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Techniques for the improvement of economic efficiency and environmental sustainability of hazelnut orchards.

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Summary

The efficiency of modern orchards is a key factor to achieve a sustainable farming system. To be efficient, it is essential to understand which practices have the greatest impact on tree growth and production. The experiments reported in this thesis aimed to investigate the response of the main inputs and agronomic operations applied in young hazelnut orchards. The work was structured as follows:

1. Effects of irrigation scheduling on plant water status and growth. Different irrigation schedules were evaluated in young hazelnut trees to assess their effects on plant water status and canopy development. In particular, the comparison between single and split daily irrigation highlighted how irrigation timing influences physiological performance and vegetative growth during orchard establishment.
2. Stem water potential (Ψ_{stem}) baseline for hazelnut irrigation management. A stem water potential (Ψ_{stem}) baseline relating midday Ψ_{stem} to vapor pressure deficit (VPD) was developed under non-limiting soil water conditions. This relationship provides a physiological reference framework to support more precise, plant-based irrigation management in hazelnut orchards.
3. Hazelnut Nitrogen (N) Fertilization: young field-grown plants were fertilized with increasing N rates to obtain different levels of leaf N concentration. Key physiological parameters (leaf photosynthesis, chlorophyll fluorescence, leaf water relations) were measured to define the optimal leaf N range.
4. Soil Management: the effects of mulching and green manuring on plant growth were assessed. Soil tillage and herbicide-based under-row management were also tested to identify the most effective practice—both physiologically and economically—for supporting tree development during the establishment phase.

Irrigation scheduling proved to be the most effective agronomic practice influencing plant performance during the establishment phase. The comparison between single and split daily irrigation highlighted how irrigation timing affects plant water status, physiological activity, and canopy development. Split irrigation promoted faster vegetative growth and higher yield without increasing management costs, confirming its suitability as an efficient strategy for young hazelnut orchards.

Stem water potential (Ψ_{stem}) baseline definition provided a physiological reference framework for interpreting plant water status in relation to atmospheric demand. The relationship established between midday Ψ_{stem} and vapor pressure deficit (VPD) under non-limiting soil water conditions supports the adoption of plant-based irrigation management approaches, improving the precision of irrigation decisions in hazelnut orchards.

Regarding nitrogen fertilization, results showed that as canopy size increased, the amount of broadcasted nitrogen fertilizer required to reach the optimal foliar concentration was more than three times higher than conventional rates applied by hazelnut growers. However, during the first two years, optimal doses were identified, and an optimal foliar N concentration was determined in correlation with photosynthetic rates.

Soil management practices did not produce marked effects on plant physiological parameters. Among the evaluated treatments, organic mulching proved to be a valid option for stimulating vegetative growth, with effects comparable to soil tillage. Nevertheless, mulching was associated with higher costs per hectare, which may limit its economic convenience under most production contexts.

In conclusion, the results of this thesis show that, during the establishment phase of hazelnut orchards, the most impactful drivers of efficiency are water and nitrogen management rather than soil management practices. While mulching can support growth, its benefits do not compensate for its higher costs under most production contexts. In contrast, irrigation scheduling and an adequate supply of nitrogen—adjusted to canopy expansion—proved essential to maximize early growth, photosynthetic performance, and yield.

Overall, this work provides a practical framework for young orchard management, highlighting which agronomic operations deliver the greatest return on investment under current climatic constraints and resource limitations. These insights can support growers in designing more efficient, resilient, and economically sustainable hazelnut production systems.

CHAPTER 1

Introduction

One of the most significant differences, other than biological ones, between herbaceous crops and fruit tree crops concerns their economic cycle. For herbaceous crops, the cycle from planting to harvesting is completed in one year for most cultivated crops (i.e. corn, wheat, etc.) and it ends with the termination of the crop to start a new cycle on the next year. For tree crops, completing a cycle requires many years. For instance, in hazelnut trees (*Corylus avellana L.)*, the average lifetime of an orchard is 40-50 years (Mehlenbacher, 1991). So, from an economic point of view, the investment in a fruit crop is riskier than an annual crop, due to the long-life period of an orchard. In addition, investment in a fruit crop is a multi-annual investment, due to the reasons explained above.

