precision management technologies could help improve resource use efficiency and increase growers’ income. Nevertheless, hazelnut production techniques are far from the so-called Agriculture 4.0.

Among the former UAV platforms are becoming increasingly available to satisfy the demand for rapid real-time monitoring for orchard management at spatial, spectral, and temporal resolutions, addressing the analysis of geometric traits such as canopy volume and area and vegetation indices. Research on remote sensing systems and especially on drone devices for hazelnut is still limited and indices for canopy characterization are needed.

Sensors for precision management include technology (UAV) or drone for canopy characterization and soil mapping devices. There are several fruits crops whose geometric traits, productivity, disease have been studied by UAV platform. However, among the dry fruits only almond and chestnut tree was found until 2019 (Zhang et al., 2021). Probably, due to the irregularity of the shrubby and complex shape of the hazelnut tree. A quick procedure to determine the canopy area of young hazelnut trees using NDVI (normal difference vegetation index) and CHM (canopy height model) values, recently was obtained from UAV images (Altieri et al., 2022). Vinci et al., 2023 have determined via UAV size and volume, providing information on hazelnut management, useful on 'pruning intensity and vegetative growth.

Technology for the mapping of soil variability can be of great assistance in planning variable rate management of crops and also in interpreting research results in experimental settings with variable soil features such as field experiments. Geophysical methods have been successfully applied in herbaceous crops and experimented in tree crops, but information is lacking for *Corylus avellana* L.

Another unexplored field in tree crops and hazelnut is the relationship between NDVI and LAI index and yield. While these aspects are widely studied in herbaceous crops, vineyards, pastures, mixed canopies and poplar groves (Bajocco et al., 2022).

## 3. Hazelnut production – global, national and local scale

FAO data show a clear growth of in-shell hazelnuts in recent decades. Figure 2 shows the total production and cultivated area at the global level from 1962 to 2022. In 1962, global in-shell hazelnut production amounted to 226,010 tons, the latest available data to 2022 shows 1,195,732.16 tons, registering an average annual growth rate of 3 %.

The area cultivated increased from 305,980 ha in 1962 to 1,061,120 ha recorded in 2022 (Fig. 2). The increase in total production is explained not only by the increase in cultivated area, but also by an increase due to improvements in agronomic techniques, improvement in pathogen monitoring techniques, and genetic quality increase by producers.

In the last 5 years, from 2018 to 2022, the Asian continent is confirmed to be a top player in production in terms of quantity, in particular, the production of Turkey with 681,009.20 tons representing 63.76%, followed by Italy with 111,026.00 tons representing 10.39% of the entire global production. The list of producing countries is very narrow, consider that the top six countries produce 91.5 % and the top 12 countries cover 98.36 % of global production (Tab. 1).

At the national level production 2023 in descending order mean total production ranks Latium, Piedmont, Campania, Sicily and a small share in the other regions with 38405.7, 31470.8, 26525.8, 5448.3 and 3198 tons, respectively. Latium, Piedmont and Campania cover 37, 30 and 25 % of national production, respectively. In terms of cultivated area, on the other hand, Piedmont, Latium and Campania recorded 25,717, 23,240 and 21,734 hectares, respectively, during the same period (fig. 3).

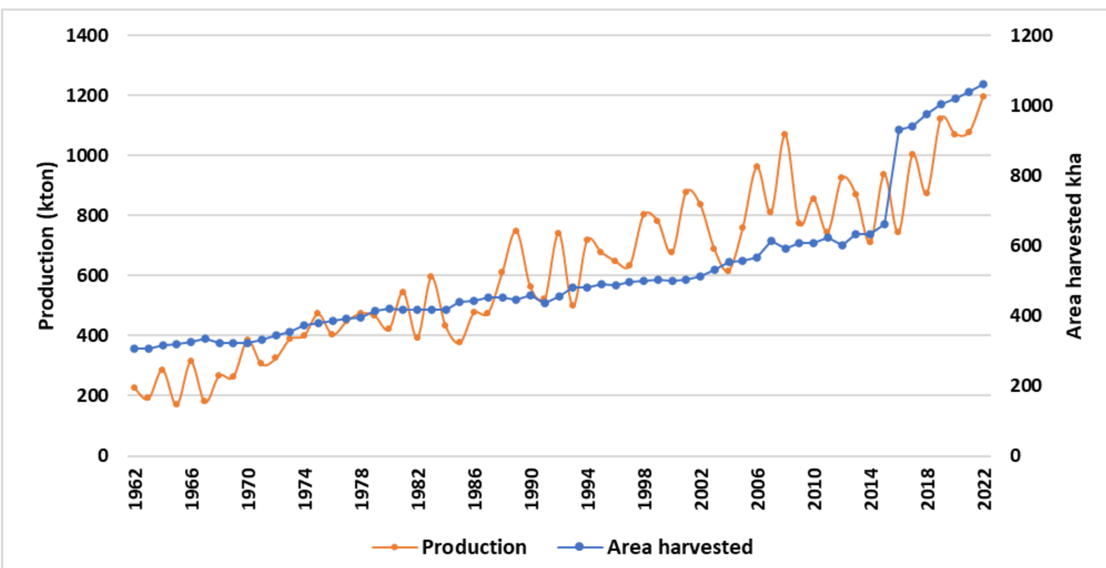


**Figure 2**. World production and harvested area of hazelnuts, in shell, from 1962 to 2022 (source: FAOSTAT 2023).

**Table 1**. Mean production for country in the last 5 years from 2018 to 2022 (source: FAOSTAT 2023).

| Country | ton | % |
|---|---|---|
| Türkiye | 681.009,2 | 63,8 |
| Italy | 111.026,0 | 10,4 |
| Azerbaijan | 59.012,0 | 5,5 |
| United States of America | 56.754,0 | 5,3 |
| Chile | 39.014,5 | 3,7 |
| Georgia | 30.620,0 | 2,9 |
| China, mainland | 24.790,5 | 2,3 |
| Iran (Islamic Republic of) | 13.719,1 | 1,3 |
| France | 12.456,0 | 1,2 |
| Spain | 8.334,0 | 0,78 |
| Poland | 7.376,0 | 0,69 |
| Others countries | 24.003,3 | 2,3 |
| World | 1.068.114,7 | 100,0 |

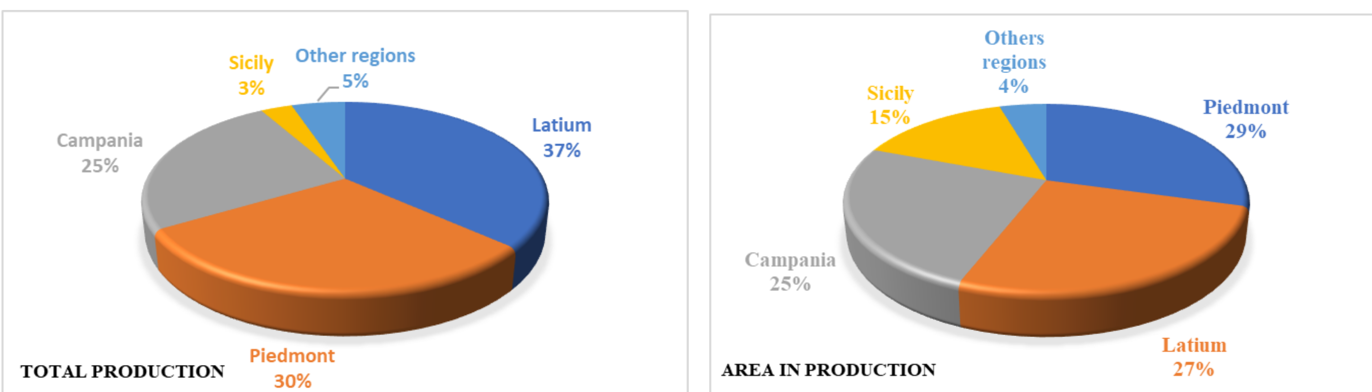


**Figure 3**. Total production (sx) and area in production by Italian region (dx) 2023 year (source: ISTAT, 2023)

Campania region is reputed the oldest site for hazelnut cultivation (Trotter, 1921) and, following a study using chloroplast microsatellites most likely from Campania, was an influential site of origin and spread of hazelnut cultivars (Boccacci and Botta, 2018). Campania's production as of 2023 stands at 26,525 tons and a production area of 21,734 hectares. Total production, in 2023, is distributed among the provinces of

Avellino, Naples, Caserta, Salerno and Benevento (Table 2), where production is concentrated in the province of Avellino with 11,000 tons, which also has the largest cultivated area with 8,300 ha. The main cultivars cultivated are Mortarella, San Giovanni, Tonda Bianca and Tonda Rossa, Camponica and Riccia di Talanico present mainly in the Avellino area, while Tonda di Giffoni mainly in the provinces of Salerno and Caserta. Mortarella and S. Giovanni are used for industrial applications, while Tonde, Camponica and Riccia di Talanico for fresh consumption.

**Table 2**. Total production and area in production in the year 2023 at the provincial level in the Campania region (source: ISTAT, 2023)

| Province | Total production (ton) | Area in production (ha) |
|---|---|---|
| Avellino | 11000 | 8.300 |
| Naples | 6.755 | 6.004 |
| Caserta | 4.600 | 3.600 |
| Salerno | 4.000 | 3.750 |
| Benevento | 170 | 80 |
| **Total Campania** | **26525** | **21734** |

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**Sitography**

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## 4. Objectives

Research work presented in this Ph.D. thesis was conducted with the general objective of gaining insight into water relations and response to irrigation of European hazelnut and techniques related to its management for devising more informed irrigation strategies and scheduling, based on soil, plant ecophysiology and early stress signs, and the use of precision agriculture tools.

Specific objectives were:

1. to define a rapid procedure to calculate geometric parameters of the canopy, such as canopy area and height, by methods using NDVI and CHM values derived from UAV images. To this end an experiment was conducted on a young *Corylus avellana* L. orchard in order to gain information useful to manage hazelnut in early years of cultivation.

2. to identify physiological parameters useful for quantifying early signs of stress in *Corylus avellana* and to provide methodological indications for the measurements of such parameters. This objective was conducted in cooperation with Oregon State University and its extension service through an internship of the doctoral candidate at the Department of Horticulture of Oregon state University Corvallis (Oregon - U.S.A.). During the internship a research scheme for agronomic and physiological characterization of the response of *Corylus avellana* L. to irrigation was applied at a farmer's field.

3. to evaluate the effects of different levels of irrigation on the physiological response, yield and production indices, commercial and analytical quality of adult hazelnuts orchard cultivar Tonda di Giffoni in suitable area of production prior to soil survey using geophysical techniques.  In addition, Using UAV and LICOR-LAI systems construct reliable relationships between normalized vegetation index (NDVI) and leaf area index (LAI) and their evolution over the season. With production data, on the other hand, the relationships between hazelnut yield and NDVI values are analyzed.

## Chapter 1 - Use of High-Resolution Multispectral UAVs to Calculate Projected Ground Area in *Corylus avellana* L. Tree Orchard.

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**Abstract**

In the last decade, research on *Corylus avellana* has focused on improving field techniques and hazelnut quality; however, climatic change and sustainability goals call for new agronomic management strategies. Precision management technologies could help improve resource use efficiency and increase grower income, but research on remote sensing systems and especially on drone devices is still limited. Therefore, the hazelnut is still linked to production techniques far from the so-called Agriculture 4.0. Unmanned aerial vehicles platforms are becoming increasingly available to satisfy the demand for rapid real-time monitoring for orchard management at spatial, spectral, and temporal resolutions, addressing the analysis of geometric traits such as canopy volume and area and vegetation indices. The objective of this study is to define a rapid procedure to calculate geometric parameters of the canopy, such as canopy area and height, by methods using NDVI and CHM values derived from UAV images. This procedure was tested on the young *Corylus avellana* tree to manage a hazelnut orchard in the early years of cultivation. The study area is a hazelnut orchard (6.68 ha), located in Bernalda, Italy (40°26.847'N 16°45.420'). The survey was conducted in a six-year-old irrigated hazelnut orchard of Tonda di Giffoni and Nocchione varieties using multispectral UAV. We determined the Projected Ground Area and, on the *Corylus avellana* canopy trough, the vigor index NDVI (Normalized Difference Vegetation Index) and the CHM (Canopy Height Model), which were used to define the canopy and to calculate the tree crown area. The projection of the canopy area to the ground measured with NDVI values > 0.30 and NDVI values > 0.35 and compared with CHM measurements showed a statistically significant linear regression, R2 = 0.69 and R2 = 0.70, respectively. The ultra-high-resolution imagery collected with the UAV system helped identify and define each tree crown individually from the background (bare soil and grass cover). Future

developments are the construction of reliable relationships between the vigor index NDVI and the Leaf Area Index (LAI), as well as the evaluation of their spatial-temporal evolution.

**Keywords:** precision agriculture; hazelnut trees; irrigation strategies; UAV multispectral images; NDVI; CHM; PGA

## 1. Introduction

The European hazelnut (*Corylus avellana* L.) is one of the most important species in the world in the category of nuts [1,2]. Hazelnut tree irrigation is an emerging management issue. Orchard water supplies have to satisfy the realistic demands of each tree species [3] and, for the hazelnut tree, the crucial period for water demand is from May to September [4]. In traditional areas of production, an average of 800–1000 mm of precipitation is needed, regularly distributed throughout the year [5]. In the Mediterranean basin, the current average annual temperature is 1.4 ◦C higher than in the late 19th century and the largest differences between the two periods are recorded during the summer. Climate change, now underway, has already stressed significant vulnerability and susceptibility of some agroecosystems. For every 1 ◦C of global warming, the average precipitation is likely to decrease by about 4% in most regions and particularly in areas in the center and the south of Italy [6].

Drought, excessive heat load, and high daily irradiation are considered limiting factors for agricultural production, with consequences on plant growth resulting in low productivity and fruit quality. Water stress in the hazelnut tree, *Corylus avellana*, adversely affects fruit production and quality, causing premature cessation of fruit growth, early leaf fall, a larger proportion of empty fruits, and increased susceptibility to diseases [7,8]. Recent studies have documented the impact of changes in temperature and precipitation on the hazelnut tree. Increasing the number of days with maximum temperature above 35 °C and relative humidity below 70% causes severe water stress, resulting in yield decline and reduced vegetative growth, combined with a reduction in nucule filling [9,10]. This is more evident for the Tonda di Giffoni variety of hazelnut, highly appreciated for its processing quality.

The interest in hazelnut cultivation is also linked to its important role in the rural land-scape of some areas of southern Italy. In fact, the planting of more sustainable crops such as hazelnut plants can be a key strategy in preventing soil erosion and land degradation [11].The advantages of remote sensing are highlighted in several works. It is fast, non- destructive, and can study a large area of detection with the possibility of quantifying biophysical parameters [12,13]. Although it is widely used in the scientific research community, it has limitations; yet, in recent years, UAVs (Unmanned Aerial Vehicles) are preferred by agricultural operators [14]. UAVs, usually called drones, are aircrafts without a human pilot on board. UAVs are controlled by an operator on the ground [15]. One limitation of multi-rotor UAVs is battery duration, although this enables UAVs to operate in relatively small-to-medium-sized orchards [16].

UAVs are becoming increasingly available to satisfy the demand for rapid real-time monitoring of orchard management at spatial, spectral, and temporal resolutions adapted to analyze geometric traits such as canopy volume and area [14,16–18]. Spatial resolution is a measure of the smallest detectable object on the ground. The number of pixels used for image building in the sensor itself, and its distance from the ground, help to determine the size of the pixels on the ground and the resulting image footprint [3]. In addition, data acquisition is fast, and images are georeferenced [19]. The mission flight setting depends on the characteristics of the case study: the size of the area, the flight autonomy, and the sensor features of the UAV that influence the Ground Sample Distance (GSD) and the image resolution.

Data produced from the use of UAVs and the photogrammetric processing allow to create orthorectified mosaics (orthophoto mosaics), digital elevation models (DEMs), three- dimensional (3D) point clouds, and vegetation indices. Therefore, vegetation monitoring is possible because these kinds of outputs allow vegetation detection and feature extraction such as tree height, projected ground area (PGA), diameter, canopy volume, and individual tree counts [15,17]. In the last decade, research on *Corylus avellana* has focused on the improvement of field management and on the quality of products; however, techniques are lagging behind advanced agronomic practices. Research works involving the use of environmental remote sensing systems are very few and the review of Zhang et al. [16] reports no published paper on the use of UAVs in *Corylus avellana*. This parallels production techniques, which are far from exploiting available technology (e.g., the so-called Agriculture 4.0) [20]. Instead, precision management could help improve resource use and increase grower income [3].

The irrigation management of trees can be greatly aided by biometric data related to evapotranspiration such as leaf area and canopy geometry. In order to delimit individual parameters, each tree must be separated from background bare soil and grass cover. Several researchers' increasing interest has focused on the extraction of tree canopies of different crops from UAV images in precision agriculture applications [17,21,22]. Marques et al. [4] propose to use the CHM (Canopy Height Model) or vegetation indices such as NDVI (Normal Difference Vegetation Index) as inputs into an image processing method to give an estimate of geometric traits in chestnut trees, such as canopy and diameter area and tree height. The individual tree detection can be run with acceptable accuracy from UAV derived CHMs [23]. The relationship between canopy cover and NDVI was shown by Tenreiro et al. [24] for various crop types, albeit at different levels of accuracy. Caruso et al. [25] highlighted the reliability of UAV imagery in estimating the geometric features of the olive tree, such as canopy volume and projected canopy area.

The Leaf Area Index (LAI) is among the most important biophysical variables of vegetation and represents the ratio between the total leaf area and the canopy projection area on the ground. LAI monitoring in the different phenological stages of the hazelnut tree allows the implementation of specific irrigation schedules. For the determination of LAI, it is necessary to calculate the PGA (Projected Ground Area) of the canopy and the leaf area. Accordingly, the objective of this study is to define a rapid procedure to calculate important geometric parameters of the canopy, such as canopy area and height, by methods using NDVI and CHM values derived from UAV images. This procedure has been tested on the young *Corylus avellana* tree to manage the hazelnut orchard in the early years of cultivation.

## 2. Materials and Methods

### 2.1. *Experimental Site*

The study area is a hazelnut orchard (6.68 ha), located in Bernalda, Italy (40°26.847′ N16°45.420′ E Figure 1), with an elevation of 84 m above sea level.

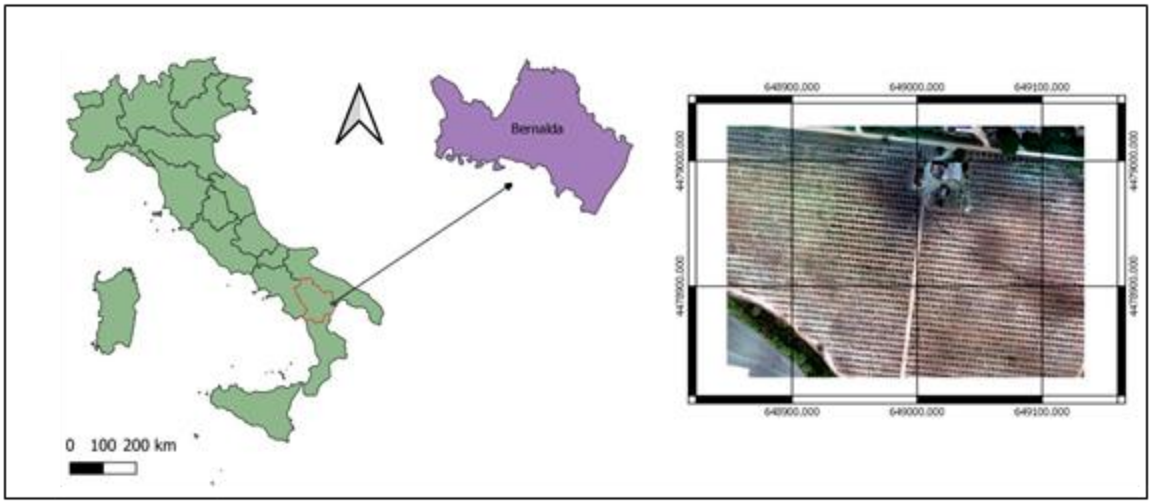


**Figure 1**. Left: geographical location of the farm, located in southern Italy; right: aerial photo of the research field taken from UAV with 6.29 cm/pixel.

The flight mission was conducted in a six-year-old irrigated hazelnut orchard of Tonda di Giffoni and Nocchione varieties. This latter represents the pollinator with 10% of the total number of plants. The plant density was 666 trees/ha, (5.0 × 3.0 m) andthe training system was multi stemmed shrubs or multisystem bushes, designed with theaim of a classic growing system but with a greater number of plants per hectare.

### 2.2. *UAV-Based Data Acquisition*

Remotely sensed data were acquired with a multi-rotor DJI Phantom 4 (P4) Multispectral UAV, a high precision drone for multispectral imaging functions. The imaging system was equipped with six CMOS (complementary metal oxide semiconductor) cameras, including one RGB camera for visible light imaging in JPEG format and five monochrome cameras for multispectral imaging in TIFF format. Each sensor has 2.08 MP effective (2.12 gross MP), focal length of lens 5.74 mm, image size in width and height 1600×1300, and size lens in width and height 4.96 and 3.72 mm, respectively. The five cameras acquire red, green, blue, red edge, and near infrared in the following imaging bands: 450 nm ± 16 nm; Green (G): 560 nm ± 16 nm; Red (R): 650 nm ± 6 nm; Red Edge 730 nm ± 16 nm; Near Infrared (NIR): 840 nm ± 26 nm.

The aircraft has an onboard RTK positioning system that provides centimeter-level accuracy.The flight mission was conducted on 20 September 2021 in a grid pattern, nadir- oriented camera, at 120 m height, with a front and side imagery overlap of 70%. The total number of pictures acquired was 594, with a spatial resolution of 0.0611 m/pixel in a flight time of $12'48''$.

*2.3 Image Processing Methods*

Photogrammetric processing of the acquired UAV imagery was carried out using Agisoft Metashape Professional software version 1.8.2 (Agisoft LLC, St. Petersburg, Russia).

The processing steps were as follows: adding photos from the multi-camera system only in Tiff format; calibrating reflectance; aligning photos based on matching points between images optimizing cameras (to improve the accuracy of the alignment for the RTK drone in a project without using GCP); building dense cloud; building DEM (Digital Elevation Model); building ortho-mosaic (Figure 2).

**Figure 2.** Orthophoto mosaic from aerial multispectral imagery collected using UAVs.

The output obtained from the image processing in the Agisoft Metashape software was a digital surface model (DSM).

Georeferenced and orthorectified images and DSM were exported in QGIS software version 3.22.4-Białowieża (Free Software Foundation, Inc., 51 Franklin Street, Fifth Floor, Boston, MA 02110-1301 USA) to be processed to calculate the Normalized Difference Vegetation Index (NDVI) [26] and the Canopy Height Model (CHM). The spatial resolution of all layers is 0.0611 m/pixel.

### *2.4 Canopy Delimited with NDVI and CHM Methods*

The projected ground area (PGA) of the canopy (tree crown area) was measured with two methods.

#### *2.4.1 NDVI*

Figure 3 shows the flow chart of the procedure to delimit the hazelnut canopy using multispectral images acquired from a UAV.

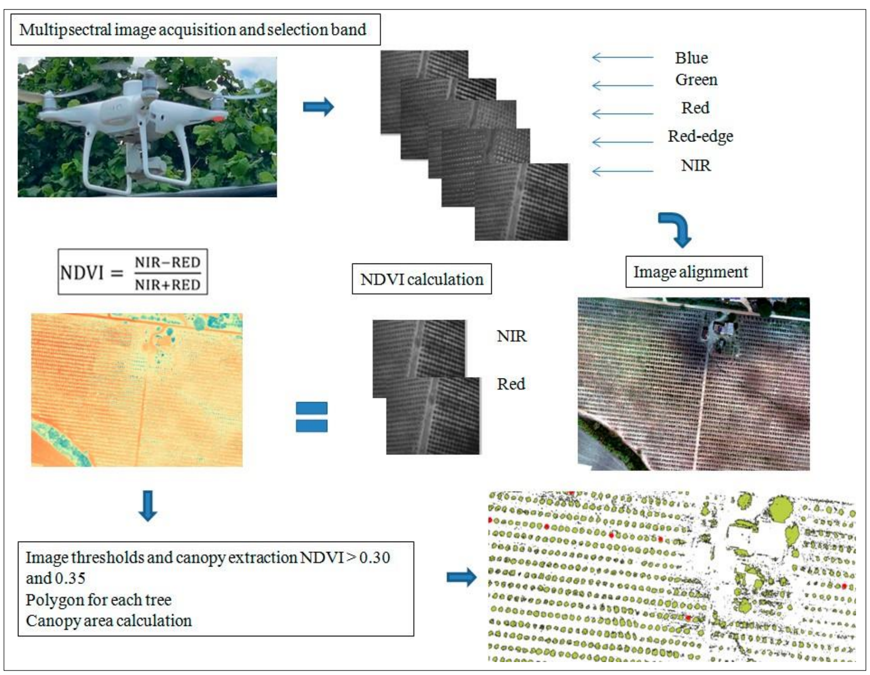


**Figure 3.** Flowchart of the procedure to delimit the hazelnut canopy using multispectral images acquired from a UAV.

The projected area of the canopy was delimited, based on the spatial distribution of the NDVI values:

$$NDVI = NIR - RED/NIR + RED$$

where NIR and RED are the values of the reflectance in the near-infrared (840 ± 26 nm) and red (650 ± 6 nm) bands, respectively.

The NDVI values of bare and grassed ground were associated with pixel values in the areas between rows not affected by tree canopies. Pixels with NDVI values between 0.1–0.32 belonged to bare and grassed ground. NDVI values between 0.3–3.5 were also associated with pixels with DSM – DTM ≥ 0.40 m of the tree canopies. Therefore, we decided to test the NDVI threshold values of 0.3 and 0.35 to select the most suitable for tree discrimination. We applied the raster calculator to the whole investigated area, using the NDVI threshold values of 0.30 and 0.35. Seventy-five trees were randomly selected within the raster, showing only NDVI values ≥ 0.30 and 0.35, respectively. The single area was calculated and associated with the tree canopy value.

### *2.4.2 Canopy Height Model (CHM) method*

From the DSM obtained with Agisoft Metashape, three lines parallel to the row and placed one meter apart were drawn in inter-row zones without canopy cover with the “advanced digitization panel tool”. Using the “points along geometry” command, measurement points were created at distances of three meters and staggered between the lines. Using the “Point Sampling Tool” (PST) plugin, the corresponding elevation values from the DSM raster were extracted at each point. Interpolation of the extracted elevation values was obtained using the “Triangulated Irregular Network (TIN) tool”. The CHM was determined by subtracting the DTM from the DSM with the raster calculator.

All processing was performed with the open-source QGIS software version 3.22.4- Białowieża (Free Software Foundation, Boston, MA, USA).

### *2.5 Leaf Area Measurement*

The leaf area of the hazelnut trees of the Tonda di Giffoni variety was measured destructively on 10 suckers taken from 10 different hazelnut plants. The circumference at 20 cm above the ground was measured on the same suckers with a centimeter ribbon, and the number of leaves was counted. The leaf area was measured using ImageJ 1.53k software (Wayne Rasband and contributors National Istitute of Health, USA) which delineates leaves with color contrast.

### **2.6 Statistical Analysis**

Statistical analysis was carried out using RStudio software version 1.4.1103.0 (RStudio, PBC, Boston, MA, USA). Statistical descriptive and regression analyses were performed.

Pairs of CHM–NDVI data were divided into two data sets: data pairs were randomly assigned to Dataset I or II. Dataset I consisted of 50 values and Dataset II comprised 25 values. Dataset I was used for regression analysis to determine the best empirical model relating the CHM and NDVI values. Regression models were compared based on the minimization of the sum of the square residuals. The regression of CHM on NDVI from Dataset I was tested on Dataset II to estimate NDVIe values. The NDVIe values of Dataset II were then regressed on the measured NDVI values (NDVIm), and the NDVIe/NDVIm pairs were compared by the Wilcoxon signed-rank test.

In addition, the allometric relationship between the leaf area and the basal diameter of the suckers was constructed by linear regression analysis.

## **3. Results**

### *3.1 CHM/NDVI Method*

The projection of the canopy area to the ground measured with NDVI values > 0.30 and NDVI values > 0.35 compared with the CHM measurements showed a statistically significant ($p < 0.0001$) linear regression ($R^2 = 0.6976$) (fig. 4) and ($p < 0.0001$) linear regression ($R^2 = 0.7064$) (fig. 5), respectively.

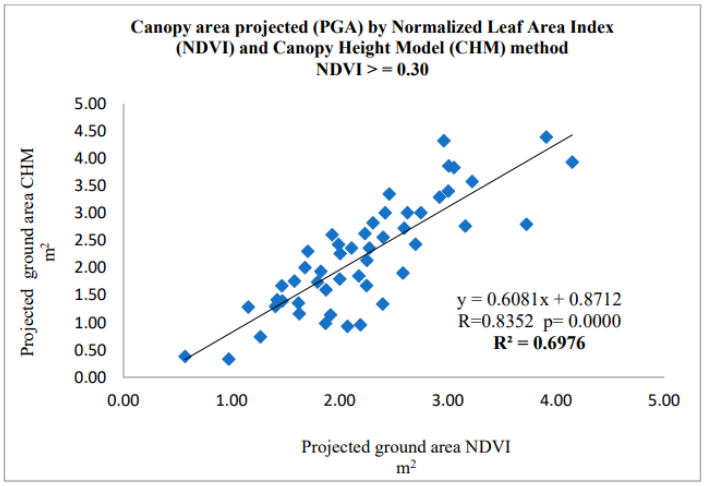


**Figure 4**. Relationship between $PGA_{CHM}$ vs. $PGA_{NDVI}$ with NDVI values > 0.30.

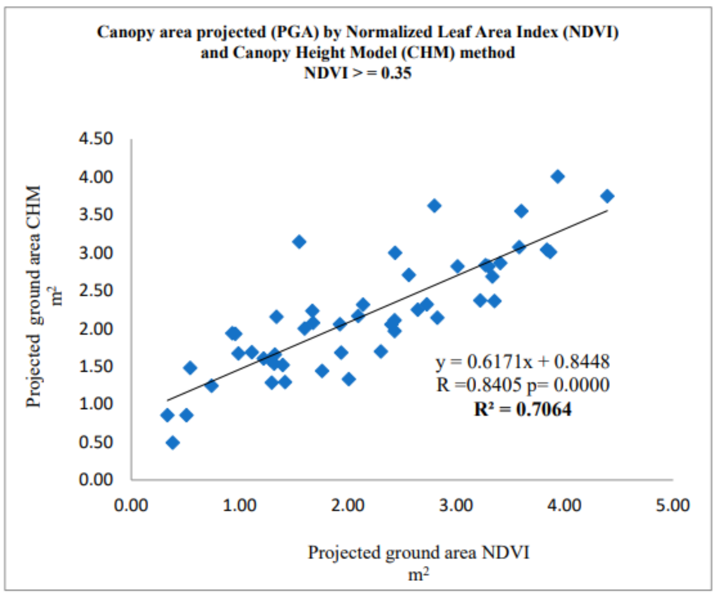


**Figure 5**. Relationship between $PGA_{CHM}$ vs. $PGA_{NDVI}$ with NDVI values > 0.35

In the analysis of the predictive ability to estimate the relationship using 25 values measured vs. estimated PGA CHM by NDVI values > 0.30 of Tonda di Giffoni, using the CHMe = 0.3457 CHMm + 1.4861 equation showed a statistically significant ($p$ < 0.001) and high linear regression ($R^2$ = 0.7241) (fig. 6).

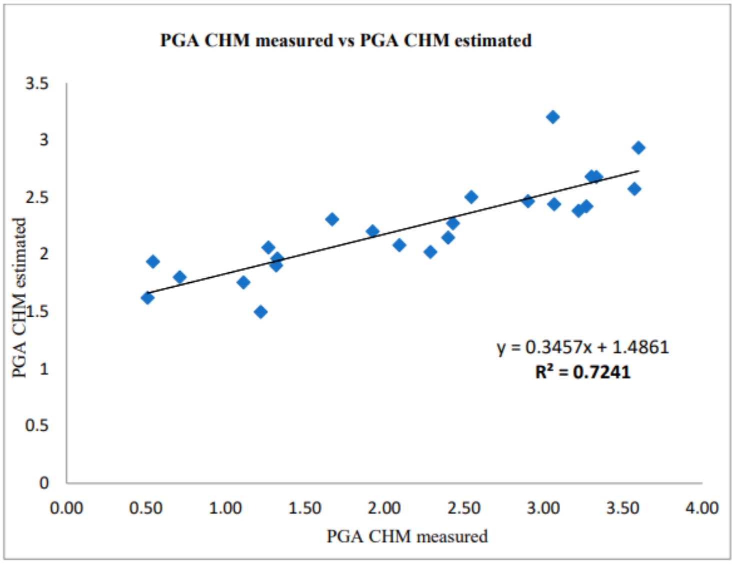


**Figure 6**. Measured vs. estimated CHM PGA with NDVI values > 0.30 of Tonda di Giffoni, using CHMe = 0.3457 × CHMm + 1.4861 equation; p < 0.001.

In contrast, the measured PGA vs. CHM estimated with NDVI values > 0.35 of Tonda di Giffoni using the CHMe = 0.3414 CHMm + 1.3817 equation showed statistical significance ($p < 0.001$) and low regression was ($R^2 = 0.5169$) (fig. 7).

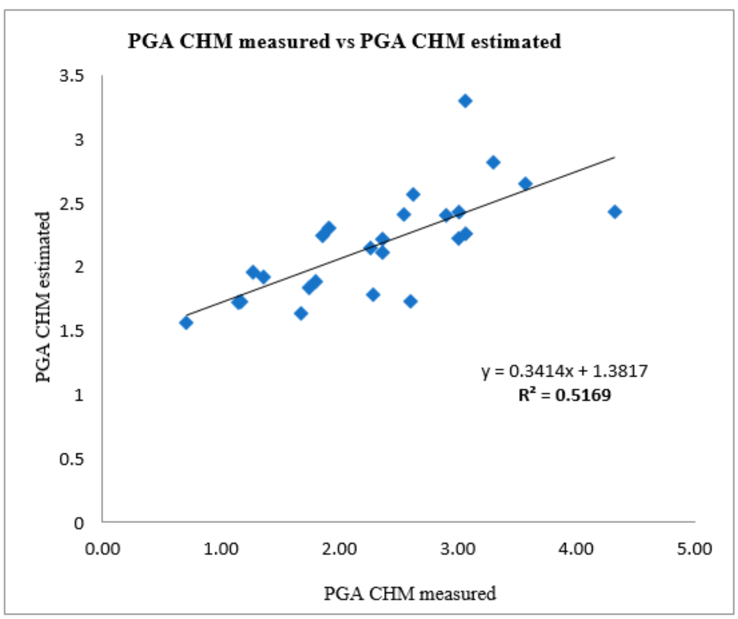


**Figure 7.** Measured vs. estimated CHM PGA with NDVI values > 0.35 of Tonda di Giffoni, using CHMe = 0.3414 × CHMm + 1.3817 equation; *p* < 0.001.

*3.2 LAI Measurement*

The relationship between the basal diameter of the sucker and its leaf area is shown in fig. 8.

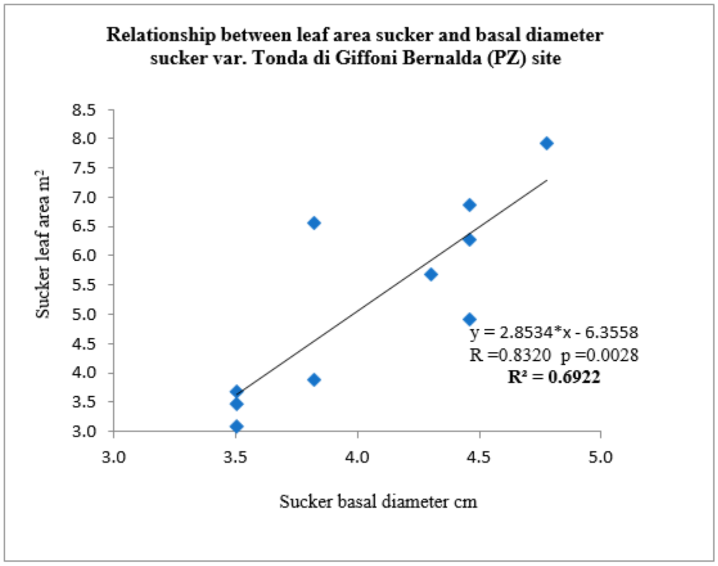


**Figure 8**. Relationship between leaf area and basal diameter of its suckers; $p < 0.0028$.

The linear regression obtained ($R^2 = 0.6922$) was found to be statistically significant($p < 0.028$). Thus, the relationship was used to estimate the total leaf area of the canopy. Theregression between the sucker diameter and its subtended leaf area was applied to eachsucker in the plant. This allowed the total area of the individual plant to be determined (tab. 1).

**Table 1.** Estimated values of Leaf Area Index from circumference measurements and leaf area of individual suckers.

| Row-No.Tree (ID Plant) | Leaves per Sucker n. | Average Leaf Area (cm²) | Sucker Leaf Area (m²) | Mean Ø Sucker per Plant (cm) | Total Canopy Area of Single Tree (m²) | Projected Ground Area from CHM (m²) | LAI |
|---|---|---|---|---|---|---|---|
| 2-17 | 1179 | 53.10 | 6.26 | 4.62 | 27.32 | 3.50 | 7.80 |
| 11-3 | 1016 | 48.34 | 4.91 | 4.34 | 24.12 | 3.30 | 7.31 |
| 12-45 | 1375 | 49.84 | 6.85 | 4.86 | 30.06 | 2.00 | 15.03 |
| 15-14 | 729 | 47.58 | 3.47 | 2.79 | 12.72 | 1.61 | 7.88 |
| 17-6 | 1360 | 48.22 | 6.56 | 4.26 | 23.20 | 2.52 | 9.22 |
| 17-25 | 1307 | 43.49 | 5.68 | 4.58 | 26.86 | 2.85 | 9.43 |
| 27-34 | 798 | 38.67 | 3.09 | 3.62 | 15.89 | 1.82 | 8.73 |
| 34-19 | 753 | 51.52 | 3.88 | 3.86 | 18.63 | 1.16 | 16.01 |
| 6-6 | 720 | 51.12 | 3.68 | 2.51 | 9.52 | 2.12 | 4.48 |
| 17-20 | 1335 | 59.26 | 7.91 | 3.90 | 19.09 | 3.03 | 6.30 |
| Mean | 1057.2 | 49.11 | 5.23 | 3.93 | 20.74 | 2.39 | 9.22 |
| ±δ | 284.8 | 5.51 | 1.66 | 0.78 | 6.72 | 0.77 | 3.63 |

Finally, from the ratio of the plant's leaf area to its ground projection (PGA), the Leaf Area Index value was obtained. The results are shown in Table 1.

## 4. Discussions

The use of CHM is of paramount importance, as it allows to identify bodies above the ground level and to analyze only the vegetation of interest (in this case, the hazelnut tree canopies), and may therefore be used as a reference for the canopies obtained from NDVI. The NDVI method allowed a satisfactory delimitation of the canopies when a threshold value > 0.30 was used (R2 = 0.7241) due to the high performance of the drone used, shown from the analysis of predictive ability. In contrast, the measured PGA vs. CHM estimated with NDVI values > 0.35 manifested a lower correlation (R2 = 0.5162) due to the exclusion of canopy pixels with NDVI values between 0.30 and 0.35. Other authors studying different crops found similar results. Mu et al. [27], obtained time-series information using a similar method in the peach crop, based on gathered images using a digital surface model to measure the crown projection area, showing R2 = 0.88. In addition, in a blueberry bush [28], it showed R2 = 0.7. The ultra-high-resolution imagery collected with UAV systems helped identify and delineate each crown of trees individually from the background, according to Caruso et al. [17], even though the flight altitude was 120 m to capture the entire field.

### *4.1 LAI Measurement*

The average value of LAI in our study was about nine, while the leaf area per plant was 20 $m^2$. Farinelli et al. [29] Farinelli 2005 found that, in the variety Tonda di Giffoni trained with medium dense pruning and planted on a spacing of 5 m × 4.5 m, the leaf area per plant was 39.44 m2 for a twenty-year-old tree. However, Bignami et al. [8] showed that, in the absence of water stress, five-to-six-year-old plants of the variety Tonda Gentile Langhe spaced 4 m × 5 m and trained in a free vase, the leaf area per plant was 12.78 $m^2$. The value of the leaf area index is strongly influenced by the pruning system and the water availability, as observable by different studies. Bignami and Natali [9] reported LAI values between 2.39–5.21 and leaf area per plant between 0.35–6.24 for a two-to-three-year-old tree at the end of the growing season. The relationship between the basal diameter of the sucker and its leaf area with R 2 = 0.69 obtained can be compared with the results of the work conducted by Pisetta [30] on the branches of the vase bush in the variety Tonda Gentile Langhe, spaced 5 m × 5 m.

The latter work showed a quadratic relationship between the diameter at the base of the branches and the subtended leaf area, with R2 = 0.93.

**5. Conclusions**

The irrigation of hazelnuts is a recently introduced and expanding practice and it is important to know the parameters required for sustainable irrigation scheduling. This work shows how, in complex farming systems, the use of UAVs allows to work in this direction. This aerial system, equipped with a camera with spectral sensors, allows for the calculation and monitoring of biophysical and geometric parameters of the canopy such as leaf area index (LAI) and canopy volume. The hazelnut orchard under study was a way to see the possibility of rapidly calculating the projected canopy in the presence of grass cover using the NDVI method. The limitation of this work is related to only measuring the canopy edge in the top view, which means that errors will increase with overlaps between trees. This limitation was highlighted by Mu et al. [26], in the case of characterizing the canopy of a peach tree using UAV, and by Patrick and Li [27], who selected in their study non-overlapping canopies only. The analysis will be extended to adult orchards to build reliable relationships between NDVI and LAI and to evaluate their spatio-temporal evolution. This extension of time makes it possible to calculate another parameter such as growth rate, which showed differences in growth over time in peach plants [26]. This study confirms that morphological traits can be extracted from hazelnut trees using high-precision UAV images. The research should be extended to the definition of UAV-assisted procedures for estimating the volume of hazelnut trees; in fact, the crown volume/PGA ratio is another frequently used character in irrigation modeling.

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## Chapter 2 - Assessment of leaf water potential and stomatal conductance as early signs of stress in young hazelnut tree in Willamette valley

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**Abstract**

*Corylus avellana* L. is a species highly susceptible to water stresses caused by vapor pressure deficit and high temperature. Under such conditions, transpiration is strongly constrained even with good soil water availability. This is due to ineffective drought resistance mechanisms and indicates the need to identify early indicators of plant stress that are easy to measure, effective and efficient. This research explored the possibility of using stomatal conductance and leaf water potentials as early indicators of stress. For this purpose, an experiment was set up in a commercial 5-year-old *Corylus avellana* L. var. 'McDonald' orchard located in Willamette valley. The experimental designed featured irrigated and rainfed trees, and potential stress indicators were monitored at different times of the day in canopy sections aligned to cardinal directions.

Results show that hazelnut trees rapidly reduced leaf stomatal conductance when the vapor pressure deficit increased to 2 and 2.5 kPa during the diurnal cycle in both irrigated and rainfed trees, even with good water availability. This suggests leaf stomatal conductance can be an efficient and effective early indicator of stress. In addition, results suggest that stomatal conductance should be measured on leaves on the west and north aspects of the canopy, where they showed lowest and highest values respectively. Leaf and stem water potential values increased during the measurement period and show a strong correlation, but their mean values do not show statistically significant differences between treatments. In Willamette valley conditions, stomatal conductance provided earlier indication of stress than water potential. The results obtained are of methodological importance for the future design of experimental plans.

**Keywords**: *Corylus avellana* L., hazelnut, McDonald, soil water potential, leaf canopy aspects, water stress

## 1. Introduction

The hazelnut tree (*Corlyus avellana* L.) is a shrubby plant that grows native in deciduous forests of Europe and Western Asia as an understory species preferring upland areas shaded by tall trees (Del Favero, 2004; Kull and Niinemets, 1993; Kirchlechner, 1900). As an important tree nut worldwide, *C. avellana*, is cultivated in monocultural orchards in Mediterranean climates, including environments characterized by experience extremes of drought and heat during the growing season (Di Lena et al., 2022). Demand for increased production of hazelnuts has resulted in further expansion of plantings in less suitable environments. (Spiegel et al., 2020). Climate change is adding to the complexity with increases in mean temperatures and reduced rainfall in some production areas (IPCC, 2013; An et al., 2020). Recently, Vinci et al. (2023) showed how temperatures and water requirements have increased significantly in hazelnut orchards cultivated in central Italy over the past 47 years, resulting in decreased of chilling accumulation. To optimize sustainable production of hazelnuts, it is critical to understand and manage drought stress. Research indicates that even moderate vapor pressure deficit (VPD) has a strong influence on drought stress and stomatal activity of hazelnuts which in turn are likely to represent a major limitation on production. *Corylus avellana* L. is believed to be a water-saving species that takes advantage of low VPD values to optimize stomatal activity and carbon uptake (Trotter 1951; Baldwin et al., 2003; Pasqualotto et al., 2021). Practice of grafting help to tolerate climatic variations during the growing season in terms of carbon allocation and optimization of stomatal activity (Portarena et al., 2021). Hazelnut shows a conservative isohydric tendencies under stress conditions, with stomata closing early in response to increasing VPD, prioritizing water use efficiency at the cost of carbon assimilation for biomass production. Several authors consider *C. avellana* to be highly sensitive to water stress with low capacity for stomatal control (Girona et al., 1994; Cristofori et al., 2014). A study conducted on three different cultivars of *C. avellana*, including Tonda Gentile delle Langhe, Tonda Romana and Tonda di Giffoni, which are typical varieties representing different climatic conditions, indicates that stomatal conductance, and thus leaf gaseous exchanges, are mainly affected by VPD (Cincera et al., 2019). Photosynthesis decreased at high levels of VPD, even if the limiting factor was increased temperature. Stomata in cultivar Tonda Gentile delle Langhe were particularly sensitive to VPD, suggesting that it is poorly adapted to more xeric environments outside of the more moderate environment of its native area, and demonstrating that VPD sensitivity can differ between hazelnut cultivars. Schulze and Küppers (1979) affirmed that with severe VPD there is sudden stomatal closure and decrease assimilation rate in *C. avellana*. Tombesi et al. (1994) state that due to stomatal dysfunction in *C. avellana*, there is high transpiration loss during water stress conditions. The susceptibility of hazelnut to severe VPD is particularly evident in the summer period with dry, hot winds, which cause leaf edge burning (Baldwin et al., 2003). Different strategy could be used to limit leaf damage. Use of kaolin spray reduces leaf temperature without interfering on photosynthetic activity, stomatal conductance, and water use efficiency (Luciani et al., 2019a). Photosynthetic activity could be enhanced, using arbuscular mycorrhizal such as *G. iranicum*, during spring. The latter promotes leaf physiological performances during the summer and post-harvest until leaf fall (Luciani et al., 2019b) contributing to support roots growth during the fall season (Tombesi, 1979). Pasqualotto et al. (2018), found that in hazelnut the diurnal trends of stomatal opening reached a maximum very early in the morning (around 9 a.m.) and then strongly declined when the vapor pressure deficit exceeds 1 kPa, even when soil water is not a limiting factor. The transpiration process is restricted at certain VPD levels in *C. avellana*, even with optimal soil water content. Consequently, low relative air humidity, often combined with high temperatures and in the presence of intense solar radiation, reduces leaf transpiration and impacts the thermoregulation effect, explaining the severe burn damage to photosynthetic tissues under these conditions (Pasqualotto et al., 2016). Pasqualotto et al. (2021) compared the conductance at the canopy level of commercial *C. avellana* orchards to VPD in different countries found that canopy conductance was strongly dependent on the VPD. Maximum canopy conductance occurred within a VPD range of 0.35–0.57 kPa with a mean VPD of 0.57 kPa. Although optimal value of VPD conditions occurred on average at 1 kPa, there was high variability among sites based on climatic conditions indicating that plants had acclimated to the more extreme sites, modifying their response to climate. In addition, at different sites, the response of the tree canopy in terms of maximum conductance was influenced by the value of Leaf Area Index (LAI), which is a function of tree spacing and training shape. Orchards with higher LAI had higher maximum stomatal conductance values associated with higher yields (Pasqualotto et al., 2021). Aside from stomatal conductance, leaf water potential is an important index to evaluate the water status of plants (Jones, 1990; Koide et al., 1989). Knipfer et al. (2020), working in almond, walnut, and grapevine showed that the relationship between dawn and midday water potentials is predictive of stomatal closure and turgor loss under drought conditions. Shackel et al. (1997) found that daily changes in stem water potential in fruit trees under well-watered conditions correlate well with midday VPD, and that midday stem water potential is a reliable method for defining plant stress state. In *C. avellana*, the relationship between water potential and stomatal closure or reduction of gas exchange activity has been little investigated. Diurnal measurements of leaf water potential decreased linearly up to values of 1 kPa of VPD. However, when VPD exceeded values of 1 kPa no significant relationship between leaf water potential and VPD was shown, demonstrating an ability of the plant to maintain leaf water potential above a minimum threshold value, below which xylem cavitation could occur (Hogg et al., 2000). Furthermore, increased leaf mass area and leaf tissue density contributed to water stress resistance through increased resistance to physical damage caused by desiccation as found in hazelnut saplings (Catoni et al., 2017). Hogg et al. (2000) found an inverse relationship between stomatal conductance and vapor pressure deficit in beaked hazelnut (C. *cornuta* Marsh.) in the boreal forest, even when soil water was not a limiting factor. However, predawn leaf water potential value could be considered the best indication of the water status at the crop level (Chastain et al., 2014). At that time there is no transpiration, and the water potential is in equilibrium throughout the plant, so it can be considered equivalent to the soil matric potential sensed by the roots (Amèglio et al., 1994). In grapevine, leaf water potential at predawn, leaf water potential at midday, and stem water potential at midday were evaluated as equally representative evaluation methods of plant water status, showing highly significant linear relationships (R2 ranging from 0.85 to 0.92) with soil water content and leaf gas exchange, particularly for midday measurements of leaf gas exchange (Williams and Araujo, 2002). In contrast, in almond, walnut, and grapevine, a nonlinear relationship was shown between leaf water potential at predawn and midday (Knipfer et al., 2020) while a low correlation was found between leaf water potential and stem water potential in apple (Naor et al., 1995). Productivity and gas exchanges in the hazelnut cultivar Tonda di Giffoni, showed no significant changes up to threshold values of midday stem water potential between − 7 and − 10 bar, while threshold values below − 13 to − 16 bar showed improved water use efficiency but lower productivity and gas exchanges (Ortega-Farias et al., 2020). However, it remains unknown if plant water potential thresholds corresponding to stomata closure, and loss of leaf turgor can be predicted directly from plant water potential measurements. This would certainly allow for a more time-efficient and less labor-intensive evaluation of both physiological responses (Meinzer et al., 2016). Water shortage, by reducing photosynthetic activity, results in a decrease in water use efficiency. The latter decreases during the day and remains with constant values up to 60% of available water, after which it drops to lower values. Consequently, to maintain high foliar assimilation, soil water content must be above 60–65% of field capacity (Tombesi et al., 1994). Several papers indicate watering onset values between 50% (Cristofori et al., 2014) and 70% of available soil water, determined by gravimetric method. Irrigation for maximizing water conservation is based on direct measurement methods of soil and plant water status. The water status of plants and soils is often defined in terms of water potential (Levin and Nackely, 2021). Understanding of physiological limits of a crop provides crucial information on crop survival and performance and can help optimize irrigation. This study aimed to:

1) Study the ecophysiological response in irrigated and rainfed hazelnut trees during the 2022 summer season through measurements of stomatal conductance and plant water potential as early indicators of drought stress;

2) measure predawn leaf water potential, midday leaf water potential, and midday stem water potential to test the hypothesis that these are equally representative assessment methods of plant water status;

3) identify canopy exposures, according to the four cardinal points, that best express the plant's physiological response.