Usually, saplings used to plant new orchards are 1-2 years old and, depending on the species, the first commercial significant fruit bearing is between 3rd to 5th or 7th years after planting, depending on variety, agronomic inputs and environment. This implies that the farmer has to invest in the crop during the first years with no remuneration. Economic studies conducted in Oregon report that, although commercial production begins as early as the third year, net cash flow becomes positive only after 9 years in standard-density orchards, and even as late as the 13th–14th year in more recent scenarios (Miller et al., 2013; Wiman et al., 2022). Analyses carried out in Italy confirm the critical nature of this period: in Latium region, the average payback time was estimated at about 10.5 years for conventional orchards, while in organic systems it exceeds 40 years (Coppola et al., 2020). During these early phases, the burden of financial charges can reach 40–50% of total costs, further increasing the economic risk (Wiman et al. 2022)

In broader terms, most tree fruit crops require at least 15 years to complete an economic cycle, with the first 4–5 years being predominantly cost-intensive and without yield, and with variable incomes exacerbating uncertainty (Reetwika et al, 2020).

In this context, there is a clear need to make hazelnut cultivation more competitive and profitable by shortening the unproductive phase, thereby reducing the length of the unproductive period. It is known how in hazelnut trees, as well as other species, the volume of the canopy is correlated to yield. To enhance growth during the first years, it is essential to identify the most effective agronomic practices and apply them in a way that they maximize plant's growth. Agronomic practices that increase vegetative growth and promote flower bud initiation have therefore been widely investigated as strategies to shorten the non-bearing period (Girona et al., 2005; Trentacoste et al., 2015; Carranca et al., 2018; Mészáros et al., 2023). Among these, nitrogen supply, irrigation management, and orchard floor management play a key role. Regarding nitrogen fertilization, there are several studies that show how important it is for the growth of the plant during first years after planting (Carranca et al., 2018). In addition, it was seen in apple that nitrogen fertilization has increased the shoot length and promoted flower induction (Mészáros et al., 2023). The other key player for sustained growth is water availability. In olive trees, it has been observed that applying deficit irrigation during the initial years can improve water-use efficiency, although it reduces vegetative growth by approximately 35%. (Trentacoste et al., 2015). Similar conclusions were reported in *Prunus* spp., where regulated deficit irrigation applied too early and negatively affected yield stability, whereas well-timed irrigation schedules supported both vegetative growth and early fruit set (Girona et al., 2005). Competition between fruit crops and weeds can limit trees growth as well. It has been observed in long-term trial on apple orchards that the competition of the weeds affects tree vegetative growth especially in the first 3-5 years after planting; treatments with herbicide or mulching strips consistently enhanced trunk cross-sectional area, shoot growth, and early yields compared with sod or unmanaged vegetation (Atucha et al., 2011). Previous studies confirmed that weed competition substantially reduces nutrient uptake and tree vigor, while maintaining a weed-free strip or organic mulch under the tree row improves early orchard performance (Merwin & Stiles, 1994).

1.1 Nitrogen fertilization

Nitrogen is one of the essential elements for the normal physiological activity of plants. It is a major component of chlorophyll, and adequate nitrogen supply determines chlorophyll content, which strongly influences photosynthetic efficiency. Through this process, plants assimilate CO_2 and convert it into carbohydrates, which are fundamental to fuel plant growth and development.

In Italy, different authors suggest different rates of nitrogen requirements at different growth stages. At third year after planting, Italian disciplinary for integrated production suggest a dose of 70 kg of nitrogen, meanwhile two important texts of reference for hazelnut cultivation suggest 100 kg (Tombesi, 1985) and 56 kg (Botta, 2018) at third year.

Regarding the modality of partition of this nitrogen, Olsen et al. (2001) showed that only a limited share of the applied labeled N is incorporated into new tissues, as hazelnut trees preferentially allocate fertilizer-derived N to storage pools while relying predominantly on pre-existing reserves to sustain early-season growth; moreover, the efficiency and distribution of absorbed N varied markedly with application timing and method, with spring ground applications being more effectively partitioned to developing organs than June applications, and foliar sprays in mid-summer or post-harvest resulting in distinct partitioning patterns among leaves, nuts, and perennial tissues. Several trials in the Upper Midwest (USA) on hybrid hazelnuts (*C. avellana* × *C. americana*) demonstrated that split applications and moderate rates enhance nitrogen uptake efficiency and promote trunk and canopy growth, while excessive fertilization reduces nitrogen use efficiency (NUE) and risks environmental losses (Braun et al., 2009; Braun & Rowley, 2011). More recent studies in Oregon highlighted the need to update N guidelines for modern irrigated orchards: fertigation systems improved both partitioning of applied N and cumulative yield, with irrigated orchards consistently outperforming dryland systems (Wiman et al., 2023).

Similar evidence comes from China, where one-year-old *C. avellana* × *C. heterophylla* seedlings responded positively to moderate N inputs (22 g plant^{-1}), which maximized root biomass, shoot growth, and photosynthetic capacity, while higher doses caused root damage and growth inhibition (Li et al., 2019).

In Turkey, subsurface applications of urea split into two doses significantly increased hazelnut yield, kernel ratio, and leaf N concentration compared with surface applications or single doses, showing that timing and placement are critical to maximize efficiency (Özkutlu et al., 2024).

Finally, recent controlled-environment experiments with 1 year old *C. avellana* 'Tonda di Giffoni' provided the first systematic description of nutrient deficiency symptoms, demonstrating that reducing N supply by 50% decreased biomass accumulation and induced visible chlorosis (Voogt et al., 2023).

1.2 Irrigation

It is known that filbert has a low tolerance to drought stress, especially young hazelnut trees. Irrigation is a critical determinant of both vegetative growth and yield. Mingeau et al., 1994 highlights how the period of drought can influence the yield, especially if the drought period extends for 10 or more days before fecundation, reaching 60% deficit in production. However, with climate change scenarios it is always more important for farmers to aim for sustainable use of water. Different studies try to provide farmers with different solutions to save water in determinate period of the season or set lower limits of deficit irrigation without jeopardizing productivity.

General reviews on deficit irrigation strategies, such as regulated deficit irrigation (RDI) and partial root-zone drying (PRD), have demonstrated their effectiveness in saving water and moderating excessive vegetative vigor in mature orchards. However, Fereres & Soriano (2007) clearly noted that in young orchards water deficits have markedly different consequences: reduced canopy expansion, lower photosynthetic capacity, and ultimately a delayed transition to full production. This distinction underscores the importance of avoiding early-season water stress when orchard establishment and canopy development are the primary goals.

Long-term lysimeter experiments in France provided the first detailed quantification of hazelnut water use under non-limiting conditions, showing that evapotranspiration (ET) nearly doubled within eight years as trees expanded, while transpiration increased more than sixfold (Mingeau & Rousseau, 1994). Crop coefficients rose from 0.4–0.5 in spring to 0.65–0.8 in summer, with maximum daily water demands of up to 6.5 mm and irrigation requirements reaching 35–50 L $tree^{-1}$ day^{-1} in July–August. These data highlight how canopy development and ground occupancy directly govern the seasonal water requirement of hazelnut. More recently, Vinci et al. (2023) provided refined estimates of midseason crop coefficients for young, grafted hazelnut trees established at high density in Central Italy. Using direct measurements of transpiration and evapotranspiration, they reported Kc values ranging from 0.55 to 0.65 in the second and third years after planting, confirming that juvenile orchards have lower water requirements than mature trees but remain highly sensitive to soil water availability.

Recent trials in Spain confirmed that not only the amount but also the spatial distribution of water is critical: maintaining about one-third of the root zone wetted under drip irrigation maximized shoot growth and nut yield, whereas both insufficient wetting (<20% WSV) and excessive wetting with microsprinklers (~67% WSV) reduced vegetative development and productivity (Gispert et al., 2015). Together, these findings demonstrate that hazelnut water requirements increase sharply with canopy expansion, and that efficient irrigation management must balance both the volume and the spatial pattern of soil wetting to sustain early growth and yield. However, several long-term studies confirmed hazelnut sensitivity to water availability. Experiments in Central Italy showed that drip irrigation substantially increased trunk cross-sectional area, crown volume, and nut yield compared with rainfed conditions, while restoring approximately 75% of crop evapotranspiration (ETc) was sufficient to optimize yield and nut quality by reducing the proportion of blank nuts (Bignami et al., 2009; Cristofori et al., 2014).