## 2. Material and Methods

### *2.1 Experimental design*

The experiment was conducted in a commercial hazelnut orchard in the Willamette Valley located at latitude of 442646.23 N 1231821.23 W, near the city of Corvallis, in Benton County, Oregon (USA), in July and August 2022 Due to continuous rainfall, it was not possible to start the trial before July.

The soil was a Woodburn silt loam (Soil Survey USDA, 2009) (supporting material - Table S1)) rated 65 on a 0–75 scale for suitability to hazelnut production based on texture, drainage, and depth of native productivity according to Olsen (2013). The Willamette valley area is characterized by Mediterranean-type climate with warm, dry summers and mild, but wet winters. The mean annual temperature is approximately 10 to 13 °C and receives consistent winter precipitation due to the westerly flow of Pacific storms. The mean annual precipitation is 1228 mm, ranging from 900 mm to 1600 mm in the mountainous foothills (Griffith, 2010). The experimental design featured three factors of variability: irrigation, leaf position in the canopy (aspect or side), and time of day. Irrigation featured two levels: irrigated and rainfed trees. Irrigation in irrigated trees was triggered when soil water potential sensors at 0–30 cm depth detected values between 80 and 90 kPa, as suggested by Irmak et al. (2016); Canopy aspect featured four levels: south, north, east, and west. Measurements were taken on leaf on five randomly replicated trees per treatment rainfed. Time of day was included for selected variables with levels specified in the following paragraphs. No rainfall was recorded during the experimental hazelnut trial, but soil matric potential was maintained near field capacity by irrigation. Rainfed plants were allowed to deplete water in the soil. The orchard was comprised of 5-year-old ’McDonald’ hazelnut trees (Mehlenbacher et al., 2016). The trees were trained on single trunk and planted 6 m between row and 3 m on the row, with a density of 555 trees per ha and north-south row orientation. Irrigation was applied between July 26 and Aug 21 (Table 1) with a drip system with one line per tree; drippers were placed 0.6 m apart, thus there were five drippers per tree. The theoretical flow rate was of 1.58 liter per hour and actual of flow rate 1.63 liter per hour. Ten random trees (Fig. 1) and plant characteristics were selected from an area within the orchard. Tree trunk diameter was normally distributed around a mean of 7 cm (Fig. 2), which was used to select trees with a 7 cm mean trunk diameter. For tree selection, trunk diameter was measured, by caliper, at 40 cm above the soil line, of 13 trees in each row from 32$^{nd}$ through 39$^{th}$, for a total of 104 trees, after discarding the first 4 border plants. This procedure allowed selection of five irrigated and five rainfed trees (green and yellow circles, respectively in Fig. 1) with statistically similar trunk size. These latter were deprived of irrigation by cutting the irrigation tubing at adjacent trees (indicated as yellow cross in Fig. 1) and splicing in blank tubing. Environmental variables were collected from the weather station nearest to the experimental field, located in Corvallis (https://www.usbr.gov/pn/agrimet/agrimetmap/crvoda.html). In addition, throughout the study period air temperature, relative air humidity and dew point were recorded every five minutes by a portable data logger (Kestrel DROP D2®).

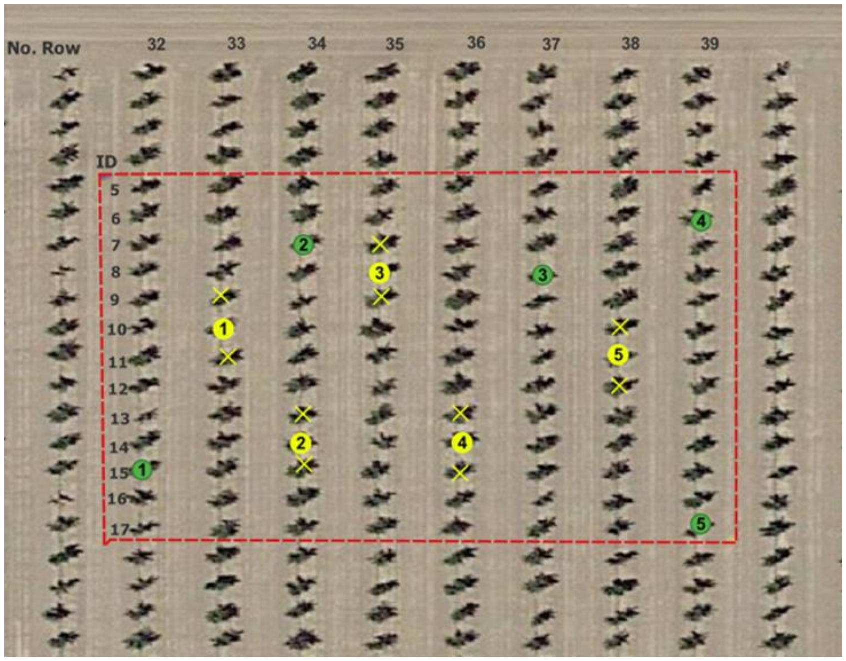


**Figure 1**. Irrigated and rainfed trial treatment, green and yellow points respectively, yellow cross indicate the tress deprived of irrigation water.

**Table 1**. Watering days of July and August

| Date watering | Irrigation hours | Liter per tree | $m^3$/ha |
|---|---|---|---|
| 26-Jul | 16 | 126.4 | 70.2 |
| 29-Jul | 6 | 47.4 | 26.3 |
| 30-Jul | 10 | 79 | 43.8 |
| 6-Aug | 10 | 79 | 43.8 |
| 13-Aug | 8 | 63.2 | 35.1 |
| 17-Aug | 5 | 39.5 | 21.9 |
| 21-Aug | 12 | 94.8 | 52.6 |
| **Sum** | | **529.3** | **293.8** |
| **Mean** | | **75.6** | **42.0** |

2.2. Measurements

*2.2.1. Soil water status*

Soil water status was monitored with resistance-type sensors, that measuring soil matric potential, Watermark® Granular Matrix model 200SS (Irrometer, Co., Riverside, California). The range of matric potential, measured by portable handheld meter is from 0 to 200 kPa, where 0 means saturated soil and 199 dry soil (www.irrometer.com). The sensors were tested before installation, following the manual's procedure. They were tested through two cycles of wetting and drying, soaking in water overnight and next day air drying. After sensors soaked in water, the handheld meter read values between 0 and 5 kPa and after air drying the reading had to greater than 150 kPa. Re soaking the sensor back in water, readings had to return below 5 kPa within 2 min. Just prior installation in the soil, the sensors were soaked in water for 30 min because wetting improves the response time by removing the air inside them (Irmak et al., 2016). The sensor's cables were put into PVC pipe which facilitates installation to the desired depth in soil. The depth of sensors was chosen considering the root zone depths which were between 40 and 60 cm. The sensors were placed in the root zone at three depths, 30, 60 and 90 cm at 20 cm away from the trunk in a triangular pattern, using a slide hammer to pilot holes in the soil. Sensors were installed for each selected irrigated or rainfed tree in the trial. Readings by portable meter were punctual and were taken at least once every other day from July 1 to August 25, 2022.

*2.2.2. Leaf stomatal conductance*

Stomatal conductance of leaves was measured using portable automatic diffusion porometer (Delta-T AP4, Delta-T Devices, Cambridge, UK). Measurements were made on fully expanded, mature and wellexposed leaves of the ten trees, measuring one leaf for each cardinal direction. Data collection started on July 26th with four measurements per day: in the morning between 8 and 9 am (a), between 10 and 11 am (b), between 12 and 1 pm (c) and from 2 pm onward. All the readings were accomplished in around 45 min to minimize variation of water status of leaves. The porometer was calibrated using the calibration leaf, before each measurement cycle, or otherwise whenever the display indicated the need for calibration, as recommended by the manual. Three measurement cycles were carried out: the first at the start of irrigation from July 26 to 30, followed by the second measurement cycle from August 4 to 6, and finally the third cycle from August 14 to 18.

*2.2.3. Plant water status: leaf and stem water potential*

The measurement of plant water status included measurement of Predawn leaf water potential (ΨPD), Midday leaf water potential (ΨML) and Midday stem water potential (ΨMS). Plant water potential readings were conducted according to the procedures of Padgett-Johnson et al. (2000) and Koide et al. (1989), using a pressure chamber (model 3005H07G4P40, Soil Moisture Equipment, Santa Barbara, Calif.). ΨPD measurements started at 4:00 am and were finished before sunrise, which started on July 1, at 5.32 am; ΨML and ΨMS occurred between 12:00 pm and 15:30 pm, Pacific Daylight Time, starting with ΨML and after ΨMS, considering that solar midday occurred at 13.15 pm (https://www.timeanddate.com/sun/@7173236). Leaves chosen for ΨPD, ΨML and ΨMS were fully expanded, mature and well-exposed leaves, taken from the same bough. At 10 am, for midday measurements only, leaves for determination of ΨMS were enclosed in aluminum bags and quickly sealed with zipper closure for 2 h prior to excising. Petioles were cut by razor blade and the time between leaf excision and chamber pressurization was generally < 10 to 15 seconds. For each tree, all measurements were conducted on four leaves, each for a cardinal direction. Thus, in total, 20 leaves per irrigated treatment and 20 leaves per rainfed trees. Measurements of ΨML and ΨMS started on July 13th and were conducted on the same days, while for five days all three potentials were conducted including ΨPD (supporting material - Table S2).

## 3. Statistical analysis

The experimental data were analyzed statistically by R software version 4.2.1 (R Core Development Team, 2022). Data were subjected to factorial analysis of variance (ANOVA) with interactions. Factorial design was used to test the following effects: irrigation treatment, canopy aspect, and interactions. Time of day and relevant interactions was also considered for selected variables: stomatal conductance, leaf and stem water potential. Following significant ANOVA, significant differences between treatment levels for different times of day and in the four aspects of canopy leaves were evaluated with Tukey's honestly significant difference (HSD) test (α = 0.05). Finally, a regression analysis was performed to determine the relationship between midday leaf and midday stem water potential.

## 4. Results

### *4.1. Environmental conditions*

Environmental parameters were collected from May 1 to October 31, and values are shown in Figs. 2 and 3. Precipitation at the study site just before the start of the trial occurred mainly in May and June, amounting to 162.3 mm and 37 mm in September and October (Fig. 2). The average maximum and minimum temperatures were 24.7 ± 6.4 and 10.5 ± 3.5 ◦C, respectively. Average daily temperatures since June 25 have exceeded 30◦C when daily humidity also decreases showing values below 80 %, with an average of 65.3 % from June 25 to August 31 (Fig. 3). Thereafter irrigation was triggered at times of high evapotranspirative demand and no precipitation when measurements were taken (Fig. 3).

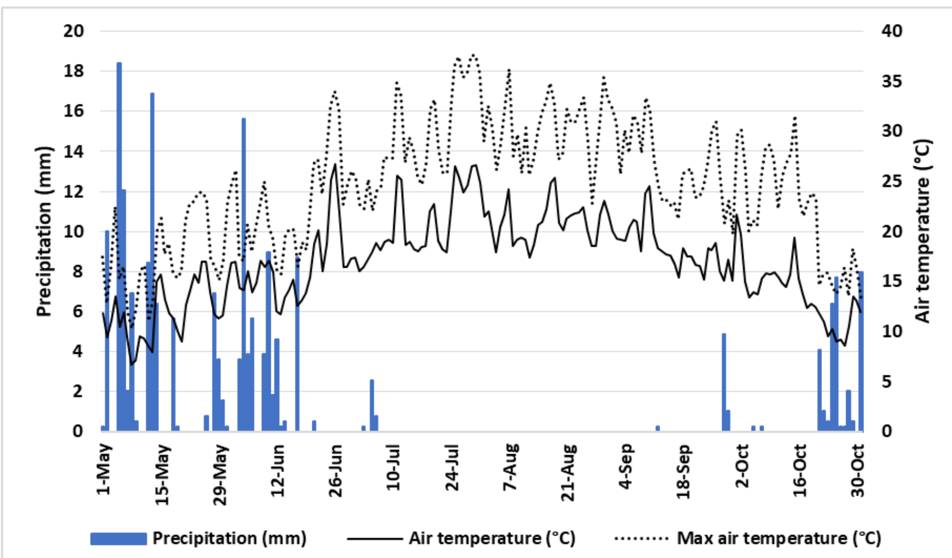


**Figure 2**. Daily precipitation (mm), air temperature and maximum air temperature (°C).

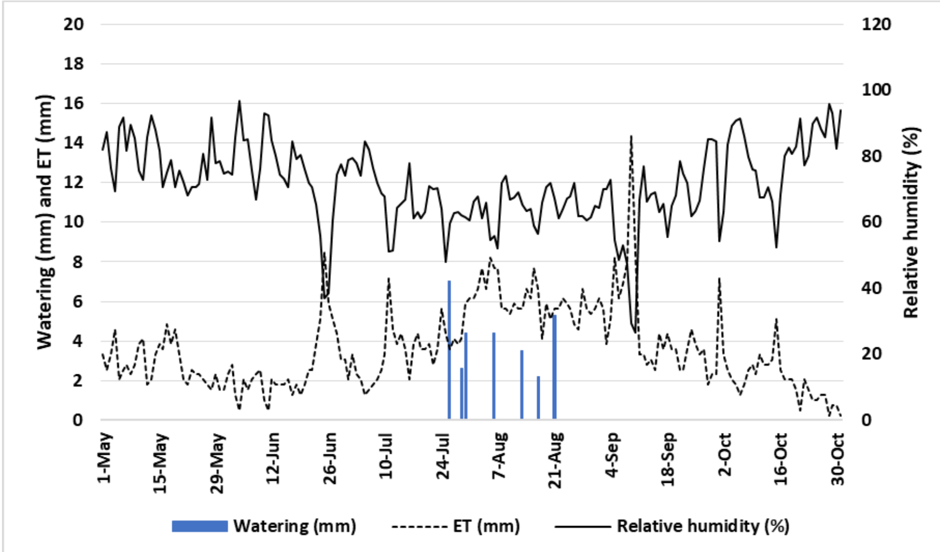


**Figure 3**. Daily watering (mm), ET (mm) and relative humidity (%).

*4.2. Soil water status*

Figs. 4 and 5 show the average soil matric potential values of the five trees at 30, 60 and 90 cm depth. The mean values of soil matric potential decreased rapidly in irrigated trees starting July 26 when irrigation was triggered. At the depth of 30 cm matric potential drops from 160 to 70 kPa, while at 60 cm the response was slower, in fact after about three days a potential of 80 kPa was measured. At the latter depth, the trend in water potential remains consistently higher than at 30 cm. At the depth of 90 cm soil matric potential was almost constant recording average values of 50 kPa (Fig. 4). In rainfed trees, soil was dried down gradually during the experimental period, as shown by the increase in the average values of soil matric potential, considering that the maximum reading of the instrument was 200 kPa. At depths of 30 and 60 cm average values above 190 kPa were reached on August 4, thus leading to possible crop stress conditions. In contrast, at the depth of 90 cm, values of matric potentials stayed lower during the experimental period and did not go beyond about 90 kPa (Fig. 5).

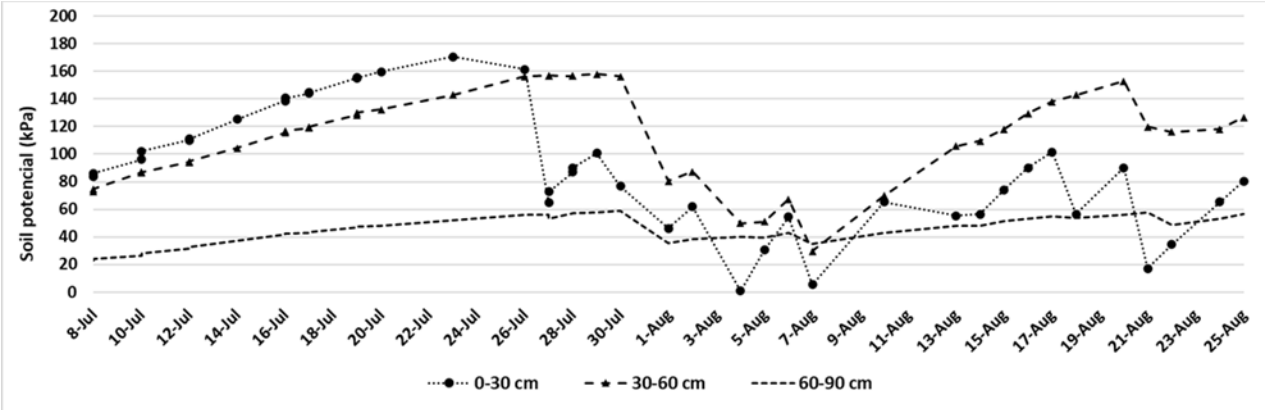


**Figure 4**. Average soil matric potential values of the five irrigated trees for each depth.

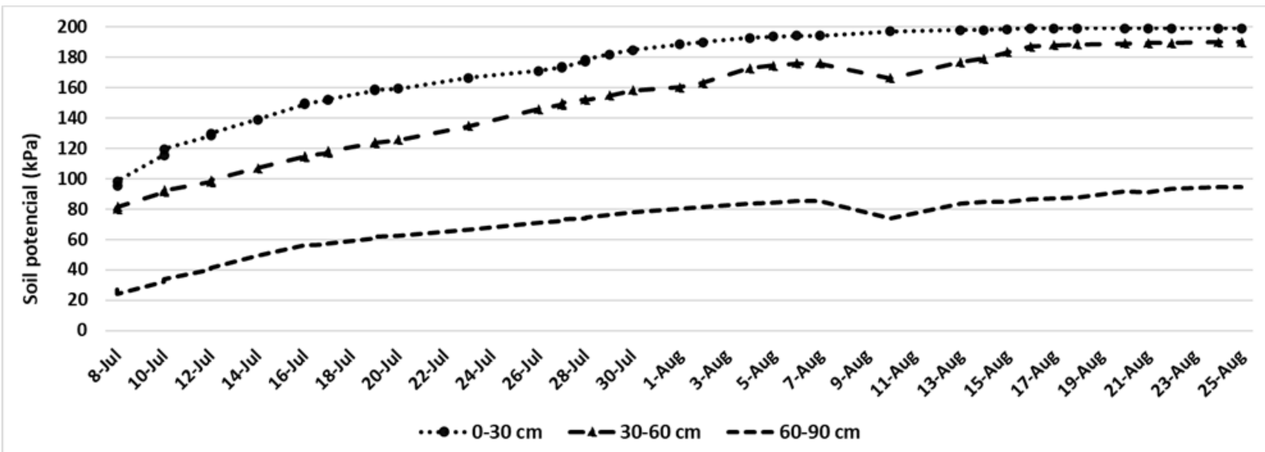


**Figure 5**. Average soil matric potential values of the five rainfed trees for each depth.

*4.3. Leaf stomatal conductance*

Results of factorial ANOVA for stomatal conductance in the first (26 to 30 July), second (4 to 6 august) and third cycle (14 to 18 august) by treatment, time slot, leaf position in the canopy (aspect) and interactions are reported in supporting material - Table S3. The time slots refer to four different measurement times, during the day, corresponding to 8–9 a.m. (a), 10–11 a. m. (b), 12–1 p.m. (c) and from 2 p.m. (d). In all measurement cycles, the parameters analyzed, such as treatment, timeslot, and aspect, were significant at $\alpha < 0.05$. Timeslot - aspect interaction is significant in all cycles, while treatment - side interaction is significant in third cycle only. Mean values of leaf stomatal conductance were 0.28 and 0.35 mol $m^2$ $s^1$ in rainfed and irrigated treatment respectively. There was a gradual divergence between irrigated and rainfed trees in stomatal conductance from the first to the third cycle (Fig. 6). In the first measurement cycle, July 26 to 30, statistically significant differences in average conductance values were recorded in the last day of the cycle only. In the second and third cycles statistically, significant differences are evident in all days. In the second cycle of measurement, values of 0.25 and 0.32 mol $m^2$ $s^1$ were found in rainfed and irrigated trees respectively, while in third cycle 0.23 and 0.36 mol $m^2$ $s^{1.}$ Maximum mean values of stomatal conductance ranged between 0.32 mol $m^2$ $s^1$ in rainfed conditions and 0.54 mol $m^2$ $s^1$ in irrigated conditions respectively. Stomatal conductance takes values above 0.35 mol $m^2$ $s^1$ when VPD is below 2.3 kPa. Above that threshold value, stomatal conductance values decrease over time. VPD and stomatal conductance, are negatively correlated as shown in Fig. 7. Values from all cycles of measurement were significantly different according to Tukey's test at $\alpha < 0.05$ for irrigation treatments rainfed, time slots (a: 8–9 a.m.; b: 10–11 a.m.; c: 12–13 a.m.; d: from 2 p.m.), and canopy aspect. The interaction, irrigation × aspect, was significantly different only in the third cycle. Regarding time slots, the mean values of stomatal conductance showed significantly higher values in a and b, followed by c and d of the first and second cycles (Figs. 8b and 9b). In the third cycle, time slot d showed significantly lower values than other treatments (Fig. 10b). In the first cycle mean values showed significantly highest value for the north side, followed by east and south which were not significantly different between each-other. Lowest values were found in the west side. (Fig. 8c); in the second cycle, the north and south sides showed higher values than east and west (Fig. 9c) and in the third cycle the north side was significantly highest (Fig. 10c). The time slot - leaf orientation interaction, in all three cycles, showed in time slot d lower mean values of stomatal conductance and statistically significant differences. (Fig. 8d, 9d, 10d). The lowest values of stomatal conductance are recorded in the west side of all timeslots and the highest values in the north side. The treatment - leaf orientation interaction showed statistically significant differences in the dry and irrigated treatments of the third cycle (Fig. 10e).

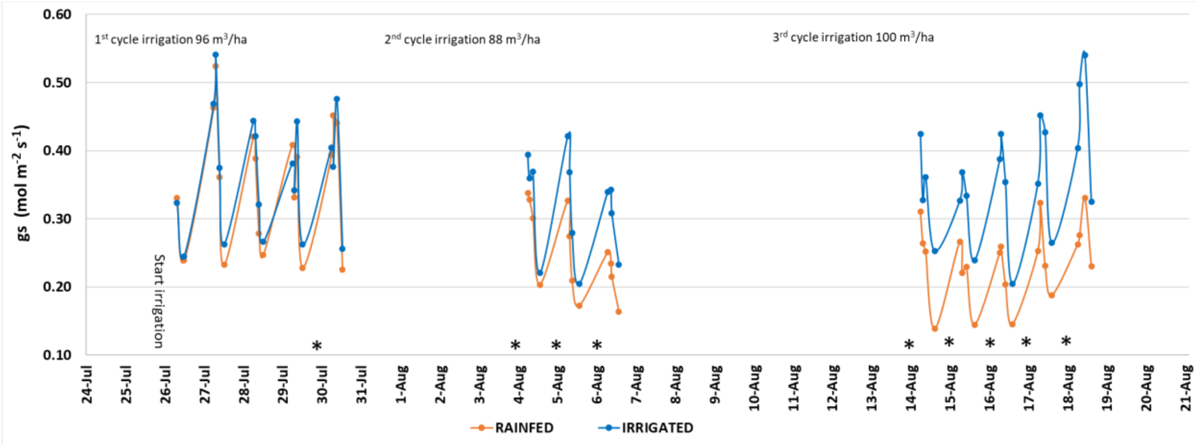


**Figure 6**. Stomatal conductance ($\mathbf{g_s}$) trend in rainfed and irrigated trees in first, second and third measurement cycle. Days marked by asterisk differed significantly according to Tukey's test at $\alpha < 0.05$.

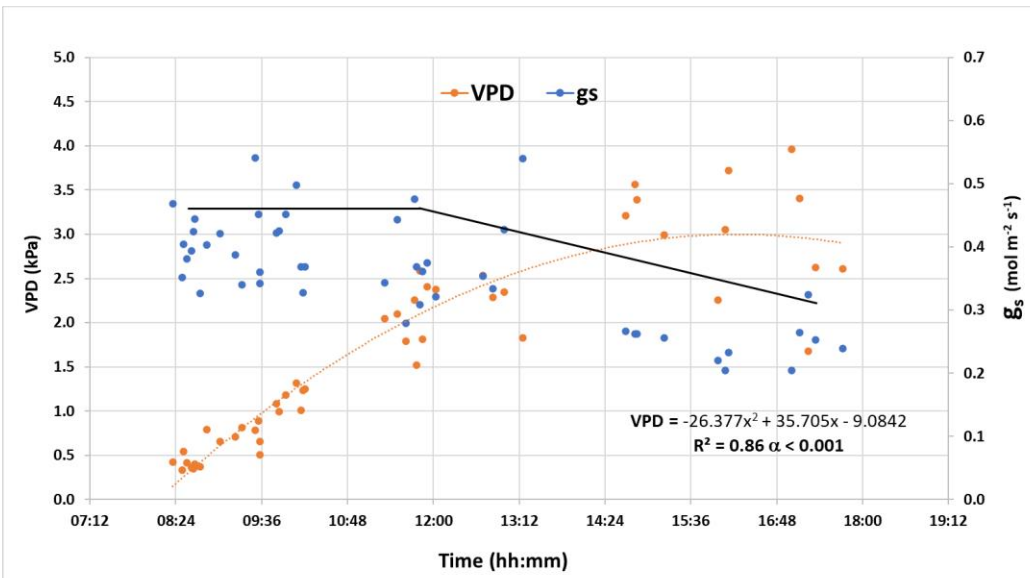


**Figure 7**. Relationship between vapor pressure deficit (VPD) and stomatal conductance ($g_s$) over the diurnal cycle. Solid black line indicates at VPD values of 2.3 kPa the $g_s$ begin to decrease.

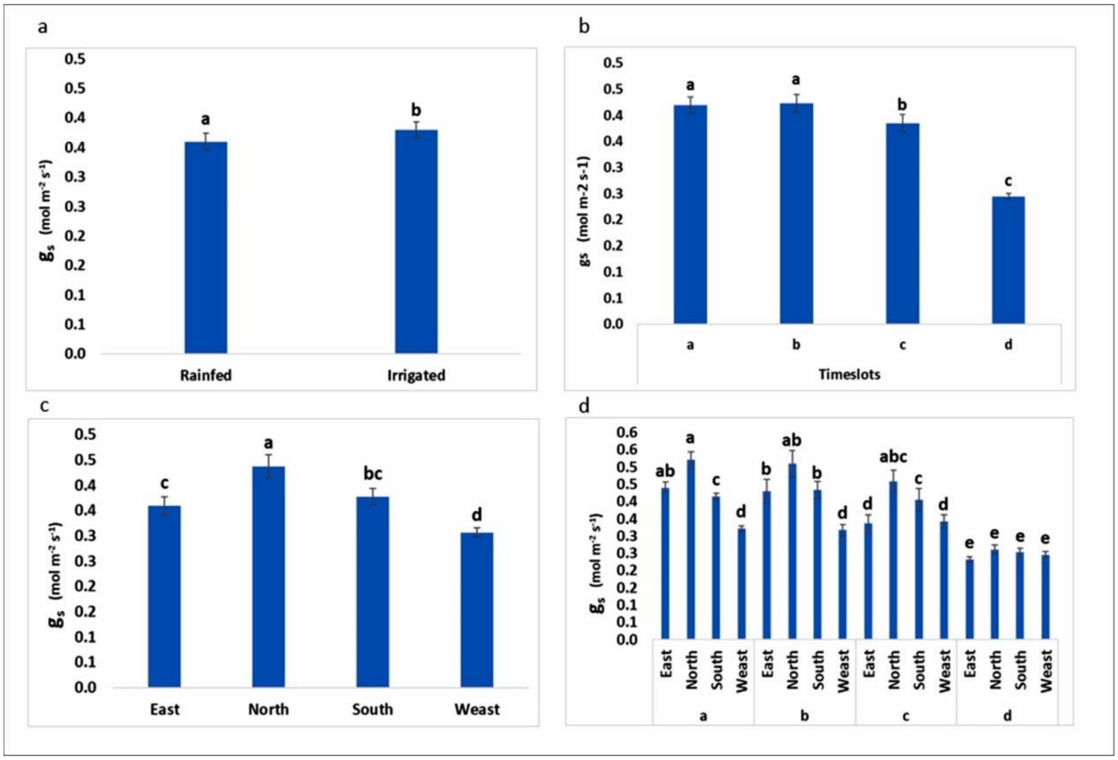


**Figure 8.** First cycle: a) leaf stomatal conductance in rainfed and irrigated trees; b) measurements of leaf stomatal conductance in different time slots (a: 8–9 a.m.; b: 10–11 a.m.; c: 12–1 p.m.; d: from 2 p.m.); c) measurements of leaf stomatal conductance in four aspects of leaves canopy; d) interaction timeslots-side. Values with different letters significantly differ according to Tukey's test at α < 0.05 and standard error bars.

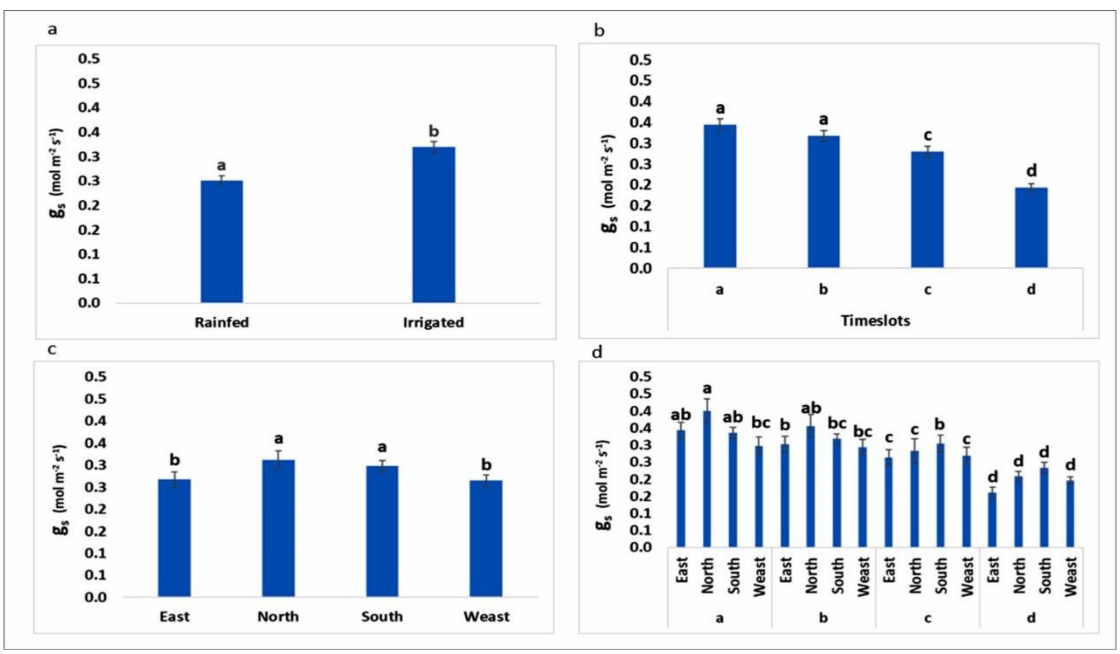


**Figure 9**. Second cycle: a) leaf stomatal conductance in rainfed and irrigated trees; b) measurements of leaf stomatal conductance in different time slots (a: 8–9 a.m.; b: 10–11 a.m.; c: 12–1 p.m.; d: from 2 p.m.); c) measurements of leaf stomatal conductance in four aspects of leaves canopy; d) interaction time slots-side. Values with different letters significantly differ according to Tukey's test at α< 0.05 and standard error bars.

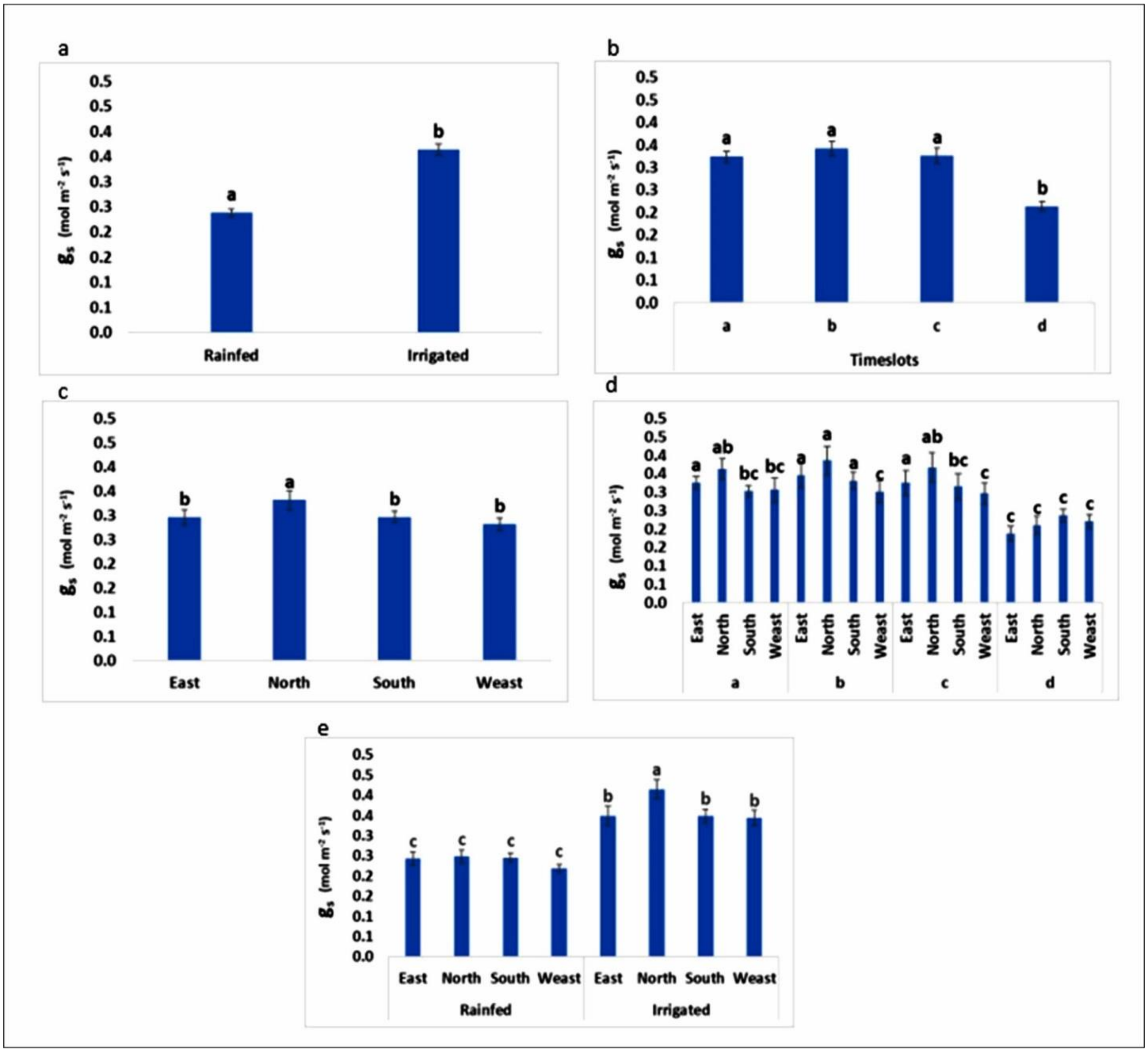


**Figure 10.** Third cycle: a) leaf stomatal conductance in rainfed and irrigated trees, with standard error bars; b) measurements of leaf stomatal conductance in different time slots (a: 8–9 a.m.; b: 10–11 a.m.; c: 12–1 p.m.; d: from 2 p.m.); c) measurement of leaf stomatal conductance in four aspects of leaves canopy; d) interaction time slots-side; e) interaction treatment-side. Values with different letters significantly differ according to Tukey's test at $\alpha < 0.05$.

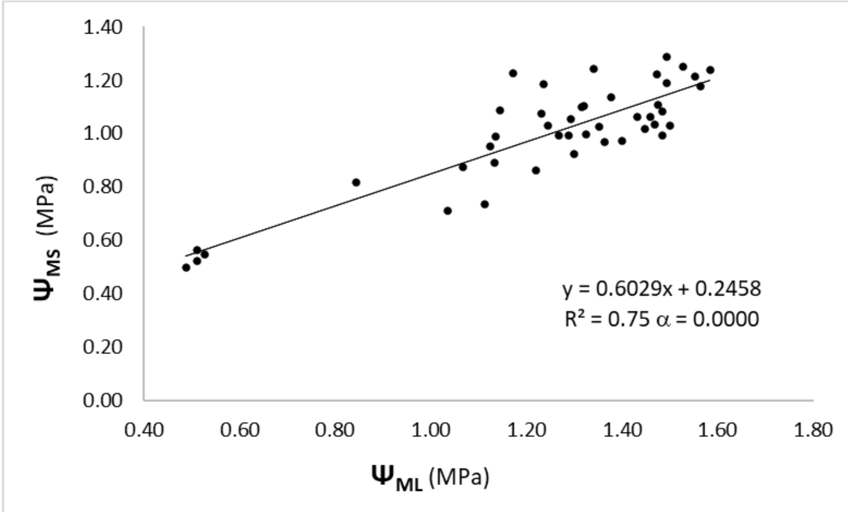


**Figure 11**. Relationship between $\Psi_{MS}$ (midday stem) and $\Psi_{ML}$ (midday leaf) in 'McDonald' hazelnut. Each point is the average of four leaves in the canopy.

*4.4. Leaf water status: leaf and stem water potential*

ΨPD, ΨML and ΨMS were measured from July to August 2022 (Table S2). ΨPD showed relatively constant values in irrigated and rainfed trees (Figure S1). The average values were 0.14 and 0.16 MPa, respectively. Table 2 shows the average values of ΨPD per each day of measurements with dew temperature and dew persistence time on leaves. ΨML, and ΨMS instead, showed a slight increase over time. The ΨML showed average values of 1.27 MPa in rainfed trees and 1.30 MPa in irrigated trees, while the same mean value of 1,00 MPa was obtained for ΨMS in both treatments. ΨML values were always higher than the ΨMS. The regression equation in Fig. 11, between ΨML and ΨMS showed a positive relationship (R2 0.75; α=0.0000). The results indicate that the two methods are linearly and positively related to each other. The ANOVA results for ΨPD, ΨML and ΨMS in the measurements of the first (July 26–30), second (August 4–6) and third cycle (August 14–18) of treatment (irrigated and rainfed trees), leaf orientation on the canopy (side) are shown in supporting material - Table S4. The effects of all factors tested, treatment, side and interactions assumed different behavior compared to results obtained for stomatal conductance. In the first cycle of measurements, no statistically significant differences were found in any of the factors tested. Statistically significant differences occurred in the second and third cycle. Significance statistically differences occurred in the treatment in second cycle of ΨML and in third cycle of ΨMS and ΨPD. Differences between aspects were found in the second and third cycle of all potentials.

In ΨML rainfed and irrigated trees showed a value of 1.31 and 1.40 MPa respectively (Fig. 12a). The ΨML values, in second cycle for the side were ranked as follows: South (1.49 MPa) > East (1.39 MPa) > West (1.32 MPa) > North (1.23 MPa) (Fig. 12b). Instead, in third cycle south (1.53 MPa) and west side (1.52 MPa) showed highest mean values than east (1.39 MPa) and north (1.36 MPa) side (Fig. 12c). The ΨMS mean values, in rainfed and irrigated trees, in the third cycle, were 1.12 and 1.02 MPa respectively (Fig. 13a). West (1.13 MPa) and south (1.10 MPa) values were highest and statistically different, than east (1.01 MPa) and north (1.01 MPa) side, in second cycle (Fig. 13b). In the third cycle west side leaves showed a value of 1.15 MPa which was significantly different from all other orientations (Fig. 13c). In the third cycle of ΨPD mean value were significantly higher in irrigated rainfed trees (Fig. 14a). Leaves orientation, in second cycle, were ranked as follows: South (0.15 MPa) > West (0.14 MPa) > North > (0.13 MPa) > Est (0.11 MPa) (Fig. 14b). In the third cycle the North side showed a value of 0.06 MPa which was significantly lowest than all other orientations (Fig. 14c).

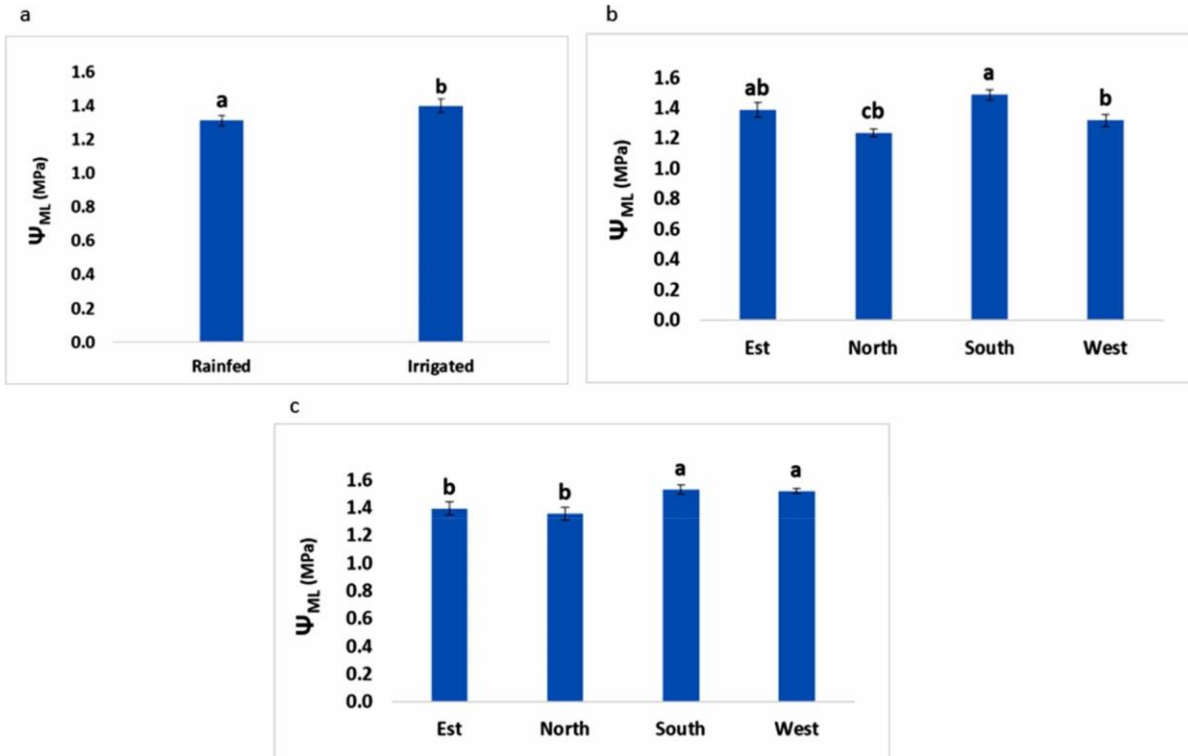


**Figure 12**. ΨML: a) rainfed and irrigated trees in second cycle,; b) leaves canopy aspects in second cycle; c) leaves canopy aspects in third cycle in rainfed and irrigated trees, with standard error bars Values with different letters significantly differ using Tukey's test at $\alpha < 0.05$.

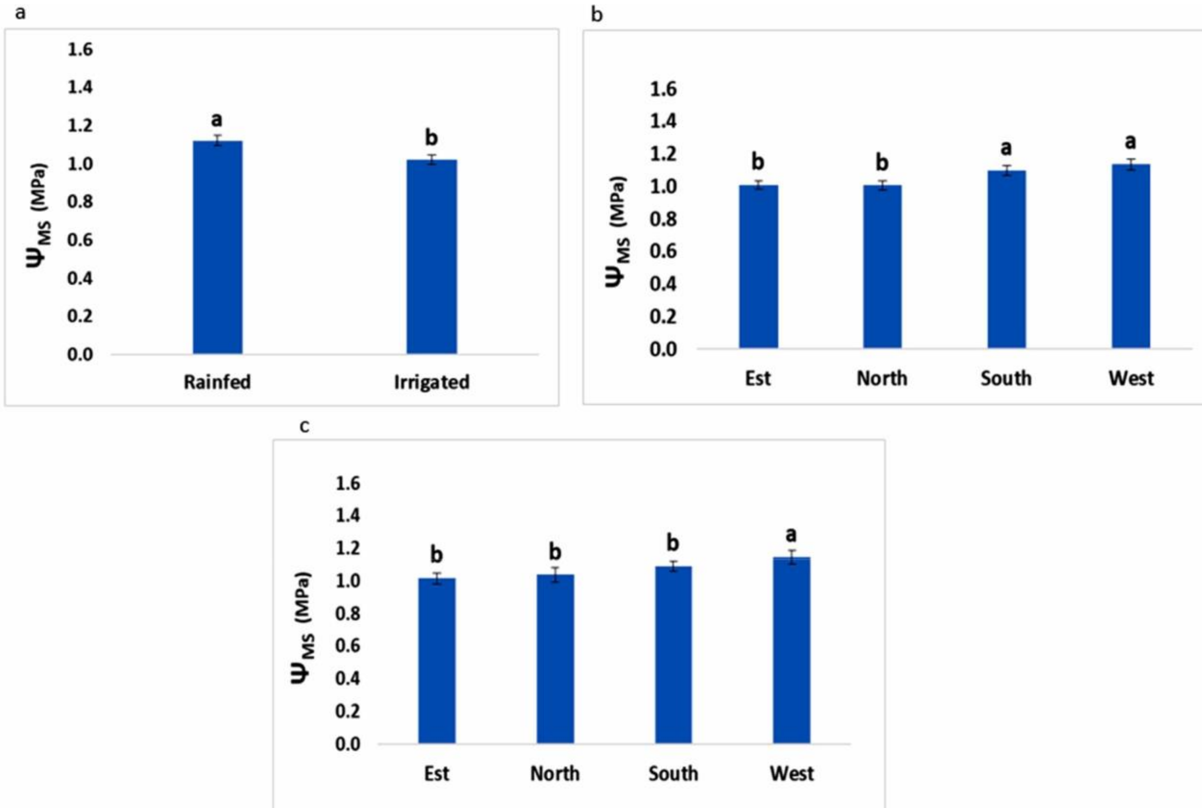


**Figure 13**. ΨMS in a) rainfed and irrigated trees in third cycle; b) Aspects of leaf of the canopy in second cycle and c) third cycle. Values with different letters significantly differ using Tukey's test at α < 0.05 and standard error bars.

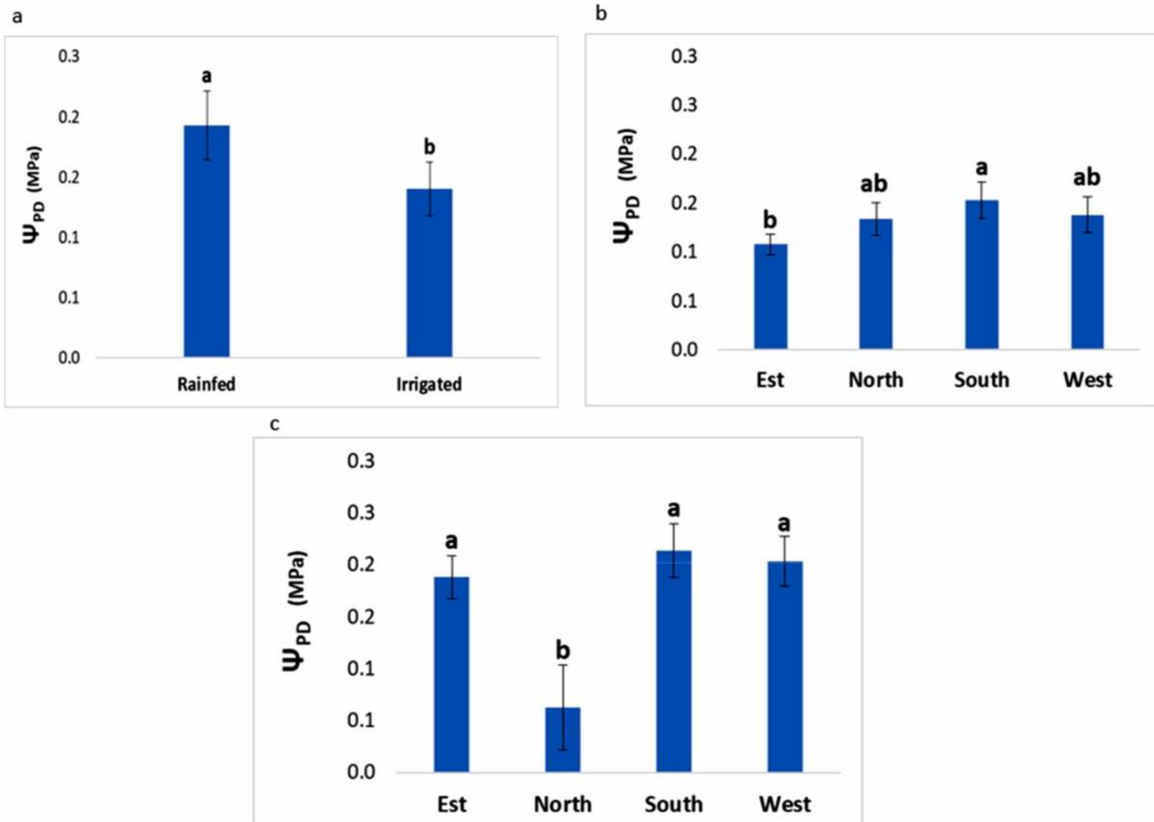


**Figure 14.** $\Psi_{PD}$ in a) rainfed and irrigated trees in third cycle b) Aspects of leaf of the canopy in second cycle and c) third cycle. Values with different letters significantly differ using Tukey's test at $\alpha < 0.05$ and standard error bars.

**Table 2**. Date, average values of ΨPD (MPa), daily maximum temperature, temperature at dew point (°C) and dew hours.

| Date | $\Psi_{PD}$ (MPa) | Maximum temperature daily (°C) | Dew point Temperature (°C) | Hourly dew interval | Dew hours |
|---|---|---|---|---|---|
| 17-Jul | 0.22 | 26.9 | 11.5 | 2 a.m. to 6 a.m. | 0 |
| 19-Jul | 0.11 | 29.8 | 11.0 | 3 a.m. to 7 a.m. | 4 |
| 20-Jul | 0.06 | 35.1 | 12.5 | 3 a.m. to 7 a.m. | 4 |
| 4-Aug | 0.09 | 37.7 | 10.2 | 1 a.m. to 6 a.m. | 6 |
| 5-Aug | 0.14 | 33.5 | 9.1 | - | 0 |
| 6-Aug | 0.13 | 36.6 | 10.0 | 3 a.m. to 7 a.m. | 4 |
| 21-Aug | 0.22 | 33.8 | 12.2 | 12 a.m. to 8 a.m. | 8 |
| 24-Aug | 0.11 | 36.6 | 12.8 | 12 a.m. to 8 a.m. | 8 |

## 5. Discussions

### *5.1. Stomatal conductance*

Stomatal conductance, in hazelnut trees, responds rapidly to induced stress, even if mild, and can be considered an indicator for detecting early signs of stress. The differences between rainfed and irrigated trees were already evident in the first cycle of measurements, four days after irrigation started. As irrigation continued, the differentiations between the two treatments became more evident. In addition, from a methodological point of view, the study of measurements taken on the four sides of canopy aspects and the timeslots are highly relevant. The north and west canopy aspects were detected for the first time, with higher and lower values, respectively, that best express the plant's physiological response in terms of stomatal conductance. The highest values of stomatal conductance were reached in the morning until 11 a.m. and from midday, the values decreased, in agreement with the findings of Pasqualotto et al., 2018 and Ozmen ¨ (2016). The average stomatal conductance decreased when VPD values reached 2–2.3 kPa from midday, while Pasqualotto et al., 2018 reported values of 1.5 kPa. Thereafter, the decrease in transpiration is driven by the decrease in VPD in accordance with findings in hazelnut (Girona et al., 1994; Tombesi, 1994; Hogg et al., 2000; Pasqualotto et al., 2018) and in other species such as olive tree (Moriana et al., 2002) pine, (Awada et al., 2002) and rose (Samartzidis et al., 2005).