1.3 Inter-row soil management

Weed control is important especially when trees are young and spontaneous flora is more efficient in absorbing water and nutrients from the soil. Maintaining the tree row free from competition during the first years is therefore critical to support canopy development and to accelerate the onset of production. There are different techniques that can be used, any of them have different efficacy per application, different cost of application and different long-term durability. In addition, all of them have an impact on soil quality and crop growth.

Evidence in hazelnuts has confirmed the detrimental effect of weed interference and the positive impact of early control measures. Pedroso and Moretti (2022) tested several pre-emergence herbicides in newly planted orchards in Oregon and reported up to 79% reduction in weed biomass, with negligible phytotoxicity and no negative impact on trunk cross-sectional area or canopy volume. However, herbicide programs require repeated applications, raise environmental concerns, and contribute to the development of herbicide-resistant species, such as Italian ryegrass, which is already problematic in many hazelnut-producing regions (Kaya-Altop et al., 2016).

Alternative approaches such as mulching and cover crops have been explored in hazelnut orchards with promising results. Mennan and Ngouajio (2012) demonstrated that hazelnut husk mulch applied at 10 cm depth reduced weed biomass by up to 83% and that brassica cover crops provided additional suppression, highlighting the potential of integrating organic residues into orchard management.

Further evidence comes from studies on related nut and fruit crops, which provide a broader perspective. In young almond orchards, mulching with synthetic materials increased plant height and trunk diameter compared with flaming or untreated controls, indicating that mulching can directly enhance vegetative growth by reducing competition and improving soil water retention (Kitiş & İbrişim, 2024). In long-term trials on almond orchards, soil management practices such as tillage, herbicide application, mowing, and cover cropping with faba bean were shown to alter ground flora composition and soil fertility, with clear implications for both costs and sustainability (Fracchiolla et al., 2015). Similarly, in olive orchards, Lodolini et al. (2024) compared synthetic mulching with mechanical hoeing and reported that mulching provided more durable weed control andincreased early tree growth and doubled yields by the third year.

These studies converge on the idea that the choice of under-row management technique involves a trade-off between short-term economic costs and long-term agronomic benefits. Chemical herbicides provide the lowest initial cost and effective weed control, but they offer limited benefits for soil health and may compromise sustainability. Mechanical cultivation and mowing reduce herbicide use but require repeated operations, with higher labor and fuel costs and potential risks of root damage. Mulching and cover crops, on the other hand, demand higher upfront investments and careful management, yet they improve soil structure, water retention, and organic matter, and in several cases have been associated with greater vegetative growth and earlier yield.

1.4 Aims and hypothesis

Given the importance of reducing the long unproductive phase that characterizes hazelnut orchards, soil management, nitrogen fertilization, and irrigation are practices that can influence early growth and physiological performance. As hazelnut cultivation expands and productivity shows signs of stagnation in several Italian regions, growers increasingly need clear guidelines to support early canopy development and anticipate the onset of bearing. Within this framework, we hypothesized that the different agronomic practices tested in this thesis would generate distinct effects on tree physiological activity—particularly carbon assimilation and water status—and that these differences would be reflected in vegetative growth during the establishment phase. We also expected that, within each experiment, the treatment achieving the strongest improvement in growth or physiology might not necessarily be the most convenient, making it essential to identify those options that offer the best balance between cost and efficiency.

The aim of this study was therefore to evaluate how contrasting agronomic practices influence the physiological functioning and vegetative development of young hazelnut trees, with particular attention to the early stages of orchard establishment. At the same time, the study intended to identify, within each experimental comparison, which treatments offered the most favorable compromise between agronomic performance and the relative cost of implementation.

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CHAPTER 2

Daily split irrigation increases plant development in young hazelnut trees.

Abstract

Irrigation has a pivotal role in promoting filbert tree growth which is fundamental in the very first phase of the life span of a new orchard to reduce the unproductive period. The aim of this work was to evaluate the effects of high frequence irrigation schedule, using previous physiological studies on other crops which highlights a higher vegetative growth in after-noon hours. The experiment was carried out on second leaf trees and fifth leaf trees. Two different irrigation schedules were tested, a single irrigation per day as control and a split irrigation featured of two irrigation ones at noon and one at evening; both irrigations spread the same volume of water per day. The split irrigation treatment resulted in higher vigor of the plants with an increase after the first year of the treatment of 30% of Trunk Cross Section Area (TCSA) and 85% of the weight of pruned suckers respectively to the single irrigation treatment. These results on vegetative indexes were obtained by the boost given by midday irrigation which increased stem water potential (Ψ_{stem}) after the midday irrigation in second leaf trees. Similar effects were noticed on fifth leaf plants where the spatial disposition of soil moisture volume (SMV) played a key factor on replicate the effect of the first experiment.

2.1. Introduction

Hazelnut (*Corylus avellana L.*) is one of the most important nut crops cultivated in the world with almost one million hectares. Türkiye and Italy are the largest producers of hazelnut followed by Chile, USA, Azerbaijan and Georgia. Over the last twenty years the area cultivated for hazelnut production increased more than 50% and world production grew more than 30% (Food and Agriculture Organization of the United Nations, 2023).

In Italy, the area dedicated to hazelnut production is almost 85.000 hectares further to 10.000 new hectares planted in the last three years, mostly located in Piedmont (north-west of Italy), Latium (in Viterbo area) and in Campania (South Italy) (Istituto Nazionale di Statistica, 2023). Depending on several factors, the very first production of a filbert orchard starts between 3rd and 5th year after planting, but the maximum productivity is reached between 12th and 15th year (Tombesi, 1985). The long initial unproductive period of filbert orchards is one of the major issues for growers who must invest money in crop management for a prolonged period without having an immediate payback. To reach early first bearing it is necessary to force plant growth; the optimization of forcing techniques such as fertilization and irrigation is fundamental to reaching this target.

Filbert requires more than 800 mm of water distributed over the year (Tombesi, 1985). Usually, in temperate climates, such as that in Italy, precipitations are concentrated between October and November, and between March and April (Brunetti et al., 2001). Due to climate change, precipitations tend to become more concentrated in autumn and spring and more erratic in summer leading to extended drought periods during the part of the season most important for filbert vegetative growth (Trenberth, 2011). For this reason, it is fundamental for irrigation to meet the water needs of the plant over the whole life of the orchard and maintain the good vegetative status of plants. In filbert the most used irrigation technique is drip irrigation (Cristofori et al., 2014), which allow a good elasticity in irrigation scheduling concerning irrigation duration and frequency, but only wets a limited area of soil (Bravdo and Proebsting, 1993)

During the vegetative season the filbert crop evapotranspiration (ET_c) doubles from the beginning of the season with a crop coefficient (Kc) of 0.4 to the warmest and arid period with a Kc of 0.8 (Mingeau and Rousseau, 1994). Another critical factor influencing ET_c in tree crops is the crop cover fraction (f_c), which represents the proportion of soil surface covered by vegetation (Allen et al., 1998; Marsal et al., 2014). This parameter is particularly significant in tree crops, where ground cover is initially limited. During the first years of growth, the gradual increase in f_c—correlated with canopy expansion and the percentage of ground occupancy—leads to a corresponding rise in transpiration. However, as trees mature, transpiration does not increase linearly due to factors like shading and radiation interception (Mingeau and Rousseau, 1994). The interplay between fc and the exposed and wetted soil fraction (f_{ew}) is also crucial. For instance, f_{ew} is calculated as the minimum of $(1 - f_c)$ and the fraction of soil wetted by irrigation (f_w). In systems like drip irrigation, where water is localized under the canopy, f_w is reduced to account for shading, often halving its effective value. Consequently, a low fc in young orchards results in higher f_{ew}, amplifying evaporation, while increasing fc in mature orchards reduces f_{ew}, shifting the balance toward transpiration and improving water use efficiency. This dynamic highlights the necessity of accurately modeling f_c and f_{ew} when optimizing irrigation strategies and calculating ET_c (Allen et al., 1998).