### *5.2 Leaf and stem water potential*

Predawn leaf water potential, leaf water potential at midday, and stem water potential at midday can be used as indicators for the plant and soil water status (Koide et al., 1989; Am`eglio et al., 1994 ; Naor, 2000; Williams and Araujo, 2002 ; Chastain et al., 2014; Knipfer et al., 2020). In the analysis by factorial ANOVA, potentials do not show statistically significant differences in all cycles. This explains that differences between treatments in water potentials could occur with more severe water stress conditions. Besides, hazelnut needs about 800 mm of precipitation distributed throughout the year (Cristofori et al., 2014) and, in this study 20% of the rainfall fell down in May and June contributing to soil moisture reserve as also observed by Ozmen ¨ (2016). In fact, soil matric potential soil didn't reach a high value in rainfed trees at maximum survey depth. This indicates that the triggering of irrigation did not have much influence on soil matric potential at this depth. Ortega-Farias et al. (2020) found no significant differences, particularly for stem water potential, at the beginning of the water restriction period, but differences became clear about a week later. However, water potential does not depend only on soil water content but is affected by the environment in which the plants are located and their interactions with the environment (García-Tejera et al., 2021). In our study, drought stress may not have been severe enough to show clear differences between water potential in irrigated compared to rainfed trees. The evaporative demand of the environment and the transpirative activity of leaves have resulted in ΨML measurements higher than ΨMS to maintain the potential gradient of the soil-plant-atmosphere system. In fact, ΨML reached average values of 1.3 MPa versus 1.0 MPa of the ΨMS. Measured values of ΨML showed a general enhancement during the measured period in accordance to Ozmen ¨ (2016) in rainfed hazelnut trees. ΨML and ΨMS, show a strong correlation with each other, which is the reason why they could be used indiscriminately to define hazelnut water stress reference values, as also demonstrated by Williams and Araujo (2002) in grapevine. However, considering that the hazelnut is very sensitive to the evaporative demand of the environment, independently of soil water availability (Pasqualotto et al., 2018), it is preferable to use ΨMS which it less variable than ΨML to environmental conditions, as highlighted by McCutchan and Shackel (1992) and Naor (2000) in fruit trees. The average values of ΨPD are very low in rainfed and irrigated trees, 0.16 and 0.14 MPa, respectively. Data from the literature suggest ΨPD values between 0.1 and 0.42 MPa (Marsal et al., 1997; Girona et al., 1994) 0.4 and 0.9 MPa (Awada, 2007). The low ΨPD values found in this study were associated to the frequent reaching of the dew point, which led to water condensation on the leaves. In fact, our study, on days of ΨPD measurement, were reached lasting conditions of presence of dew, probably responsible of leaf water recovery. Burgess and Dawson (2004) state that leaf wetting events, especially in plants with weak stomatal control, could help restore the amounts of water lost in the previous day and thus suppress leaf water loss. Occult water, absorbed by leaves, may play an important role in plant physiology (McHugh et al., 2015; Tomaszkiewicz et al., 2015). Fog water absorbed by leaves and transported to the xylem improved leaf water potential, photosynthesis, stomatal conductance and growth compared to plants unexposed to fog water (Eller et al., 2003). This indicates that occult moisture, typical of specific environments, such as Willamette Valley, interacts with plant physiology and this would allow plants such as hazelnut, originally an understory plant, to take advantage of such events in overcoming heat and drought stress, especially in the early part of the day. This phenomenon should be investigated in hazel because although there is much work supporting uptake through the leaf surface of occult moisture and mist water, it does not represent the main pathway for leaf water uptake among all species (Berry et al., 2019). Soil water potential and leaf water potential could not be related because of the limitation of the instrument's measurement, which was up to 200 kPa. Although the induced water stress was mild during the experimental period, the increase in water potential over time suggests that, under those environmental conditions, it is due to the evaporative demand of the environment independent of soil water availability.

**6. Conclusions**

The application of water stress, although mild, resulted in large differences in hazelnut trees physiological behavior. Water potential and stomatal conductance showed different sensitivity in establishing the response to stress of trees under irrigated and non-irrigated condition. Leaf conductance measurements were found to be useful, easy to interpret and extremely sensitive, compared to leaf and stem potential measurements, because of the ability of the hazelnut trees to regulate stomatal opening under mild stress conditions. Hence, this study indicates leaf conductance as a potential early indicator of stress. Besides, data show that stomatal conductance should be measured in the north and west aspects which assume the highest and lowest of the range, respectively. Time of day also plays a key role in the measurement of plant stress. Measurements from 11 a.m.- 12 p.m. are more appropriate for detecting stress conditions. Unlike stomatal conductance, however, water potential does not show a rapid response to stress, so it may not be considered in this study as a method to detect early signs of stress. Results show that there are no statistically significant differences, between the mean values of ΨML, ΨMS and ΨPD in irrigated and rainfed trees, in the second and third measurement cycles. No differences were found between the different canopy leaves orientations on which measurements were taken. However, the northeast and southwest sides showed similar behaviors, with lower and higher mean values, respectively. Based on the results, we suggest that further research is needed on the usefulness of water potentials as early indicators of water stress in hazelnut, since in our data differences between irrigated and rainfed treatments only occur when the stress becomes significant. Furthermore, the high positive correlation between leaf and stem water potential connotes them as equivalent methods for measuring plant water status. From a methodological point of view this research fills a gap in knowledge relative to the hazelnut about the variability in potential and stomatal conductance response related to canopy aspect. Leaf stomatal conductance showed different responses in relation to leaf location on the canopy, and the North and West positions showed to represent the extreme values in all measurement cycles. This may guide measurements on trees if the focus is investigating areas with major differences in physiological responses. Further studies on the role of hidden precipitation water absorbed by leaves in hazelnut, especially in areas with large temperature excursion, would be useful.

## Supporting materials

**Table S1**. Soil texture (Soil Survey USDA, 2009)

| Horizont (cm) | Texture |
|---|---|
| 0-23 | silt loam |
| 23-43 | silt loam |
| 43-63,5 | silty clay loam |
| 63,5-81 | silty clay loam |
| 81-100 | silt loam |
| 100-137 | silt loam |
| 137-173 | silt loam |
| 173-203 | stratified fine sandy loam to silt loam |
| 203-233 | stratified fine sandy loam to silt loam |

**Table S2**. Date of leaf and stem water potential measurements.

| Measurements cycle | Date | | |
|---|---|---|---|
| | Ψ Pre-dawn | Ψ Midday leaf | Ψ Midday stem |
| I° | 16-Jul-22 | 16-Jul-22 | 16-Jul-22 |
| I° | 17-Jul-22 | 17-Jul-22 | 17-Jul-22 |
| I° | 19-Jul-22 | 19-Jul-22 | 19-Jul-22 |
| | | 20-Jul-22 | 20-Jul-22 |
| II° | 4-Aug-22 | 4-Aug-22 | 4-Aug-22 |
| II° | 5-Aug-22 | 5-Aug-22 | 5-Aug-22 |
| II° | 6-Aug-22 | 6-Aug-22 | 6-Aug-22 |
| III° | | 14-Aug-22 | 14-Aug-22 |
| III° | | 15-Aug-22 | 15-Aug-22 |
| III° | | 16-Aug-22 | 16-Aug-22 |
| III° | | 17-Aug-22 | 17-Aug-22 |
| III° | 21-Aug-22 | 21-Aug-22 | |
| III° | 24-Aug-22 | 24-Aug-22 | |

**Table S3**. Summary statistics from ANOVAs for stomatal conductance in first, second and third cycles by treatment, time slots and sides and interactions.

| | Treatment | Timeslots | Sides | Treatment x timeslots | Treatment x side | Timeslots x side | Treatment x Timeslots x side | Error |
|---|---|---|---|---|---|---|---|---|
| | | | | ***Stomatal conductance*** | | | | |
| | | | | ***First cycle*** | | | | |
| df | 1 | 3 | 3 | 3 | 3 | 9 | 9 | 608 |
| SS | 0.6688 | 26.3652 | 7.3221 | 0.2369 | 881 | 3.2991 | 0.3337 | 31.3885 |
| MS | 0.6688 | 8.7884 | 2.4407 | 0.079 | 0.0294 | 0.3666 | 0.0371 | 0.0516 |
| F | 12.9549 | 170.2324 | 47.2765 | 1.5298 | 0.5686 | 7.1005 | 0.7183 | |
| P | **0.0003451** | **<0.001** | **<0.001** | 0.2056188 | 0.6358833 | **<0.001** | 0.6923679 | |
| | | | | ***Second cycle*** | | | | |
| df | 1 | 3 | 3 | 3 | 3 | 9 | 9 | 448 |
| SS | 2.2914 | 6.5688 | 0.7498 | 0.0947 | 0.0913 | 0.5884 | 0.2277 | 8.8223 |
| MS | 2.2914 | 2.18961 | 0.24995 | 0.03157 | 0.03042 | 0.06538 | 0.0253 | 0.01969 |
| F | 116.3586 | 111.1892 | 12.6924 | 1.6033 | 1.5446 | 3.3199 | 1.2846 | |
| P | **<0.001** | **<0.001** | **<0.001** | 0.1878583 | 0.2022365 | **0.0006116** | 0.2427758 | |
| | | | | ***Third cycle*** | | | | |
| df | 1 | 3 | 3 | 3 | 3 | 9 | 9 | 768 |
| SS | 15.918 | 12.955 | 1.218 | 0.225 | 0.552 | 1.578 | 0.336 | 31.928 |
| MS | 15.9182 | 4.3183 | 0.406 | 0.075 | 0.184 | 0.1753 | 0.0374 | 0.0416 |
| F | 382.905 | 103.8747 | 9.7669 | 1.8049 | 4.4264 | 4.2178 | 0.899 | |
| P | **<0.001** | **<0.001** | **<0.001** | 0.144795 | **0.004275** | **<0.001** | 0.525619 | |

Note: Numbers in bold indicate significant differences at $\alpha < 0.05$.

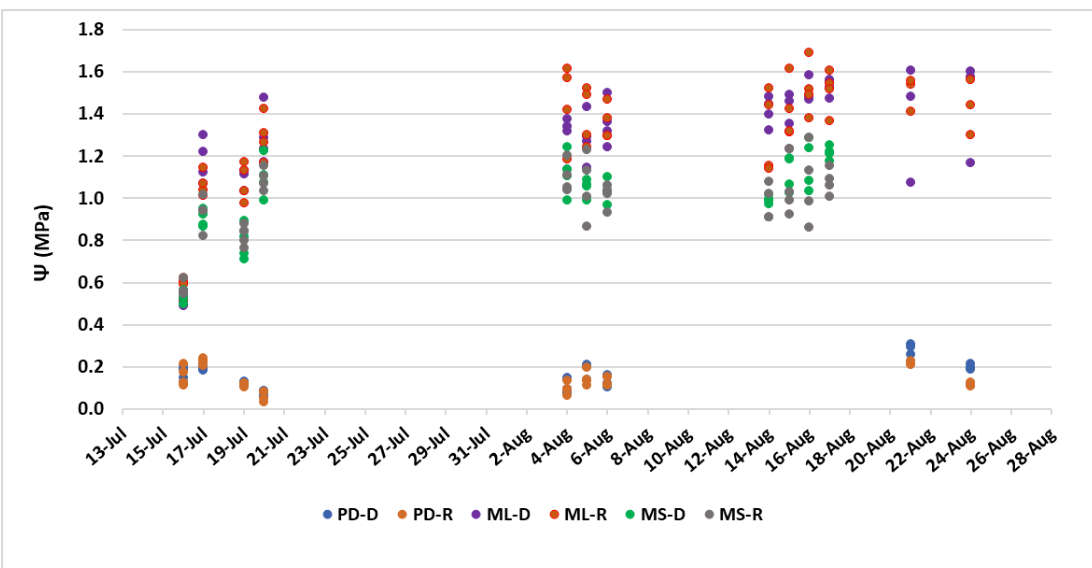


**Figure S1**. Trends of $\Psi_{PD}$ in rainfed and irrigated trees (PD-D and PD-R respectively), $\Psi_{ML}$ in rainfed and irrigated trees (ML-D and ML-R respectively) and $\Psi_{MS}$ in rainfed and irrigated trees (MS-D and MS-R respectively) during the measurement period of July and August 2022.

**Table S4**. Summary statistics from ANOVAs for pre-dawn, leaf and stem water potential in first, second and third cycle, by treatment, sides and their interactions.

| | Treatment | Sides | Treatment x sides | Error |
|---|---|---|---|---|
| | | ***Midday leaf water potential*** | | |
| | | ***First cycle*** | | |
| df | 1 | 3 | 3 | 152 |
| SS | 0.0003 | 0.5366 | 0.1255 | 17.2561 |
| MS | 0.0003 | 0.1789 | 0.0418 | 0.1135 |
| F | 0.003 | 1.576 | 0.368 | |
| P | 0.9589 | 0.197596 | 0.775917 | |
| | | ***Second cycle*** | | |
| df | 1 | 3 | 3 | 112 |
| SS | 0.2341 | 1.0355 | 0.0569 | 3.6927 |
| MS | 0.2341 | 0.3452 | 0.019 | 0.033 |
| F | 7.1 | 10.469 | 0.575 | |
| P | **0.008848** | **0.000004** | 0.632517 | |
| | | ***Third cycle*** | | |
| df | 1 | 3 | 3 | 128 |
| SS | 0.0093 | 0.9316 | 0.1448 | 2.8203 |
| MS | 0.0093 | 0.3105 | 0.0483 | 0.022 |
| F | 0.33 | 11.08 | 1.72 | |
| P | 0.565333 | **<0.001** | 0.164649 | |
| | | ***Midday stem water potential*** | | |
| | | ***First cycle*** | | |
| df | 1 | 3 | 3 | 152 |
| SS | 0.0179 | 0.2528 | 0.0156 | 8.0074 |
| MS | 0.0179 | 0.0843 | 0.0052 | 0.0527 |
| F | 0.339 | 1.599 | 0.099 | |
| P | 0.561357 | 0.191904 | 0.960585 | |
| | | ***Second cycle*** | | |
| df | 1 | 3 | 3 | 112 |
| SS | 0.0023 | 0.3721 | 0.0277 | 1.8615 |
| MS | 0.0023 | 0.124 | 0.0092 | 0.0166 |
| F | 0.141 | 7.463 | 0.556 | |
| P | 0.708156 | **0.000134** | 0.645093 | |
| | | ***Third cycle*** | | |
| df | 1 | 3 | 3 | 128 |
| SS | 0.2318 | 0.5173 | 0.0505 | 1.6661 |
| MS | 0.2318 | 0.1724 | 0.0168 | 0.013 |
| F | 13.4 | 9.97 | 0.97 | |
| P | **0.000346** | **0.000005** | 0.407156 | |
| | | ***Pre-dawn water potential*** | | |
| | | ***First cycle*** | | |
| df | 1 | 3 | 3 | 352 |
| SS | 0.000036 | 0.013276 | 0.004796 | 2.192333 |
| MS | 0.000036 | 0.004425 | 0.001599 | 0.006228 |
| F | 0.006 | 0.711 | 0.257 | |
| P | 0.93815 | 0.546248 | 0.856575 | |
| | | ***Second cycle*** | | |
| df | 1 | 3 | 3 | 172 |
| SS | 0.002402 | 0.060665 | 0.004096 | 0.746123 |
| MS | 0.002402 | 0.020222 | 0.001365 | 0.004338 |
| F | 0.5538 | 4.6616 | 0.3148 | |
| P | 0.45777 | **0.003699** | 0.814686 | |
| | | ***Third cycle*** | | |
| df | 1 | 3 | 3 | 112 |
| SS | 0.082163 | 0.443797 | 0.012997 | 0.49104 |
| MS | 0.082163 | 0.147932 | 0.004332 | 0.004384 |
| F | 18.7404 | 33.7415 | 0.9881 | |
| P | **0.000033** | **<0.001** | 0.401156 | |

Note: Numbers in bold indicate significant differences at $\alpha < 0.05$.

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# Chapter 3 – Irrigation effects on hazelnut (*Corylus avellana* L.) yield and quality


## Abstract

Hazelnut (*Corylus avellana* L.) represents the main nut crop in Italy. At the national level Campania region is reputed to be the oldest site of hazelnuts cultivation. Thanks to climatic and environmental factors, human skills and technological knowledge acquired over time, and the careful selection of superior cultivars, hazelnut production in Italy is focused regionally and highly specialized.

The aims of this work were: (i) to evaluate the effects of three levels of irrigation, corresponding to the daily restitution of 0, 40 and 100% crop evapotranspiration (ETc), respectively D, T2 and T1, on physiological responses, yield and production indices, commercial and analytical quality of 15-year-old hazelnuts orchard cultivar Tonda di Giffoni (ii) construction of reliable relationships between Normalized Vegetation index (NDVI) and Leaf Area Index (LAI) and their evolution in the season (iii) analyze the relationships between hazelnut yield and NDVI values.

The study area was a non-irrigated commercial hazelnut orchard of 0.32 ha, located in Montoro (Avellino), south Italy, which is traditional area for hazelnut production. The ETc calculated with the Blaney-Criddle method, was about 6 mm/day in July and 5 mm/day in August).

Yield no showed significant differences in mean values between treatments, while in the qualitative analysis of the kernels, the dryland treatment showed lowest (17.39 %) total discard significantly different from the treatment with full ETc restitution (32.82 %). A high percentage of hidden bug damage was recorded in the 100 % Etc daily restitution treatment (19.82 %) compared to the dryland treatment (8.76 %). The NDVI-LAI relationship suggests that in the dryland orchard it is possible to estimate LAI using NDVI values. Linear relationships were significant and positive in June ($R^2$ = 0.79) and negative in July ($R^2$ = 0.66). While linear relationship NDVI-Yield showed the treatment with 40% ETc daily restitution (T2) was significative and negative from June to September, suggesting that T2 treatment, may have achieved good trade-off between vegetative renewal and production. In addition, T2 treatment showed the highest efficiency in terms of amount of seed produced per leaf area.

Based on the results, the dryland treatment and the treatment with daily restitution of 40 % ETc showed the best performance. The T2 treatment resulted in 63 % water saving compared to T1, and appears to be a good strategy with reduced water inputs for sustainable hazelnut orchard management.

**Keywords:** irrigation strategy, quality, physiological response, NDVI-LAI, NDVI-yield, productive indices

## 1. Introduction

The processing industry's increasing demand has led to a rise in interest in hazelnut (Liso et al., 2017). Hazelnut is the main nut crop in Italy (CREA, 2018). Italy, after Turkey, is the world's second largest producer with a share of 12 %. (FAOSTAT, 2021). At the national level, on the other hand, Campania is the region that ranks second with 31 % of production while at the province level, the largest share belongs to the province of Avellino with 39 % (ISTAT 2016-2018). However, Campania region is reputed to be the oldest site of hazelnuts cultivation in Italy (Boccacci and Botta, 2018).

Thanks to climatic and environmental factors, human skills and technological knowledge acquired over time, and the careful selection of superior cultivars, hazelnut production in Italy is focused regionally and highly specialized (Piacentini et al., 2015).

In Italy, the transformation sector receives more than 90 % of the harvest (USDA, 2014), which is increasingly demanding in terms of quality (Cristofori et al., 2008). Farmers are therefore rather well paid for their produce, and the price is strongly affected by factors like kernel size, shelling and commercial yield, the quantity produced and the quality defects (Zinnanti et al., 2019). The impacts of water stress on hazelnut quality and physiological response have been reported. These effects include a reduction in photosynthetic activity, an early cessation to fruit growth, early leaf fall, an increase in blank nuts, a decrease in the percentage of kernels and an increased susceptibility to infections (Girona, 1987; Natali et al., 1988; Girona et al., 1994; Tombesi, 1994; Bignami and Natali, 1996; Bignami et al., 2000; Diaz et al., 2005). In traditional areas suited to hazelnut production, annual average rainfall is between 800-1000 mm, uniformly distributed throughout the year (Cristofori et al., 2014).

In this scenario, even in an area where hazelnut has been traditionally grown as a rainfed crop defining an irrigation strategy in order to make rational use of water, and good production in terms of quantity and quality (Fereres and Soriano, 2007; Ruiz-Sanchez et al., 2010; Medrano et al., 2015) improves not only water productivity but also farmers' income (Fereres and Soriano, 2007). Deficit irrigation, which involves applying water below the amount needed by the crop for evapotranspiration, is a crucial strategy for reducing irrigation water use. Several cases of controlled deficit irrigation have been studied for fruit trees and vines, showing how it increases farmers' income in addition to water productivity (Fereres and Soriano, 2007).

The aims of this work were: (i) to evaluate the effects of three levels of irrigation, corresponding to the daily restitution of 0, 40 and 100 ETc, on the physiological response, yield and production indices, commercial and analytical quality of an adult hazelnut orchard of the cultivar Tonda di Giffoni in a suitable area of production (ii) construction of reliable relationships between Normalized Vegetation index (NDVI) and Leaf Area Index (LAI) and their evolution in the season (iii) analyze the relationships between hazelnut yield and NDVI values. The manuscript is in process for submission.

## 2. Material and Methods

### *2.1 Study area and experimental design*

The study area was a non-irrigated commercial hazelnut orchard of 0.32 ha, located in Montoro (Avellino), south Italy, at latitude of 40°50'21.01 N - 14°46'40.02 E, at 193 m above sea level, traditional area to the production of hazelnut. The field under study is delimited by the white rectangle in fig.1.

The Montoro area is characterized by fertile and well-drained soils of volcanic origin, with a mild and breezy climate. Mapping soil was taken by the spatial variability of soil using the EMP-400 GSSI Electro Magnetometer Profiler. Very low spatial variability of the soil was detected.

The thermometric regime is regular with an increasing period from January to July and decreasing from August to January. The rainfall regime ranges from a maximum in November/December to a spring period of intermediate precipitation and a summer minimum in July/August.

The study focused on 15-year-old trees ‘Tonda di Giffoni’ cultivar (fig. 1). The trees were trained on single trunk and planted 4 m between row and 4 m on the row, with a density of 625 trees $ha^{-1}$ in east-west row orientation.

The orchard was never irrigated until the start of the treatments, in the summer season 2023. The experimental trial was conducted from June to September 2023. The irrigation system was installed from June but due to continue rainfall, measurements started in July.

The treatments were arranged in a randomized block design, with two replications. Six trees per treatment were used for experimental observations and measurements (fig. 2).

The experimental design featured three treatments, two watering levels corresponding to daily restitution of 100 % (T1) and 40 % (T2) crop evapotranspiration (ETc) respectively and dryland (D) (tab.2).

Drippers were placed 0.5 m apart, thus there were eight drippers per tree. The flow rate was 3.8 and 2.4 l/h for T1 and T2, respectively. Irrigation was applied from July 14 to 18 August, by a drip system with one line per row (tab. 2).

*2.2 Soil Physical and Chemical analysis*

The soil before treatments was analyzed at depths of 0-20 and 20-50 cm for physical and chemical properties, listed in tab. 1. The soil texture was classified as sandy loam based on the FAO soil classification system (Bashour and Sayegh, 2007). Soil texture was assessed using the hydrometer method (Bouyoucos, 1962). The pH was measured in distilled water (soil/solution ratio 1:2.5) with a glass membrane electrode. Electric conductivity (EC) was determined in distilled water using a 1:5 soil/water suspension mechanically shaken at 15 rpm for 1 h and then detected with a Hanna instrument conductivity meter. Cation exchange capacity (CEC) was determined using the Mehlich methodology (Mehlich, 1953). Organic carbon was assessed with the dichromate oxidation method (Walkley and Black, 1934) and transformed into organic matter by multiplying by 1.72; Nitrogen (N) was measured with the Kjeldahl method (Kjeldahl, 1883). C/N was determined as a carbon/nitrogen ratio. Water-soluble phenols (WSPs) were extracted in triplicate, as reported by Kaminsky et al. (Kaminsky and Muller, 1977) Gallic acid was used as a standard, and the concentration of WSP compounds was expressed as Gallic Acid Equivalents (μg GAE g−1 d.s).