In filbert, soil moisture above 60% of field capacity causes no reduction of leaf photosynthesis (Tombesi, 1995). However, vegetative growth is usually linearly correlated with water potential (Williams and Araujo, 2002). Indeed, water potential depends on the VPD and on the soil water potential which is influenced by water content and soil texture. At field capacity soil water potential can be -0.27 MPa in clay soil and -0.18 MPa in sandy soil (Jabro et al. 2009). The availability of free water (i.e. water in the soil microporosity), as during irrigation, can lead to the increase (i.e. less negative) of tree water potential (Améglio, et al., 1999).

Filbert root apparatus is concentrated between 5 and 50 cm in depth in medium texture soil in adult plants and the surface occupied by roots is larger than the canopy projection (Fregoni and Zioni, 1962). In drip irrigation, the soil moisture volume (SMV) is proportional to the emitter flow, total emission volume, time of irrigation, numbers of emitters per plant and it is influenced by soil texture and depth (Gispert et al., 2015). Gispert et al. (2015) reported that the greater vegetative shoot growth were achieved with a percentage of 33% of SMV, despite the others SMV of 6%, 15% and 70%.

Vegetative growth in filbert is fundamental both in the initial part of orchard life since it determines the rate of the increase of yield when trees have not yet filled the allotted space and a fundamental determinant of productivity in mature orchards since it influences the length of shoots that determine the number of female flowers. Furthermore, shoot length and the number of vegetative buds formed in the current year determine carry over effects in the following seasons by influencing plant architecture and bearing (Grisafi and Tombesi, 2023).

The hypothesis of this work was that providing the same quantity of water split in multiple applications could allow filbert trees to increase their water potential and to have larger vegetative growth. This could be a no-cost strategy to force young filbert tree growth and advance the first bearing.

Our aim was to evaluate the effect of irrigation schedule (same volume provided in a single application or split in two applications) on filbert physiology and on the vegetative reproductive activity of trees during the second year after planting, and in adult trees.

2.2. Material & methods

Experimental site and plant material

The experiment was carried out in Piacenza at the experimental hazelnut orchard of the Università Cattolica del Sacro Cuore (45°02'03.2"N 9°43'51.7"E; 61 m a.s.l.) in 2023. The orchard (*cv* Tonda di Giffoni) was drip-irrigated. Piacenza is located in the south-central part of the Po Valley where the climate features are between the Mediterranean climate and the continental/oceanic one of Central and Western Europe (Nistor, 2016). In 2023 between bud break and leaf senescence (from April to November) the daily average temperature varied from 10°C to 27°C and a cumulate annual precipitation of 421.2 mm. The soil was silty clay loam texture based on USDA soil classification (20% sand, 43% silt and 37% clay) and the volumetric soil water content at field capacity (θ_{FC}) and wilting point (θ_{WP}) were 33,9% and 20,2% respectively (WP4C, Soil Water Potential Lab Instrument, METER group, Pullman WA, USA) (Fig 2.1).

Two experiments have been carried out over 2023 and 2024. The hazelnut orchard used in Experiment 1 was planted in January 2022 with spacing 4 m on the row and 4 m amid the rows (625 tree ha^{-1}) and trained single-stem system. The second leaf orchard was irrigated by a single drip line with a single emitter (4 l h^{-1}) per each tree placed at 50 cm above the soil level over the tree. The filbert plants used in the Experiment 2 were at the fifth leaf and they were irrigated by a single drip line with two emitters, rispectively 4 l h^{-1} and 8 l h^{-1}placed 50 cm far from the plant trunk. Normal horticultural cares were applied, in detail: 50 kg ha^{-1} of nitrogen were broadcasted at 6 times during the season (in first two broadcasting urea 46% was used and in the last four broadcasting ammonium nitrate 27% was used). Orchards were tilled (10 cm depth) just on the row. In both, second and fifth leaf plants, the irrigation was scheduled to replenish 100% of the actual evapotranspiration ($ET_a = ET_0 \times K_c \times K_r$, where ET_0 correspond to reference evapotranspiration (mm day^{-1}), K_c correspond to crop coefficient (dimensionless), K_r correspond to ground occupancy of the canopy (dimensionless) from April (bud break) to October (leaf fall). ET_0 was estimated using Penman–Monteith equation using as input air temperature (Ta), relative humidity (RH), solar radiation (Rs), and wind speed (Ws) (Allen et al., 1998). Actual evapotranspiration (ET_a) was calculated as $ET_a = ET_o \times Kc \times Kr$, assuming non-limiting soil water conditions. Reference evapotranspiration (ET_o) was estimated using the FAO Penman–Monteith method (Allen et al., 1998), which is internationally recognized as the standard for determining atmospheric evaporative demand.