**Table 1**. Soil chemical and physical characteristics at depths of 0-20 and 20-50 cm

| Parameters | Depth (cm) | |
|---|---|---|
| | 0-20 cm | 20-50 cm |
| Sand (%) | 78.00 | 78.67 |
| Silt (%) | 14.80 | 12.83 |
| Clay (%) | 7.20 | 8.50 |
| U.R. (%) | 17.33 | 16.00 |
| C (%) | 2.37 | 1.52 |
| N (%) | 0.22 | 0.16 |
| C/N | 10.8 | 9.5 |
| pH | 7.28 | 7.35 |
| EC (μS/cm) | 48.57 | 58.85 |
| WSP (μg GAE/g ds) | 33.50 | 33.92 |
| CEC (cmol(+)/kg) | 14.70 | 15.02 |


**Figure 1**. Study area delimited by white rectangle.


**Figure 2**. Experimental design: T1: 100% ETc, T2: 40% ETc and dryland: 0% ETc

**Table 2**. Watering days of July and August, irrigation hours and watering volume in treatments T1 (100% ETc) and T2 (40% ETc).

| T1 | | | | | | T2 | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Date watering** | **Irrigation hours** | **ETc (mm/day)** | **Liter per tree** | **m³/ha** | **mm/day** | **Irrigation hours** | **Liter per tree** | **m³/ha** | **mm/day** |
| 14-lug-23 | 2.65 | 5.00 | 80.6 | 50.4 | 5.0 | 0.80 | 15.4 | 9.6 | 1.0 |
| 18-lug-23 | 2.65 | 5.00 | 80.6 | 50.4 | 5.0 | 0.80 | 15.4 | 9.6 | 1.0 |
| 19-lug-23 | 2.65 | 5.00 | 80.6 | 50.4 | 5.0 | 1.60 | 30.7 | 19.2 | 1.9 |
| 20-lug-23 | 3.15 | 6.00 | 95.8 | 59.9 | 6.0 | 1.60 | 30.7 | 19.2 | 1.9 |
| 24-lug-23 | 3.7 | 7.00 | 112.5 | 70.3 | 7.0 | 1.36 | 26.1 | 16.3 | 1.6 |
| 25-lug-23 | 3.15 | 6.00 | 95.8 | 59.9 | 6.0 | 1.36 | 26.1 | 16.3 | 1.6 |
| 26-lug-23 | 2.65 | 5.00 | 80.6 | 50.4 | 5.0 | 1.36 | 26.1 | 16.3 | 1.6 |
| 28-lug-23 | 2.35 | 4.50 | 71.4 | 44.7 | 4.5 | 1.36 | 26.1 | 16.3 | 1.6 |
| 31-lug-23 | 2.35 | 4.50 | 71.4 | 44.7 | 4.5 | 1.36 | 26.1 | 16.3 | 1.6 |
| 01-ago-23 | 2.1 | 4.00 | 63.8 | 39.9 | 4.0 | 1.36 | 26.1 | 16.3 | 1.6 |
| 02-ago-23 | 1.85 | 3.50 | 56.2 | 35.2 | 3.5 | 1.36 | 26.1 | 16.3 | 1.6 |
| 03-ago-23 | 1.85 | 3.50 | 56.2 | 35.2 | 3.5 | 1.36 | 26.1 | 16.3 | 1.6 |
| 04-ago-23 | 1.85 | 3.50 | 56.2 | 35.2 | 3.5 | 1.36 | 26.1 | 16.3 | 1.6 |
| 07-ago-23 | 1.6 | 3.00 | 48.6 | 30.4 | 3.0 | 1.36 | 26.1 | 16.3 | 1.6 |
| 08-ago-23 | 2.1 | 4.00 | 63.8 | 39.9 | 4.0 | 1.36 | 26.1 | 16.3 | 1.6 |
| 09-ago-23 | 2.1 | 4.00 | 63.8 | 39.9 | 4.0 | 1.36 | 26.1 | 16.3 | 1.6 |
| 10-ago-23 | 2.1 | 4.00 | 63.8 | 39.9 | 4.0 | 1.36 | 26.1 | 16.3 | 1.6 |
| 11-ago-23 | 2.1 | 4.00 | 63.8 | 39.9 | 4.0 | 1.36 | 26.1 | 16.3 | 1.6 |
| 14-ago-23 | 2.1 | 4.00 | 63.8 | 39.9 | 4.0 | 1.36 | 26.1 | 16.3 | 1.6 |
| 15-ago-23 | 2.1 | 4.00 | 63.8 | 39.9 | 4.0 | 1.36 | 26.1 | 16.3 | 1.6 |
| 16-ago-23 | 1.6 | 3.00 | 48.6 | 30.4 | 3.0 | 1.36 | 26.1 | 16.3 | 1.6 |
| 17-ago-23 | 1.85 | 3.50 | 56.2 | 35.2 | 3.5 | 1.36 | 26.1 | 16.3 | 1.6 |
| 18-ago-23 | 2.1 | 4.00 | 63.8 | 39.9 | 4.0 | 1.36 | 26.1 | 16.3 | 1.6 |
| **Sum** | | | **1602.1** | **1001.3** | **100.0** | | **588.3** | **367.7** | **36.8** |
| **Mean** | | | **69.7** | **43.5** | **4.3** | | **25.6** | **16.0** | **1.6** |

*2.3 Crop evapotranspiration (ETc)*

The crop evapotranspiration (ETc) was calculated as:

$$ETc = ET_0 \times Kc$$

where:

$ET_0$ = reference evapotranspiration

Kc = crop coefficient according to Silvestri et al., 2021

Reference evapotranspiration was calculated by the Blaney-Criddle method (Allen and Pruitt, 1986):

$$ET_0 = \{a + b \times [P(0.46T + 8.13)]\}\left[1 + 0.1\left(\frac{Elev}{1000}\right)\right]$$

where $ET_0$ is reference crop evapotranspiration (mm/d);

*a* and *b* are correction factors;

$P$ is the mean daily percentage of total annual daytime hours for a given time period and latitude;

$T$ is the mean daily air temperature (°C) in the period of observations;

*Elev* is the site elevation in meters above sea level.

Daily precipitation and temperature data were collected from weather station nearest to the experimental field, located in Mercato San Severino (Salerno-Italy) (https://centrofunzionale.regione.campania.it).

The $a$ and b factors adjust the ET estimate based upon measured or estimated mean daily minimum percentage relative humidity ($RH_{min}$), mean ratio of actual to possible sunshine hours ($N_{ratio}$), and mean daytime wind speed in meters per second at a 20 m height ($U_{day}$). The $a$ factor is calculated as:

$$a = 0.0043\,(RH_{min}) - N_{ratio} - 1.41$$

where $N_{ratio}$ is calculated as follows:

$$Nratio = 2\left(\frac{R_s}{R_a}\right) - 0.5$$

where $R_s$ is estimated global solar radiation in millimeters per day water equivalent (http://www.solaritaly.enea.it/CalcRggmmOrizz/Calcola3.php) and $R_a$ is extraterrestrial short-wave solar radiation in millimeters per day water equivalent based on latitude of 40° of Table 2 by Allen and Pruitt (1986). Both solar radiations are based on latitude and longitude.

The $b$ factor was calculated as follows:

$$b = 0.81917 - 0.0040922(RHmin) + 1.0705(Nratio) + 0.065649\,(Uday) - 0.0059684\,(RHmin)(Nratio) - 0.0005967(RHmin)(Uday)$$

where $U_{day}$ is:

$$Uday = \frac{U24(Uratio)}{43.2(1 + Uratio)}$$

where, *U24* is the 24 hours wind speed in m/s, taken by Copernicus Climate Data Store website for the specific area (https://cds.climate.copernicus.eu/cdsapp#!/software/app-era5-explorer?tab=app).

and $U_{ratio}$ is the ratio of daytime to night-time wind speeds, but when this latter is unavailable, Doorenbos and Pruitt suggested using a value of 2.0.

The hazelnut crop coefficients used for July and August were 0.70 and 0.55 respectively (Silvestri et al., 2021). The calculated ETc values were around 6 mm/day on July and 5 mm/day on August).

*2.4 Tree measurements: LAI, trunk size, leaf area and leaf dry weight*

To choose homogeneous trees and to complete leaf eco-physiological measurements in a short time hazelnut trees were selected based on trunk size and leaf area index (LAI $m^2$ $m^2$) value. Trunk circumference was measured by a measuring tape, 30 cm above the ground, and LAI-2200 Plant Canopy Analyzer (LI-COR Inc., Lincoln, Nebraska) was used to measure LAI, following calibration. Measurements were taken in all treatments, totaling 30 trees. Measurements of LAI and trunk size, for trees selection, were conducted in late June. In addition, LAI measurements were also taken in July, when the hazelnut trees reached leaf maturity, in order to calculate production indices.

The values of tree trunk diameter and LAI were normally distributed. Based on the mean trunk diameter value of 15.5 cm and the mean LAI value in June of 4.5, three trees were selected in treatments T1.1, T2.1 and dryland (fig. 3).

From the trunk circumference values, the trunk cross-sectional area (TCA) was calculated.

To calculate leaf area (LA) and leaf dry weight (LDW), on August 18 and 25 and September 11 two leaves were taken from each of 3 trees used for eco-physiological measurements in treatments T1.1, T2.1 and D (rainfed). Leaves were photographed and then leaf area was measured with ImageJ 1.53k software (Wayne Rasband and contributors National Institutes of Health, USA. Leaves were thereafter dried in oven at 72 °C for 75 hours and weighed to obtain dry mass.

*2.5 Eco-physiological measurements*

Leaf gas exchange of leaves was measured by a portable infra-red gas analyzer, CIRAS-1 IRGA Portable Photosynthesis System (Hitchin, UK). It was set up and calibrated according to the manufacturer instructions.

Measurements were taken on fully expanded, mature, well-exposed leaves on July 21 and 28, August 4, 11, 18 and 25, and September 11, in the morning and afternoon. Measurements were taken on three plants of T1.1 (tree n. 2, 3 e 6), T2.1 (tree n. 2, 3 e 6) and dryland (tree n. 3, 4 e 6) treatments, selected based on trunk size and leaf area index (LAI) value. Two leaves in the west cardinal side were measured for each tree. From the gas exchange measurements, it was possible to calculate water use efficiency (WUE) as the ratio of:

$$WUE = \text{net photosynthesis} / transpiration$$

*2.7 Hazelnut yield and production efficiency index*

Nuts were harvested on August 24 and September 12 in all treatments and weighed directly in the field. Composite samples were collected from 3 neighboring trees.

Parameters considered to calculate production efficiency indices were yield (Y) is total tree production, leaf area (LA) trunk cross section area (TCA), total dried good kernels (TGK) and total dry weight leaf of the tree (LDWT).

Total leaf area of the tree was calculated by the product of the July LAI value and the projected ground area (PGA) of the canopy (see section Calculating the NDVI of the canopy). TGK was calculated as follows:

$$Kernels\ per\ tree\ (kg) = \left(Shelling\ yield\ (\%)\ \times\ yield\ tree\ (kg)\right)/100$$

$$Good\ kernels\ per\ tree\ (kg) = (Good\ kernels\ (\%)\ \times\ kernels\ per\ tree\ (kg))/100$$

Shelling yield and good kernels percentage were obtained from commercial quality analysis.

LDWT was calculated as follows:

$$(Dry\ weight\ leaf\ (kg)/\ leaf\ area\ (m^2) \times (Total\ leaf\ area\ tree\ (m^2))/1000)$$

Where total leaf area of the tree was:

$$PGA \times LAI$$

A July LAI value was used, to calculate total leaf area of the tree.

The production efficiency indices considered were:

- Y/LA (g $m^2$)
- Y/TCA (g $cm^2$)
- TCA/LA ($cm^2$ $m^2$)
- TGK/LDWT

*Water use efficiency at crop field level and irrigation efficiency*

Water use efficiency at crop field level (WUE) and irrigation efficiency (IF) were calculated. Rainfall from April 1 to September 11, when the first leaves started to occur on the tree until the end of harvest, was considered for the calculation of WUE.

WUE was calculated as follows:

$$WUE\ (m^3/kg) = ((precipitation\ (mm) + watering\ (mm)) \times 100) / (Yield\ (kg/ha))$$

IF, instead was calculated as follows:

$$IF\ (Liter/kg) = ((watering\ (mm) / Yield\ (kg/ha)) \times 100000)$$

*2.8 Analysis of commercial quality of hazelnuts*

Two kg of each sample of nuts was transported to the laboratory to be dried in an oven at a temperature of 50 °C for 48 hours. The final moisture content of kernel was between 3.5 and 4.5% in all samples according to Commission Regulation (EC) N. 1284/2002. Next, nuts were analyzed for commercial and chemical quality.

A sample of 100 nuts for each replication, both from the first and second harvest, was submitted to commercial analysis according to commercial practice and literature (Bioversity International, FAO and CIHEAM 2008). The merceological requirements that were submitted were as follows: blanks nuts, twin kernels, shelling yield, commercial yield, shriveled kernels (fig. 3a), visible (fig. 3b) and hidden rot (fig. 3c), visible and hidden pest damage (stink bug damage) (fig. 3d), kernels with diameter ≥ 11 mm and percentage of total good kernels. All the nuts were shelled manually, assessed for visible defects and were weighted for each parameter considered.

Blank nut percentage was calculated as follows:

$$(blank\ nuts/initial\ weight\ in\ shell\ nuts) \times 100$$

Twin nut percentage was calculated as follows:

$$(twin\ nuts/initial\ weight\ in\ shell\ nuts) \times 100$$

Shelling yield percentage was calculated as follows:

$$(Kernels\ weight/initial\ weight\ in\ shell\ nuts) \times 100$$

Shriveled nut percentage was calculated as follows:

$$(shriveled\ nuts/shelled\ nuts)\ \times\ 100$$

Visible rot and bug damage percentage were calculated as follows:

$$(Visibile\ rot\ or\ stink\ bug\ damage/shelled\ nuts)\ \times\ 100$$

Commercial yield was calculated by the following weights:

$$[weight\ in\ shell\ nuts - \sum(blank + twin + shells + shriveled + visible\ rot/initial\ \ weight\ shell\ nuts) \times 100]$$

Kernels with diameter ≥ 11 mm percentage were calculated as follows:

$$(kernels\ with\ diameter\ \ > 11\ mm/shelled\ nuts)\ \times\ 100$$

Hidden rot and stink bug damage percentage were calculated as follows:

$$(Visibile\ rot\ or\ bug\ damage/shelled\ nuts\ with\ diameter\ \ > 11\ mm)\ \times\ 100$$

Hidden rot and stink bug damage were calculated as follows:

$$(Hidden\ rot\ or\ bug\ damage/shelled\ nuts\ with\ diameter\ \ > 11\ mm)\ \times\ 100$$

Total good kernels percentage was calculated as follows:

$$[((shelled\ nuts\ with\ diameter > 11\ mm - (Hidden\ rot + Hidden\ bug\ damage/\ weight\ shelled\ nuts)) \times 100]$$

The kernels diameter was evaluated by certified stainless steel sieves mesh with 11-mm holes (Giuliani technology, Torino-Italy). A diameter of 11 mm is commercially considered for hazelnut cultivars outside regulatory specifications.

From the lot resulting from the commercial yield calculation, the visible bug damage was identified, and it was weighed and reintroduced into the sample of hazelnuts continuing the selection. Visible bug damage will not necessarily evolve into occult damage as well. This latter may conform or not.

Using the Magra hazelnut cutting unit (Teserba GmbH, Rüti, Switzerland), hazelnuts were cut in half and observed for rot and sting bug internal damage (fig. 4)

The amount and type of damage caused depends on the stage of nut development when stink bug feeds (Hedstrom et al., 2014). Occult damage with typical cork around the white spot (fig. 3d) indicated a non-conforming kernel, while the absence of cork suggested a commercially conforming kernel (fig. 3e).

Total discard was composed of shriveled, visible rot, hidden rot and hidden cork while the percentage of total good kernels was the ratio of kernels net of defects to kernel weight.

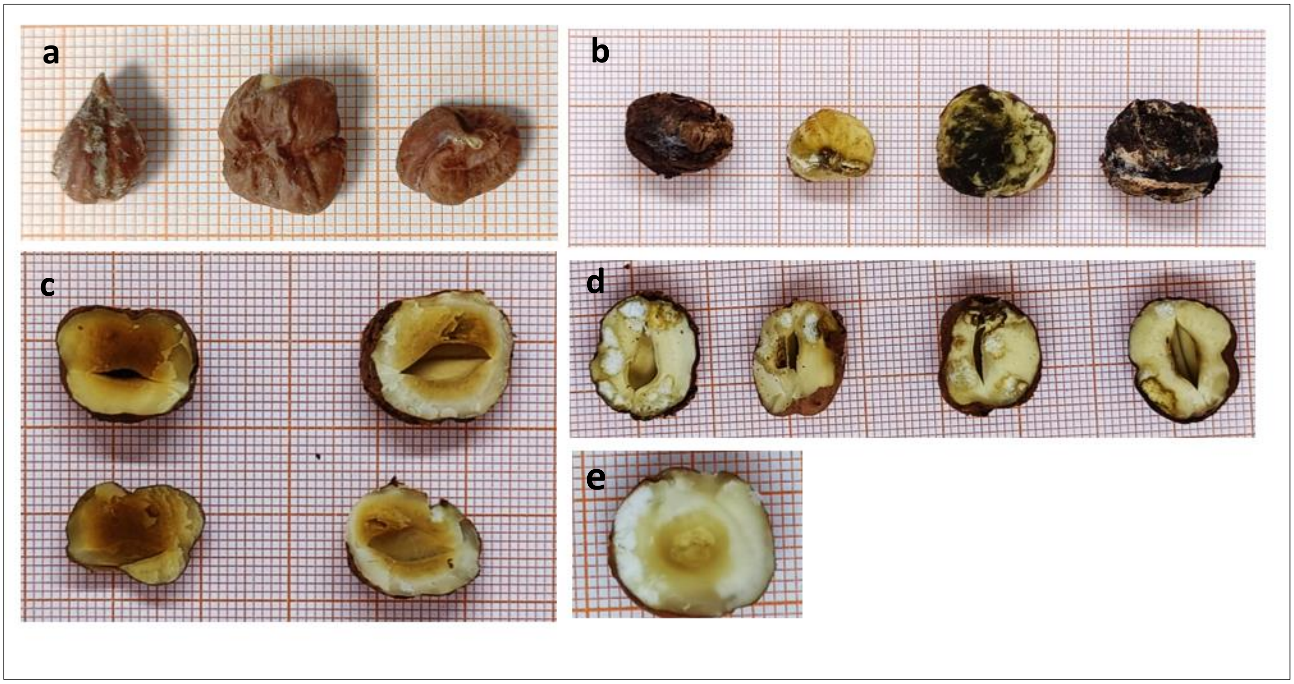


**Figure 3**. External and internal defects in shelled hazelnuts. **a)** shriveled, **b)** visible rot, **c)** hidden rot, **d)** hidden bug damage, **e)** conforming nut with hidden bug damage.

**Figure 4**. Shelled hazelnuts cut in half to observe internal defects.

*2.9 Chemical and fatty acid determination of kernels*

Proximate composition (moisture, crude protein, lipid, ash) was determined using the Official Methods of Analysis of AOAC International (AOAC, 2016). Total carbohydrates were determined by difference: 100 − (crude protein + crude fat + total ash + moisture) %.

*2.91.Extraction and determination of total phenolic compounds (PCs) with the Folin-Ciocalteu (FC) assay*

Phenolic compounds were extracted from 1.0 g of each of the previously ground hazelnut samples with 10 mL of 80% (v/v) aqueous methanol in ultrasonic bath for 30 min at room temperature. The two-phase system was then centrifugated for 20 min at 5000 g and the polar solution (upper layer) was filtered on disposable 0.22 μm nylon (Merck-Millipore, Darmstadt, Germany). The filtrate was stored in glass vials at - 26 °C until further analysis. The total polyphenols of the extracts were determined by the Folin-Ciocalteu method (Singleton & Rossi, 1965). Specifically, inside the cuvettes, they were added in the respective order: 2.3 mL of distilled water, 50 μL of Folin- Ciocalteu 1:2 (v/v) reagent, 50 μL of extract of the sample under examination and after 3 min, 100 μL of 20% sodium carbonate ($Na_2CO_3$) aqueous solution. The mixture thus obtained was kept for 90 minutes in the dark and at room temperature, and then the absorbance at a wavelength of 765 nm was measured (GE-Healthcare Ultrospec 2100 UV-Vis; Uppsala, Sweden). Total phenolics were quantified against a calibration curve ($R^2$ >0.99) built with gallic acid (≥ 99% purity). Results were expressed as mg of gallic acid equivalent (GAE) per kg of hazelnut (mg GAE $kg^{-1}$).

*2.9.2 Gas chromatography-flame ionization detection (GC-FID) analysis of fatty acids*

Analysis of the FAME (Fatty Acid Methyl Ester) was performed according to Siano et al. (2018).

The oil samples of hazelnut (about 0.2 g), obtained with Soxhlet extraction, were transferred into Pyrex test tubes with screw caps, and 2 mL of 1.25 M HCl-$CH_3OH$ solution was added. Samples were incubated in a water bath at 90 °C for 60 min. FAME were extracted with n-hexane, after the addition of 2 mL of distilled water. The organic phase was filtered using 0.22 μm nylon (Merck- Millipore, Darmstadt, Germany), and 1 μL was directly injected into the gas chromatograph for analysis. FAME were analyzed with a 7890A gas chromatographer (Agilent, Santa Clara, CA, USA) equipped with a FID, using an ZB-FAME (100 m × 0.25

mm × 0.20 μm) capillary column (Phenomenex, Torrance, CA, USA). Samples were introduced through a split-splitless injection system of an 7683 Series autosampler (Agilent, Santa Clara, CA, USA) in split mode (ratio 1:100) at 260 °C. The oven temperature program started at 140 °C (held for 5 min) and linearly increased to 260 °C (4 °C min -1) up to the end of the analysis, according to previously described operating conditions. FID temperature was 260 °C. Data acquisition was performed with a GC ChemStation Rev. B.04.03-SP2 (Agilent) integration software. Fatty acid composition of all samples was obtained by comparison with the retention times of the standard mixture FAME 37 components (Merck-Millipore, Darmstadt, Germany) and was expressed as a percentage area.

*3. UAV platform, data acquisition and image processing*

The multi-rotor DJI Phantom 4 Multispectral UAS (Unmanned Aircraft System) was used to carry out flight missions in hazelnut orchard from June to September. The imaging system was equipped with six CMOS (complementary metal oxide semiconductor) cameras, including one RGB camera for visible light imaging in JPEG format and five monochrome cameras for multispectral imaging in TIFF format. Each sensor has 2.08 MP effective (2.12 gross MP), focal length of lens 5.74 mm, image size in width and height 1600×1300, and size lens in width and height 4.96 and 3.72 mm, respectively.

The five cameras acquire red, green, blue, red edge, and near infrared in the following imaging bands: 450 nm ± 16 nm; Green (G): 560 nm ± 16 nm; Red (R): 650 nm ± 6 nm; Red Edge 730 nm ± 16 nm; Near Infrared (NIR): 840 nm ± 26 nm.

The UAV (Unmanned Aerial Vehicle) has an onboard RTK positioning system that provides centimeter-level accuracy. The flight missions were conducted on 20 June, 21 July, 20 August and 20 September 2023 in a grid pattern, nadir- oriented camera at 20 m height and resulting resolution of 1 cm/pixel. Front and side imagery overlap were 80 and 75%, respectively. The total number of pictures acquired was 270 in a flight time of 12′26″ on 0.32 ha.

Photogrammetric processing was carried out using Agisoft Metashape Professional software version 1.8.2 (Agisoft LLC, St. Petersburg, Russia). Image processing steps were performed according to Altieri et al. (2021).

*3.1.1 Canopy NDVI calculation*

The output obtained from image processing was a georeferenced orthophoto, which was exported to QGIS software version 3.22.4 Biatowieza (Free Software Foundation, Inc., 51 Franklin Street, Fifth Floor, Boston, MA 02110-1301 USA), to be processed to calculate the normalized differential vegetation index (NDVI) (Rouse et al., 1974).

NDVI was calculated as follows:

$$NDVI = NIR - RED/NIR + RED$$

where NIR and RED are the values of the reflectance in the near-infrared (840 ± 26 nm) and red (650 ± 6 nm) bands, respectively.

Afterwards, the canopy area was manually delimited based on the spatial distribution of the NDVI map for each canopy of the experimental trees. Then, the NDVI map was clipped into the individual canopy using the *clip raster by mask layer* tool. Finally, through the *zonal statistics* tool, the canopy raster statistics was calculated for each overlapping polygonal vector (single canopy) and the mean NDVI value of the canopy was obtained. In addition, from the canopy delimitation of each tree in experimental field, the Projected Ground Area (PGA) was also measured.

3.2 Statistical analysis

The experimental data were analyzed statistically by STATISTICA 64 v.12 (StatSoft.Inc.2014, USA) software and by Excel to descriptive statistics. Homogeneity of variance and normality were tested, respectively, with the tests by Bartlett and Shapiro with a P value of 0.05. Where the hypothesis of normality/homogeneity was rejected, the Kruskal-Wallis non-parametric test was used to assess the significance of differences. For all other variables, one-Way ANOVA ($P < 0.05$) was performed followed by Tukey's post hoc test tests to find significant differences between treatments ($P < 0.05$).

## 4. Results

*4.1 Soil characteristics*

The soil texture was classified as sandy loam according the FAO soil classification system (Bashour and Sayegh, 2007). In table 3 are listed the chemical and physical parameters of soil characteristics and in table 4 are listed soil hydraulic parameters.

**Table 3**. Soil chemical and physical characteristics at depths of 0-20 and 20-50 cm

| Parameters | Depth (cm) | |
|---|---|---|
| | 0-20 cm | 20-50 cm |
| Sand (%) | 78.00 | 78.67 |
| Silt (%) | 14.80 | 12.83 |
| Clay (%) | 7.20 | 8.50 |
| C (%) | 2.37 | 1.52 |
| N (%) | 0.22 | 0.16 |
| C/N | 10.8 | 9.5 |
| pH | 7.28 | 7.35 |
| EC (µS/cm) | 48.57 | 58.85 |
| CEC (cmol(+)/kg) | 14.70 | 15.02 |

**Table 4**. Soil hydraulic parameters (estimated according to Saxton et al., 1986)

| Parameters | |
|---|---|
| Field capacity (cm/cm) | 0.16 |
| Wilting point (cm/cm) | 0.085 |
| Available water (cm/cm) | 0.08 |
| Ksat (mm*h) | 83.36 |

*4.2 Environmental conditions*

Precipitations occurred in 2018 – 2023 years during the hazelnut vegetative-productive period from March to September were reported in fig. 8. Except for the year 2021, we see that from March to September rainfall are well distributed at 536 mm on average, especially in May and June, when irrigation should start.

Climatic parameters measured from January 1 to November 30, 2023 were showed in figs. 6 and 7. Rainfall, at the study site, was well distributed during the year 2023, totaling 1588 mm. During vegetative growth, 711 mm of precipitation occurred from March to September. Before the start of the experiment, a total of 373 mm took place in May and June, and during the measurement period, 23.8 mm in July and 49 mm in August.

The average maximum and minimum temperatures in July and August were 33 ± 3.0 and 19 ± 2.5 °C, respectively. Since June 21, temperatures have exceeded 30°C, recording temperatures above 35°C since

July 7 when daily relative humidity also decreases showing values below 50%, with an average of 38% from June 21 until the end of September (fig. 7).

Thereafter irrigation was triggered at times of high crop evapotranspiration demand and no precipitation when measurements were taken. (fig. 6).

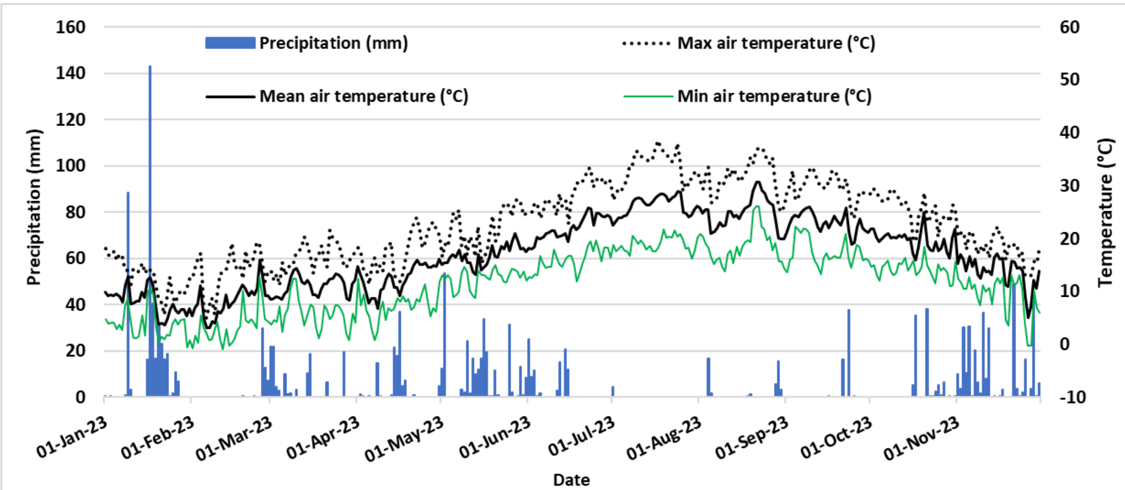


**Figure 5**. Daily precipitation (mm), mean air temperature, maximum and minimum (°C).

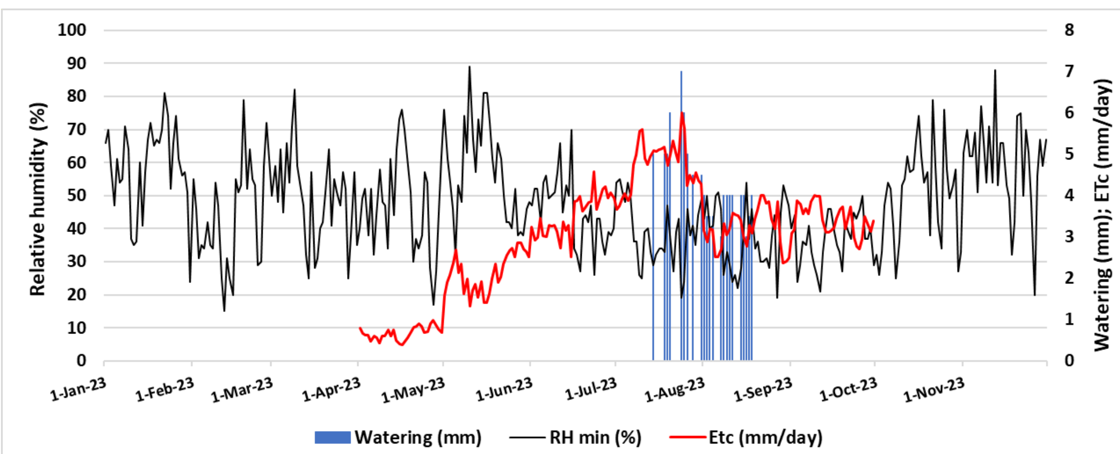


**Figure 6**. Daily watering (mm), ETc (mm) and relative humidity (%).

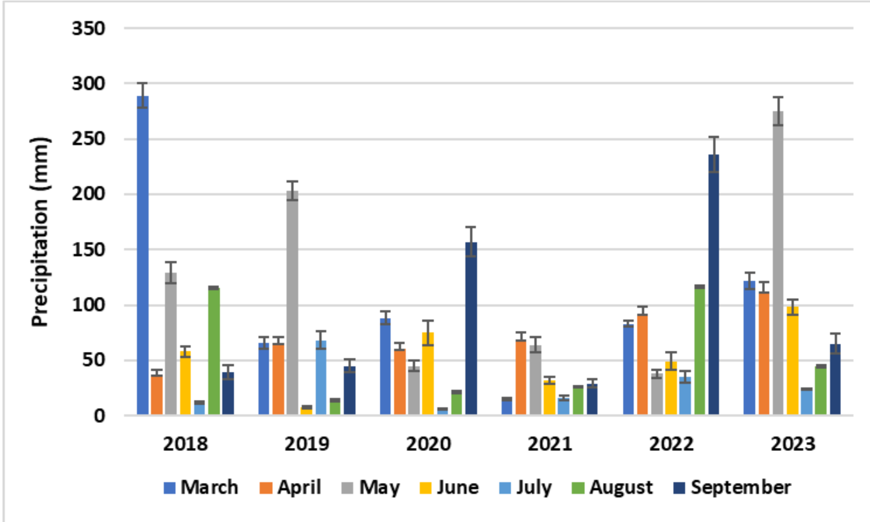


**Figure 7**. Sum and standard deviation of precipitation from 2018 to 2023 during the hazelnut vegetative-productive season from March to September

*4.3 Tree measurements: LAI, TCA, leaf area tree, leaf area and leaf dry weight*

Tables 5 and 6 show leaf area index (LAI), trunk cross-sectional area (TCA), leaf area of the tree (PGA x July LAI), leaf area and leaf dry weight, respectively. No significant differences between treatments were found in any of the parameters. The mean values of LAI in June and July were 3.8 and 7, respectively. TCA averaged 226.3 $cm^2$ and tree leaf area averaged 95 $m^2$. Leaf area and leaf dry weight were 73.6 $cm^2$ and 0.80 g, respectively.

**Table 5**. Mean and standard deviation of leaf area index (LAI) and trunk cross section area (TCA).

| Treatment | LAI | | TCA ($cm^2$) | Total tree leaf area ($m^2$) |
|---|---|---|---|---|
| | June | July | | |
| T1 | 4.5 ± 0.96 | 7.1 ± 0.65 | 252.5 ± 44.9 | 98.70 ± 20.5 |
| T2 | 3.2 ± 1.23 | 6.8 ± 0.53 | 214.2 ± 37.6 | 83.14 ± 10.4 |
| D | 3.8 ± 0.97 | 7.2 ± 0.83 | 212.31 ± 43.4 | 103.42 ± 21.6 |

**Table 6**. Mean and standard error of leaf area and leaf dry weight.

| Treatment | Leaf area ($cm^2$) | Leaf dry weight (g) |
|---|---|---|
| T1 | 76.2 ± 1.5 | 0.84 ± 0.04 |
| T2 | 75.2 ± 2.0 | 0.79 ± 0.02 |
| D | 69.4 ± 1.6 | 0.78 ± 0.01 |

*4.4 Eco-physiological measurements*

Net photosynthesis showed significant different in mean values at $\alpha < 0.05$ in treatment (fig. 9), while stomatal conductance and water use efficiency were not significantly different in mean values at $\alpha < 0.05$ (fig. 10 and 11). Net photosynthesis was significantly different on two days, August 18 and 25 (fig. 12). On both days the highest and lowest values of net photosynthesis were recorded in T2 and D treatments. On August 18 in T2 and D, 6.7 and 1.4 µmol $CO_2$ $m^2$ $s^1$ were recorded, respectively, while on August 25, 10.7 and 7.4 µmol $CO_2$ $m^{-2}$ $s^1$ were recorded, respectively. In these days treatment T1 was statistically equal to treatments T2 and D (fig. 12).

During the trial mean values of A resulted 7.51 ± 1.04, 8.03 ± 0.65 and 6.73 ± 1.18 µmol $CO_2$ $m^{-2}$ $s^1$ in T1, T2 and D, respectively (fig. 9); G mean values were 0.165 ± 0.02, 0.141 ± 0.01 and 0.038 ± 0.02 mmol $m^{-2}$ $s^{-1}$ in T1, T2 and D, respectively (fig. 10) and WUE mean values were 1.80 ± 0.26, 1.84 ± 0.17 and 1.63 ± 0.28 µmol $CO_2$/mmol $H_2O$ in T1, T2 and D, respectively (fig. 11).

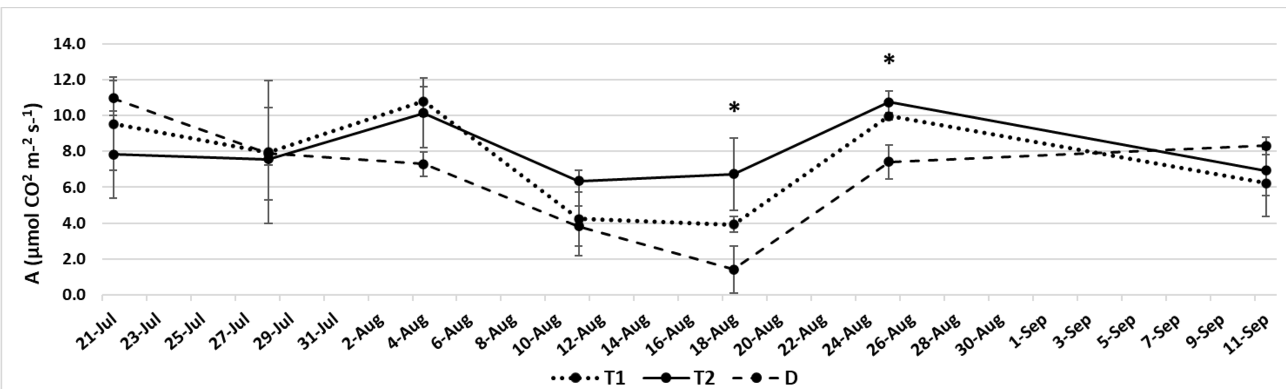


**Figure 8**. Net photosynthesis (**A**) trend in treatments T1 (100% ETc), T2 (40% ETc) and D (0% ETc) on each measurement day. Values are mean ± standard error (N=6). Days marked by asterisk differed significantly according to One Way ANOVA at $\alpha < 0.05$.

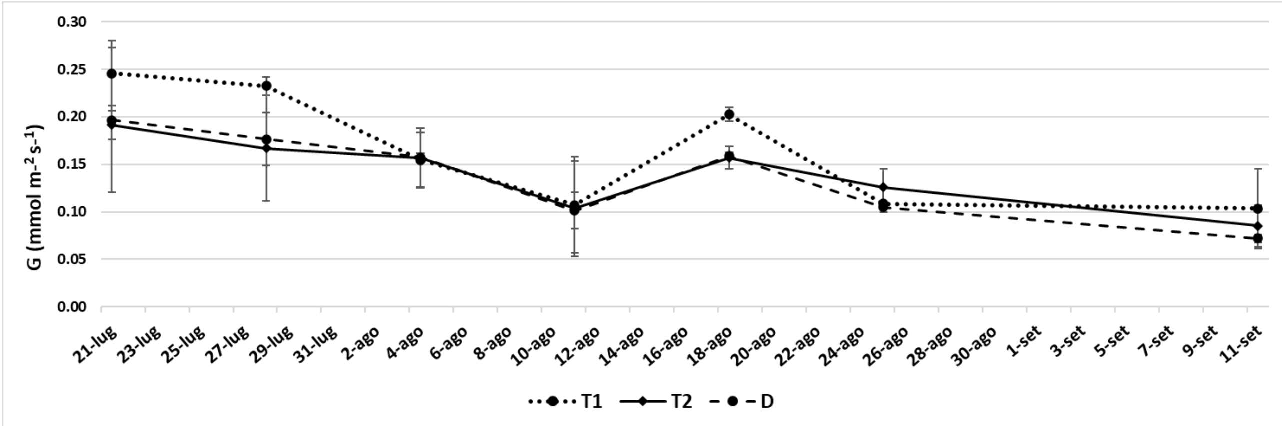


**Figure 9**. Stomatal conductance (**G**) trend in treatments T1 (100% ETc), T2 (40% ETc) and D (0% ETc) on each measurement day. Values are mean ± standard error (N=6). Differences in mean values were tested according to One Way ANOVA at $\alpha < 0.05$.

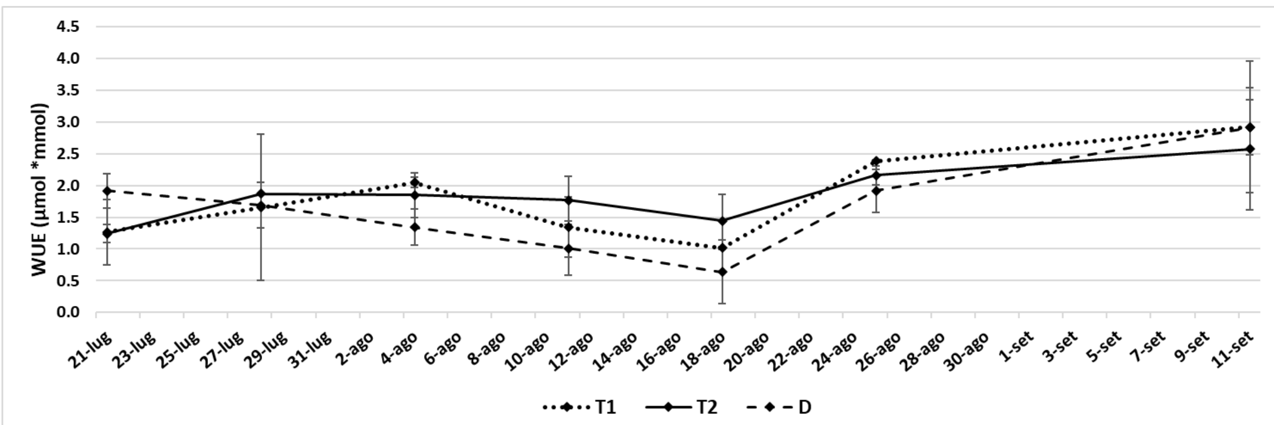


**Figure 10**. Water use efficiency (**WUE**) trend in treatments T1 (100% ETc), T2 (40% ETc) and D (0% ETc) on each measurement day. Values are mean ± standard error (N=6). Differences in mean values were tested according to One Way ANOVA at $\alpha < 0.05$.

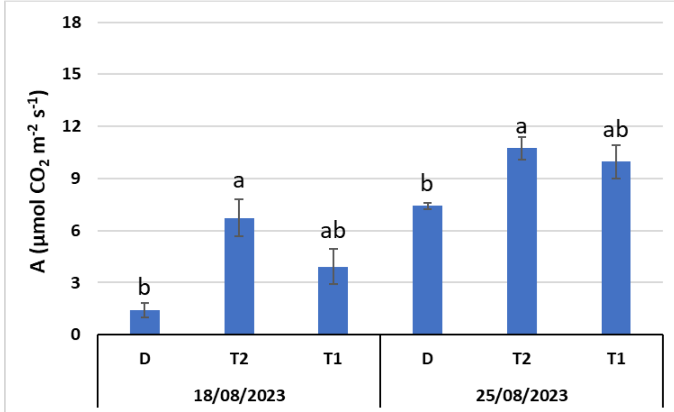


**Figure 11**. Means and standard error (N=6) of net photosynthesis (**A**) in treatments T1 (100% ETc), T2 (40% ETc) and D (0% ETc) on August 18 and 25. Means values with different letters significantly differ according to Tukey's test at $\alpha < 0.05$.

*4.5 Yield and production efficiency indices*

The yield was not statistically different between treatments, mean production was 3.61, 3.95 and 4.22 kg per tree in T1, T2 and D, respectively (fig. 13). There were also no statistically significant differences between treatments for the calculated production efficiency indices (Y/LA; Y/TCA and TCA/LA) (fig. 14). The ratio of seeds weight produced per total leaf area of the tree is shown in fig. 15. The index was statistically different between treatments, highest in T2 and lowest values in D treatments respectively, recording a value of 0.19 and 0.14 kg $m^2$, respectively, while T1 was equal to T2 and D with 0.17 kg $m^2$.

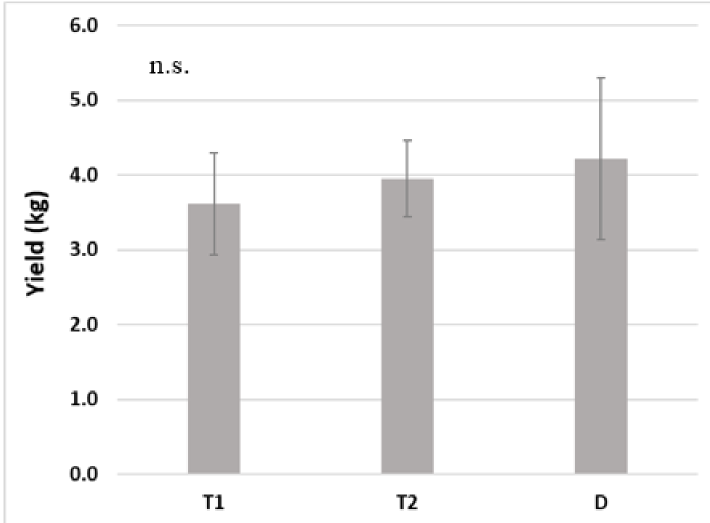


**Figure 12**. Mean values and standard error of yield (kg) per tree in treatments T1 (100% ETc), T2 (40% ETc) and D (0% ETc). Differences in mean values were tested according to Kruskal-Wallis H-test at α < 0.05.

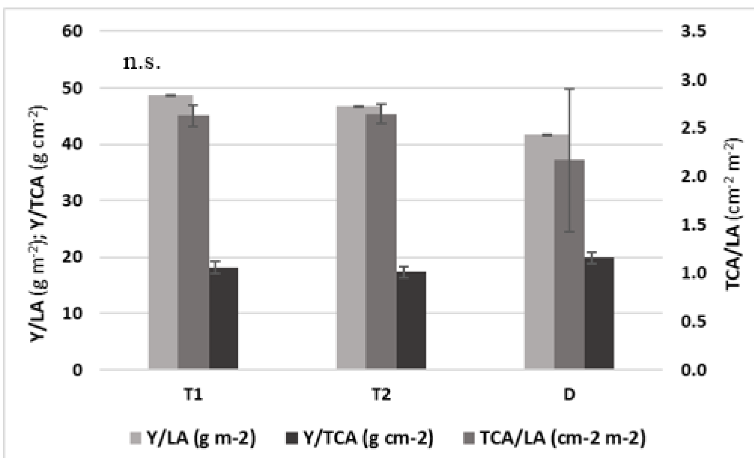


**Figure 13**. Mean values and standard error of production efficiency indices Y/LA (yield/leaf area); Y/TCA (yield/trunk cross section area); TCA/LA (trunk cross section area/leaf area) in T1 treatment (100% ETc), T2 treatment (40% ETc) and D (0% ETc). Differences in mean values were tested according to Kruskal-Wallis H-test at α < 0.05.

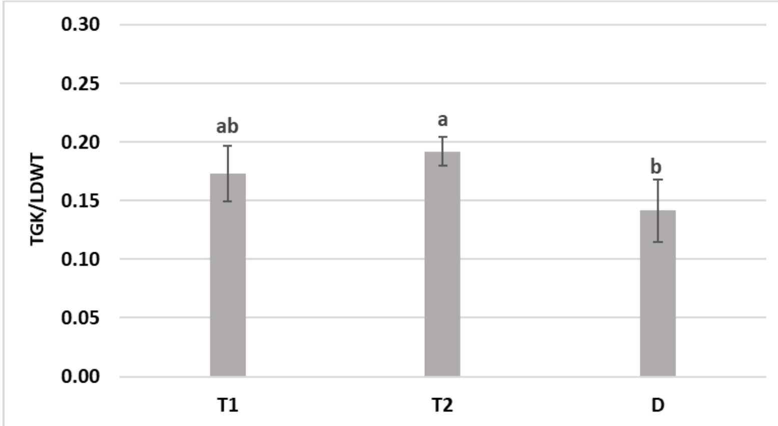


**Figure 14**. Mean values and standard error of amount of seeds produced/total leaf area tree of the tree (TGK/LDWT) in T1 treatment (100% ETc), T2 treatment (40% ETc) and D (0% ETc). Means values with different letters significantly differ according to Kruskal-Wallis H-test at $\alpha < 0.05$.

### *4.6 Water use efficiency at crop field level and irrigation efficiency*

Table 7 shows water use efficiency (WUE) at the crop field level and irrigation efficiency (IF). In terms of WUE at crop field level, 2.59, 2.11 and 1.83 $m^{-3}$ of water per hectare were consumed, while at the IF level, T1 and T2 treatments consumed 443 and 149 liters of water per kg of crop.

**Table 7**. Water use efficiency (WUE) and irrigation efficiency (IF). Precipitation from April 1 to September 11 were considered.

| Treatment | Precipitation (mm) | Yield (kg/ha) | Watering (mm) | WUE crop field ($m^3$/kg) | IF ( L/kg) |
|---|---|---|---|---|---|
| T1 | 484 | 2256 | 100 | **2.59** | **443** |
| T2 | | 2469 | 37 | **2.11** | **149** |
| D | | 2638 | 0 | **1.83** | - |

### *4.7 Analysis of commercial quality*

Yield commercial quality was affected by treatments T1, T2 and D for hidden bug damage, total discard (fig. 15) and good kernels (fig. 16), in which the differences were statistically different at $\alpha < 0.05$. Hidden bug damage was highest in T1 and lowest in D with a mean value of 19.82% and 8.76%, respectively, while T2 was equal to treatments T1 and D with a mean value of 13.46%. However, total discard showed statistically different between T1 and D with highest value of 32.82% and lowest value of 17.39%, respectively. T2 treatment, instead, was equal to both with 23.77% of total discard.

All other parameters showed no differences between treatments: twins kernels resulted only a 0.10% in T1 treatment, blank kernels were 0.50, 0.42 and 0.29% in D, T2 and T1 respectively, shriveled resulted 2.21, 3.01 and 3.19% in D, T2 and T1 respectively, visible rot were 3.24, 3.95 and 6.39% in D, T2 and T1 respectively, visible bug damage were 1.20, 1.02 and 1.52% in D, T2 and T1 respectively and hidden rot resulted 3.18, 3.35 and 3.41% in D, T2 and T1 respectively.

Percentage of good kernels showed statistically differences with higher value in D compared to T1 treatment with values of 83.19% and 69.34% respectively, while T2 was statistically equal to D and T1 treatments, assuming a percentage of 77.28%.

All other parameters showed no differences between treatments: shelling yield was 48 % in D and 47% in T2 and T1, commercial yield was 45, 44 and 42% in D, T2 and T1 respectively and kernels with diameter ≥ 11 mm was 94, 93 and 92% in D, T2 and T1 respectively.

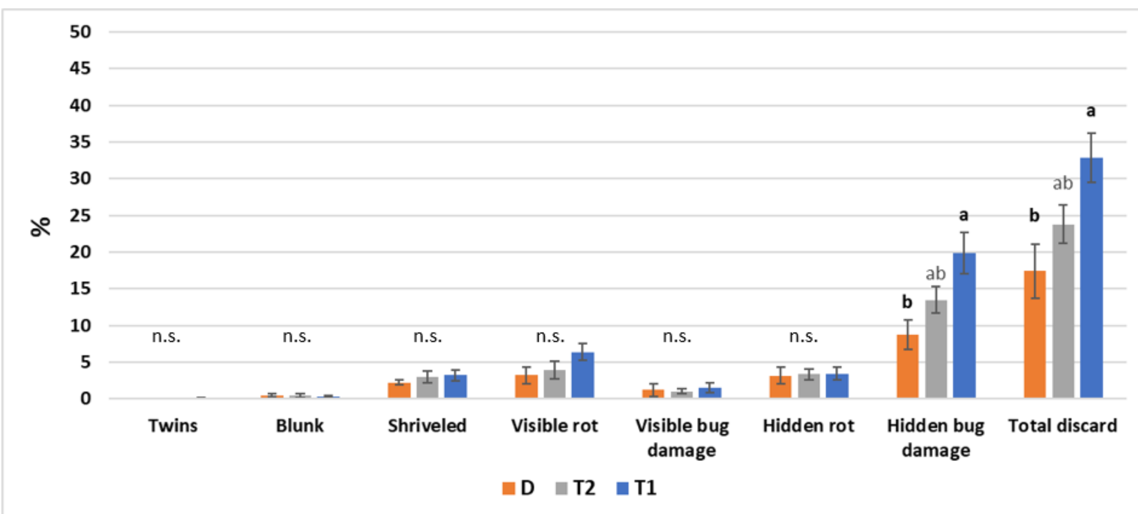


**Figure 15**. Mean values and standard error (N=4) of hazelnut defects in T1 treatment (100% ETc), T2 treatment (40% ETc) and D (0% ETc). Means values with different letters significantly differ according to Kruskal-Wallis H-test at $\alpha < 0.05$.

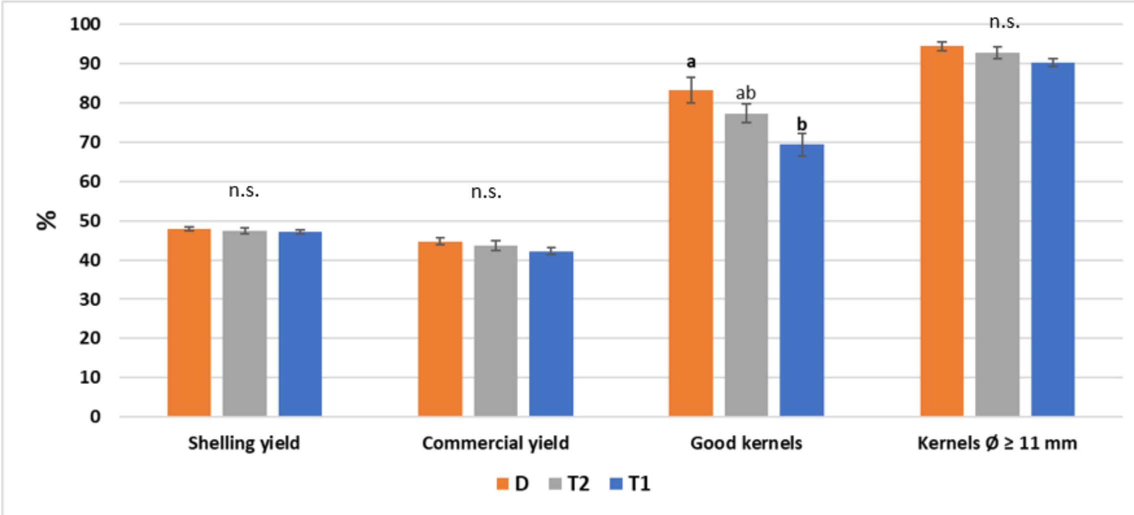


**Figure 16**. Mean values and standard error (N=4) of shelling and commercial yield, good kernels and kernels with diameter ≥ 11 mm in T1 treatment (100% ETc), T2 treatment (40% ETc) and D (0% ETc). Means values with different letters significantly differ according to Kruskal-Wallis H-test at α < 0.05.

### *4.8 Chemical and fatty acid characterization of hazelnut kernels*

Mean values of chemical and fatty acid characterization on dry weight (DW) are shown in tabs. 8 and 9, respectively. Chemical characterization showed a statistical difference at α < 0.05 in protein and carbohydrates. Saturated (**S-SFA**), monounsaturated (**S-MUFA**) and polyunsaturated (**S-PUFA**) fatty acids composition was not statistically different among treatments. Protein was higher in D and lower in T1, with values of 11.9% and 10.7% d.w. respectively, while in T2 protein were equal to treatments T1 and D, assuming 11% d.w. In contrast, carbohydrates were higher in T1 and lower in D with values of 20.3% d.w. and 17.9% d.w. respectively, again T2 was equal to the treatments T1 and D assuming a value of 18.7% d.w.

**Table 8**. Means values and standard error (N=4) of chemical characterization of kernels in T1 (100% ETc), T2 (40% ETc) and D (0% ETc) treatments. Means values with different letters significantly differ according to Kruskal-Wallis H-test at $\alpha < 0.05$.

| Treatments | Lipid | | Protein | | Carbohydrates | | Ash | | Total Biophenols | |
|---|---|---|---|---|---|---|---|---|---|---|
| | % d.w. | | | | | | | | (mg kg$^{-1}$ d.w.) | |
| **D** | 67.5 ± 0.1 | a | 11.9 ± 0.2 | **a** | 17.9 ± 0.3 | **b** | 2.7 ± 0.0 | a | 750.5 ± 11.8 | a |
| **T2** | 67.4 ± 0.6 | a | 11.0 ± 0.3 | **ab** | 18.7 ± 0.3 | **ab** | 2.6 ± 0.1 | a | 838.1 ± 113.5 | a |
| **T1** | 66.1 ± 0.1 | a | 10.7 ± 0.1 | **b** | 20.3 ± 0.1 | **a** | 2.8 ± 0.1 | a | 881.0 ± 8.9 | a |

**Table 9**. Mean values and standard error of fatty acid composition and saturated (**S-SFA**), monounsaturated (**S-MUFA**) and polyunsaturated (**S-PUFA**) fatty acids of the hazelnut kernels of T1 (100% ETc), T2 (40% ETc) and D (0% ETc) treatments.

| Fatty acids | D | T2 | T1 |
|---|---|---|---|
| | n. s. | n. s. | n. s. |
| Palmitic, C16:0 | 6.2 ± 0.1 | 6.3 ± 0.2 | 6.0 ± 0.3 |
| Palmitoleic, C16:1 | 0.2 ± 0.0 | 0.2 ± 0.0 | 0.2 ± 0.0 |
| Stearic, C18:0 | 3.1 ± 0.2 | 3.0 ± 0.1 | 3.0 ± 0.2 |
| Oleic, C18:1, w-9 c | 82.2 ± 1.4 | 81.1 ± 0.9 | 81.4 ± 0.2 |
| Asclepic, C18:1, w-7 c | 1.0 ± 0.0 | 1.0 ± 0.1 | 1.0 ± 0.1 |
| Linoleic, C18:2 | 6.7 ± 1.9 | 7.9 ± 0.8 | 7.9 ± 0.4 |
| Arachidic, C20:0 | 0.2 ± 0.0 | 0.2 ± 0.0 | 0.2 ± 0.0 |
| Linolenic, C18:3 | 0.1 ± 0.0 | 0.1 ± 0.0 | 0.1 ± 0.0 |
| cis-11-Eicosenoic, C20:1 | 0.2 ± 0.0 | 0.1 ± 0.0 | 0.2 ± 0.0 |
| **Σ-SFA** | 9.6 ± 0.4 | 9.6 ± 0.1 | 9.2 ± 0.2 |
| **Σ-MUFA** | 84.5 ± 1.4 | 83.5 ± 0.8 | 83.8 ± 0.3 |
| **Σ-PUFA** | 6.8 ± 1.9 | 8.0 ± 0.8 | 7.9 ± 0.4 |

*4.9 Relationship NDVI-LAI*

The NDVI-LAI relationship was studied in the months from June to September in all treatments T1 (100 % ETc), T2 (40 % ETc) and D (0% ETc).

In irrigated treatments, a linear NDVI-LAI relationship was not found in any month. However, the NDVI-LAI relationship was found in the dryland treatments only in June and September only. Therefore, results from the dryland treatments only will be reported.

The NDVI-LAI regression equation for June in dryland treatment showed a positive relationship ($R^2$ 0.79; $\alpha$ = 0.017) (fig. 17) using June LAI and NDVI values, while in September the regression equation is negatively correlated ($R^2$ 0.66; $\alpha$=0.048) using July LAI and September NDVI values. (fig. 18).

Complete LAI and NDVI values for June and August are reported in the supporting material in table S1.

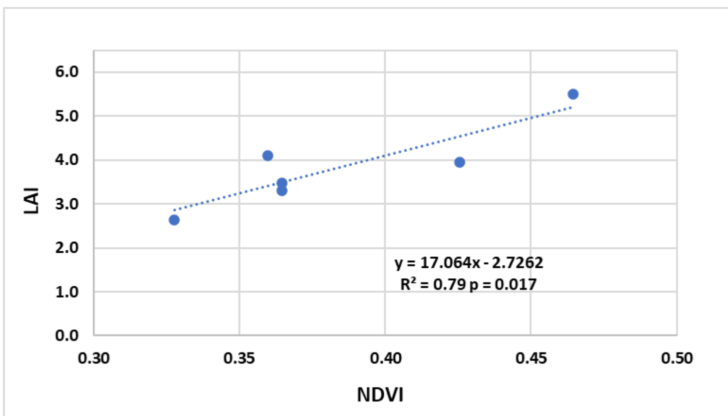


**Figure 17**. Linear relationship between normalized difference vegetation index (NDVI) and measured leaf area index (LAI) of June in dryland treatment.

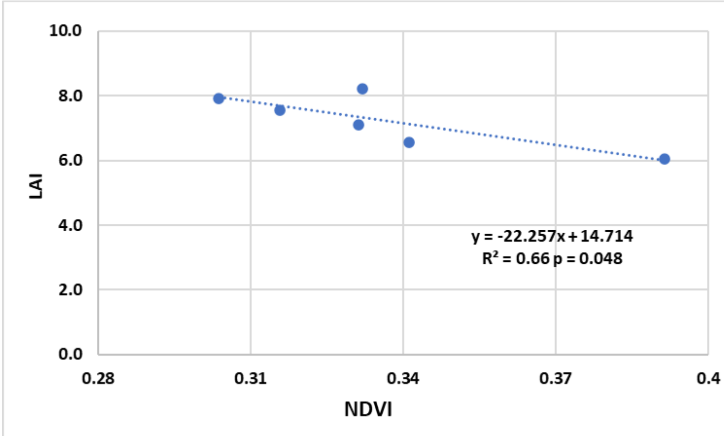


**Figure 18**. Linear relationship between normalized difference vegetation index (NDVI) of September and measured leaf area index (LAI) of July in dryland treatment.

*4.10 Relationship NDVI-Yield*

In table 10 are reported mean values of NDVI and mean yield per tree, while in tab. 5 is reported the NDVI-Yield relationship in months from June to September per each treatment T1 (100 % ETc), T2 (40 % ETc) and D (0% ETc).

NDVI-Yield relationship, showed in tab. 11, is negatively correlated in all months from June to September in all treatment. However, only in treatment T2 relationship was statistically significant at $\alpha < 0.05$ ($R^2$ 0.59 $\alpha = 0.017$; July $R^2$ 0.54 $\alpha = 0.006$; August $R^2$ 0.41 $\alpha = 0.024$; September $R^2$ 0.72 $\alpha = 0.0005$) from June to September respectively.

In treatment T1 the relationships in months were very weak although the significant relationship occurred only in July (June $R^2$ 0.17 $\alpha$ n.s.; July $R^2$ 0.38 $\alpha = 0.034$; August $R^2$ 0.33 $\alpha$ n.s.; September $R^2$ 0.22 $\alpha$ n.s.).

In treatment D, the relationship was discrete in June and July, but statistically significant only in June and very weak and not significant in August and September (June $R^2$ 0.54 $\alpha = 0.003$; July $R^2$ 0.51 $\alpha$ n.s; August $R^2$ 0.19 $\alpha$ n.s.; September $R^2$ 0.32 $\alpha$ n.s.).

**Table 10**. Mean values and standard errors of mean normalized difference vegetation index (NDVI) values and yield per tree (kg) in June to September of T1 (100% ETc), T2 (40% ETc) and D (0% ETc) treatments.

| Treatments | Mean value NDVI | | | | Yield per tree (kg) |
|---|---|---|---|---|---|
| | June | July | August | September | |
| **$T_1$** (n=12) | 0.47 ± 0.08 | 0.41 ± 0.09 | 0.45 ± 0.05 | 0.41 ± 0.08 | 3.62 ± 0.41 |
| **$T_2$** (n=12) | 0.45 ± 0.06 | 0.42 ± 0.07 | 0.47 ± 0.05 | 0.41 ± 0.07 | 3.95 ± 0.31 |
| **D** (n=6) | 0.38 ± 0.05 | 0.29 ± 0.03 | 0.34 ± 0.07 | 0.34 ± 0.03 | 4.22 ± 0.39 |

**Table 11**. Linear regression between mean normalized difference vegetation index (NDVI) and yield values per tree from June to September (Y=Yield) of T1 (100% ETc), T2 (40% ETc) and D (0% ETc) treatments.

| Trial plots | NDVI *vs* YIELD | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | June | | | July | | | August | | | September | | |
| | Regression | $R^2$ | p value | Regression | $R^2$ | p value | Regression | $R^2$ | p value | Regression | $R^2$ | p value |
| **$T_1$** (n=12) | Y= -2.23*NDVI + 4.67 | 0.17 | ns | Y= -2.95*NDVI + 4.82 | 0.38 | 0.034 | Y= -4.31*NDVI + 5.5611 | 0.33 | ns | Y= -2.29*NDVI + 4.5622 | 0.22 | ns |
| **$T_2$** (n=12) | Y= -3.90*NDVI + 5.70 | 0.59 | **0.004** | Y= -3.07*NDVI + 5.25 | 0.54 | **0.006** | Y= -3.64*NDVI + 5.6729 | 0.41 | **0.024** | Y = -4.00*NDVI + 5.5949 | 0.72 | **0.0005** |
| **D** (n=6) | Y= -5.72*NDVI + 6.42 | 0.54 | 0.003 | Y = -9.47*NDVI + 6.93 | 0.51 | ns | Y = -2.42*NDVI + 5.0472 | 0.19 | ns | Y= -7.36*NDVI + 6.6922 | 0.32 | ns |

## 5. Discussions

### *5.1 Environmental conditions*

Uninterrupted rainfall in May and June, totaling 373 mm, lasted until July 3 with 24 mm and 48 mm in August of which about 40% (fig. 5) was concentrated at the beginning of the month probably increasing groundwater reserves. This condition would not have allowed rainfed trees to deplete water in the soil**.**

Moreover, in Fig. 7 it is evident how the precipitation is well distributed in the late spring, concentrating in June. Curci et al. (2021) reported how in Abruzzo region, a rise in precipitation over the warm season, that was attributed to a combination of increasing precipitation between the months of April to June and September and decreased precipitation during the summer (July–August).

Changing in rainfall regime has been observed in the past in several work. In fact, Mosmann et al. (2003) showed that in the southern areas of continental Spain, areas where temperatures are on average higher, convective summer precipitation shows an increase (especially inland) in July and August, by 20%. Additional work in North Carolina shows that, in general, the summer season has had a slightly increasing precipitation trend over the past 60 years (Sayemuzzaman and Jha, 2014).

*5.2 Eco-physiological responses*

During the measurement period from July 21 to August 11, no statistically significant differences in mean values were shown in net photosynthesis and stomatal conductance. The continuous rainfall that occurred until the beginning of August ensured the maintenance of water reserves, added to moderate temperature values. Thereafter, the suspension of watering and the concomitant increase in temperature resulted in significant differences in the T2 and D treatment with the highest and lowest values, respectively, on August 18 and 25.

Leaf assimilation values were highly variable in both treatments T1 and T2, contrary to data reported by Cristofori et al. (2008) in 5-year-old Tonda di Giffoni trees.

Ortega-Farias et al. (2020) reported significantly higher mean values of net photosynthesis in well-watered treatments than in less-watered treatments of the 8-year-old cv Tonda di Giffoni, contrary to our study, also higher values of stomatal conductance. Girona et al. (1994) also showed some differences among treatments, especially in the deficit irrigation regime, where this latter was unsuitable for hazelnut. In contrast, with a longer period of water stress, A and G were significantly reduced (Ortega-Farias et al., 2020). Thus, in this study, the lower values of stomatal conductance in T2 and D indicate that stomatal conductance is a sensitive tool for induced stress, even if it is mild (Altieri et al., 2023), compared to net photosynthesis. Several papers have observed that the tree response, which reduces stomatal activity, is a strategy to reduce water loss and thus yield (Flexas et al., 2004; Marino et al., 2018).

Average WUE values over the measurement period, although there were no differences, were slightly higher in T2 than T1, and D recorded the lowest values (T2>T1>D). Goldhamer and Beede, (2004) in pistachios also occurred higher WUE with deficit irrigation. In T1 and D in Fig. 9, WUE decreases with the reduction of A, according to Tombesi (1994). However, the T2 treatment maintains more constant average WUE values.

*5.3 Yield and production efficiency indices*

Our study showed no significant differences between treatments, although the best production was in D, then in T2 and finally the lowest production in T1 (4.22, 3.95 and 3.61 kg per tree, respectively). In addition, 63% water was saved in T2 treatment. Gispert et al. (2005) reported how in the summer in Terragona (Spain) a reduction of 30% in supply of water, from April to September can be managed in hazelnut trees without having significant effects on nut quality or yield while when achieved 60%, yield and quality lowered significantly.

Tonda di Giffoni starts hazelnut growth in mid-June, reaching more than 30% of final volume on June 23 and more than 70% in early July, after which kernel, development start and continue for about 5-6 weeks until full size was reached (Valentini et al., 2015). There are probably no significant differences because all treatments benefitted from rainfall during the hazelnut development stage and, in part, also during kernel development in early August.

Ortega-Farias et al. (2020) reported that the deficit irrigation treatment, although reducing gas exchange, did not lead to a decrease in yield on hazelnut trees. Contrast this with reports from other studies in which the application of deficit irrigation on hazelnut trees did not increase yield but the latter was promoted by well-irrigated treatments (Girona at al., 1994; Cristofori et al., 2008; Bignami et al., 2009). While in other crops, such as 14-year-old walnut, a good yield was obtained as a water response at 50% ET0 (Cristofori et al., 2009b), and in pistachios the best yield was obtained with deficit irrigation at 50% ETc (Goldhamer and Beede 2004).

Among the production efficiency indices, the ratio of amount of total dried good kernels produced per total leaf area of the tree (TGK/LDWT) indicated T2 treatment, i.e., the treatment with daily restitution of 40% ETc, as the most efficient.

*5.4 Commercial, chemical, and fatty acid characterization of hazelnut kernels*

The final percentage of good kernels and the total discard of the incidence of defective nuts were significant in favor of treatment D, which is a dryland treatment (fogs. 15 and 16). This indicates a positive effect of the limitation or unavailability of irrigation. The defects analyzed in commercial quality, both among the parameters that showed statistically significant differences and those that did not show significance, the lowest values were in favor of D and T2 treatments except for blank defect. Also, among shelling and commercial yield and kernels with diameter ≥ 11 mm, although they did not showed differences in mean values, they showed higher percentages in D and T2 treatments.

Cristofori et al. (2008) showed, in 5-year-old Tonda di Giffoni, higher percentages of defective and blank nuts in conditions of restricted water availability, where only the blank is similar to the results of our study, but not for the defectives. Similar resulted on blank nuts were showed in walnut, while in general, again, the incidence of defective walnuts was higher in non-irrigated than in irrigated trees (Cristofori et al., 2009). Interestingly, hidden bug damage has an incidence of 19% in the treatment with daily restitution of 100% ETc, significantly different from the 8.76% in the dryland treatment (fig.15). Sconiers and Eubanks (2017) found that intermittent water stress increased the presence of phytophagous insects compared to plants with severe water stress.

Regulated deficit irrigation strategies, in the case of almond trees, have had a positive effect on reducing the presence and damage of several pests (González-Zamora et al., 2021).

The average lipid percentage was the same between treatments (tab. 6) probably the treatments also received benefits from the rainfall, especially in the first half of August, when the maximum accumulation of oil in the kernel occurs (Farinelli et al. 2001, Gonçalves et al. 2009). Cristofori et al. (2008) found higher oil content in non-irrigated plants with daily return of 50 % Etc. The average lipid value among treatments was 67 % similar value was found in Tonda di Giffoni by Botta et al., 1997. Generally, the average fat content between 62 and 65% ensures good hazelnut flavor (Cristofori, 2005), higher amounts could promote fast rancidity and loss of the product (Ozdemir et al., 2001). Carbohydrates, significantly higher in the T1 (20 % d.w.) and lower in the D (18 % d.w.) treatments, respectively, could be attributable to the higher and lower average net assimilation values in the two treatments, respectively. In contrast, opposite situation for protein, which was significantly higher in D (12 % d.w.) and lower in T1 (10 % d.w.) treatments, respectively. Total biophenols and fatty acids did not differ between treatments, probably due to the mild stress that occurred due to the rainfall recorded especially in early August, when there was the kernel growth phase.

*5.5 Relationship NDVI-LAI*

The NDVI-LAI relationship on hazelnut, addressed for the first time in this study. In fact, in the past, NDVI-LAI relationship was developed in several herbaceous crops, vineyards, pastures, mixed canopies and poplar plantations (Bajocco et al., 2022) and several tree crops. In olive trees, the relationship between NDVI and LAI by UAV was well correlated in both irrigated and rainfed trees (Caruso et la., 2019), grapevine (Caruso et la., 2017), apple orchards (Liu et al., 2021) and hedgerow olive orchards from satellite images (Cantini et al., 2023).

The research identified a significant relationship between LAI and NDVI in dryland treatments. This suggests that only in the dryland hazelnut orchard LAI can be estimated using NDVI values. In June (Fig. 17), the relationship is positive because the leaves were still young, and the leaf area was not complete. In September, instead, the relationship is negative (Fig. 18) because the leaves were towards senescence and LAI value was referred to mature leaves. The negative NDVI-LAI relationship in September has already been found in a previous study of a six-year-old unirrigated hazelnut orchard (unpublished data).

*5.6 Relationship NDVI-Yield*

The NDVI-Yield relationship addressed for the first time in this study, was found to be negative and significant in all months from June to September in the T2 treatment (Tab. 9). This indicates that as NDVI values increase, production decreases explaining that in hazelnut vigorous plants are not indicative of high production. In the T2 probably, compared to the other treatments, there is a good trade-off between vegetative renewal and production, which would explain the significance in all months. The relationship has been studied mainly in olive orchard (Caruso et al., 2019; Caruso et al., 2021; Sola-Guirado et al., 2017; Stateras et al., 2020) and apple (Liakos et al., 2018; Van Beek et al., 2015).

## 6. Conclusions

The study area is historically an area suitable for hazelnut production, characterized by seasonal precipitation exceeding the needs of the hazelnut and well distributed throughout the year. But, in recent years a change in the distribution of precipitation events has been observed, affecting mainly the months of May and June, when irrigation would be appropriate.

Total yield did not manifest statistically significant differences in mean values between treatments with different level of ETc restitution. In the qualitative analysis of the kernels, the dryland treatment showed lesser defects in total and significantly different from the treatment with full ETc restitution.

Of particular relevance was the significant high percentage of hidden bug damage in the 100 % ETc daily restitution treatment compared to the dryland treatment. This aspect if confirmed in the future is to be considered in sustainable defense management. Full irrigation could therefore result in an increase in insecticide use as well as a greater environmental and economic impact in the 100% ETc treatment. A novel aspect of the research was the construction of NDVI-LAI and NDVI-Yield relationships in the studied hazelnut orchard. The NDVI-LAI relationship suggests that in the dryland orchard hazelnut it's possible to estimate LAI using NDVI value. In contrast, the NDVI-Yield relationship indicates that vigorous hazelnut trees are not indicative of high productivity. In fact, treatment T2 showed a negative and significant LAI/Yield correlation in all months from June to September. It is hypothesized that a good balance between vegetative renewal and production was reached in the T2 treatment. In addition, the same treatment manifested the highest efficiency in terms of amount of seeds produced per total leaf area tree (LDWT).

Based on one year's results, the dryland treatment and the treatment with daily restitution 40 % ETc showed the best performance. The treatment with restitution daily 40 % Etc, which saved 63 % water compared to the T1 treatment, appears to be a good compromise with reduced water inputs for sustainable hazelnut orchard management. Considering the climatic changes occurring, not watering would expose the crop to extreme weather events during the summer period, increasingly more frequent, which combined, often, with abnormal years would compromise production.

The experiment should be extended for at least a two-year production cycle to evaluate the effects of irrigation levels on the crop's reproductive and production cycle.

In the future, it will certainly be necessary to investigate NDVI/LAI and NDVI/Yield relationships over time and in systems of different ages. In addition, verify the impact of the action of irrigation levels on insect bug damage, which has important repercussions, not only on yield results, but especially on crop defense management.

### Supporting materials

**Table S1**. LAI and NDVI values for June and July per each tree.

| Treatment | Plot | Tree number | LAI June | LAI July | Mean NDVI value- June | Mean NDVI value- August |
|---|---|---|---|---|---|---|
| 100% ETc | T1.1 | 1 | 3.4 | 7.5 | 0.54 | 0.46 |
| | T1.1 | 2 | 3.6 | 6.4 | 0.35 | 0.37 |
| | T1.1 | 3 | 4.0 | 8.0 | 0.35 | 0.36 |
| | T1.1 | 4 | 5.7 | 7.3 | 0.54 | 0.45 |
| | T1.1 | 5 | 5.0 | 6.7 | 0.44 | 0.42 |
| | T1.1 | 6 | 5.4 | 6.4 | 0.39 | 0.42 |
| 40% ETc | T2.1 | 1 | 2.5 | 6.7 | 0.50 | 0.51 |
| | T2.1 | 2 | 1.9 | 6.0 | 0.53 | 0.54 |
| | T2.1 | 3 | 4.3 | 6.4 | 0.55 | 0.49 |
| | T2.1 | 4 | 4.5 | 7.2 | 0.46 | 0.49 |
| | T2.1 | 5 | 1.9 | 6.7 | 0.47 | 0.48 |
| | T2.1 | 6 | 4.1 | 7.5 | 0.54 | 0.43 |
| 40% ETc | T2.2 | 1 | 5.8 | 5.4 | 0.35 | 0.42 |
| | T2.2 | 2 | 3.0 | 7.3 | 0.39 | 0.45 |
| | T2.2 | 3 | 3.3 | 7.1 | 0.43 | 0.44 |
| | T2.2 | 4 | 2.1 | 5.1 | 0.44 | 0.51 |
| | T2.2 | 5 | 4.7 | 5.6 | 0.50 | 0.51 |
| | T2.2 | 6 | 3.8 | 7.0 | 0.52 | 0.55 |
| 100% ETc | T1.2 | 1 | 3.8 | 7.2 | 0.51 | 0.54 |
| | T1.2 | 2 | 4.8 | 7.3 | 0.51 | 0.50 |
| | T1.2 | 3 | 5.5 | 7.1 | 0.47 | 0.48 |
| | T1.2 | 4 | 4.2 | 5.8 | 0.49 | 0.49 |
| | T1.2 | 5 | 4.1 | 6.7 | 0.41 | 0.39 |
| | T1.2 | 6 | 6.7 | 7.5 | 0.37 | 0.39 |
| 0% ETc | D | 1 | 3.5 | 7.6 | 0.36 | 0.33 |
| | D | 2 | 2.6 | 6.6 | 0.33 | 0.23 |
| | D | 3 | 4.1 | 7.9 | 0.36 | 0.38 |
| | D | 4 | 3.3 | 6.0 | 0.36 | 0.45 |
| | D | 5 | 4.0 | 7.1 | 0.43 | 0.35 |
| | D | 6 | 5.5 | 8.2 | 0.46 | 0.31 |

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**Sitography**

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## Final conclusions

The research presented includes a comprehensive investigation of various aspects of hazelnut cultivation, combining insights into UAV technology, irrigation practices, physiological responses to water stress, and impact on yield and quality.

1. **UAV technology for orchard management**

The integration of UAVs equipped with spectral sensors emerges as a valuable tool for hazelnut orchard management.

The technology facilitates the calculation and monitoring of key biophysical and geometric parameters, such as leaf area index (LAI) and canopy volume. The study acknowledges limitations related to measuring only the canopy edge in the top view, highlighting potential errors with tree overlaps.

2. **Physiological responses to water stress**

Mild water stress induces significant differences in hazelnut trees' physiological behavior.

Stomatal conductance, especially in the north and west aspects, are identified as sensitive indicators of early stress. Water potential does not exhibit a rapid response to stress, suggesting its limited utility as an early stress indicator in hazelnuts.

3. **Implications for sustainable irrigation practices**

The research emphasizes the need for sustainable irrigation scheduling that takes into account rainfall patterns.

The dryland and the treatment with 40 % daily ETc restitution show superior performance, suggesting reduced water inputs for sustainable hazelnut management.

Full ETc restitution, while not having a significant impact on total yield, shows a higher percentage of hidden bug damage, pointing to potential implications for sustainable defense management.

The study suggests that full irrigation could lead to increased insecticide use, resulting in environmental and economic impact.

The construction of NDVI-LAI and NDVI-Yield relationships introduces new insights. In the dryland orchard, the LAI can be estimated using NDVI values, but the NDVI-Yield relationship indicates that, in hazelnut, vigorous plants do not correlate with high productivity.

**Future research directions**

Future investigations are recommended to explore NDVI/LAI and NDVI/Yield relationships over time and in orchards of different ages. Further investigation of the impact of irrigation levels on insect damage is essential for crop defense management.

In conclusion, this research not only contributes useful information on hazelnut orchard management, but also highlights the need to continue exploring sustainable practices, taking into account technological advances, physiological responses, and changing climatic conditions. The results provide a series of implications of practices for hazelnut cultivation in agricultural landscapes in both suitable and evolving areas.

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