The crop coefficient (K_c) was fixed at 0.8 from April to October in accordance with lysimetric measurements on filbert (Mingeau and Rousseau, 1994), while K_r accounts for changes in effective ground cover. K_r was calculated following FAO-56 as the reduction factor associated with the fraction of soil shaded by the canopy, defined as $K_r = 1 - f_c$, where fc is the canopy ground cover fraction. In the early years of the orchard, f_c was estimated geometrically from the canopy projection on the soil; thus K_r decreased progressively as trees grew and ground cover increased. This approach ensures that ET_a represents the actual water requirement of trees under the specific orchard structure and developmental stage. In the experimental orchard, a weather station (Netsens s.r.l., Calenzano (Firenze), Italy) was installed, which measured Ta, RH, Rs, Ws, and precipitation (Pp).

In the experimental orchard, was installed a weather station (Netsens s.r.l., Calenzano (Firenze), Italy) which measured Ta, RH, Rs, Ws, and precipitation (Pp). The K_c value used in this study was 0.8 from April to October following Mingeau et al. (1994). Detailed monthly ETc values and the corresponding daily irrigation supply per plant (L plant^{-1} d^{-1}) are reported in Table S1 of the Supplementary Materials

Experimental design

Experiment 1

Two treatments were applied on second leaf trees (08/17/2023). Both treatments were irrigated by drip irrigation system with 100% of ET_c, one irrigated in a single shift (control) in the evening (19:00) and the other one irrigation was split in two shifts (split) at midday (12:00) and in the evening (19:00). Per each treatment a single row of 25 plants was irrigated, 10 plants were randomly selected as replications. Midday stem water potential (Ψ_{stem}) stomata conductance (g_s), transpiration rate (E) and net photosyntesis (P_n) where were measured over the day. The Ψ_{stem} for the daily trend was measured 4 times during the day (04:00; 10:00; 12:00; 16:00 UTC+1) using a pressure chamber (model 3005H07G4P40, Soil Moisture Equipment, Santa Barbara, CA, USA). Fully mature and healthy leaves located in the middle of the current-year shoot were sampled. One leaf for each of the 10 replicates was covered with completely hermetic aluminum foil for 30 minutes before the measurement time. The leaves were cut and immediately placed in the chamber. g_s, E and P_n were measured right after Ψ_{stem} measurement using a portable gas analizer (LC*pro* T, ADC BioScientific, Hoddeston, UK).

In 2024 , in the same orchard, the same treatments of the previous year where applied; Ψ_{stem}, g_s, P_n and electron transport rate (ETR) were measured each 15-20 days during the vegetative season from July to November, (between 12:00 and 15:00 h; UTC+1). Trunk cross section area (TCSA) (cm^2) was measured before bud break and after fall leaves. The weight of pruned sucker growth in the courrent year (kg), the length of the longest shoot of the previos year and of the courrent year (cm), the number of shoots of the courrent year and the number of female flower was measured in december 2023 and december 2024. The senescence index was calculated the ratio between the length of the longest shoot formed in the current year on an apical two year old shoot and the length of the same two year old shoot.

Experiment 2

Six plants, half of them irrigated in a single turn (control) in the evening (19:00) and in the other half the irrigation turn was split in two shift (treated) at midday (12:00) and in the evening (19:00). The experiment was repeated over two distinct days (06/26/2023 and 07/20/2023) . On the first date drip irrigation was used while on the second date flooding irrigation was applied. The Ψ_{stem} for the daily trend in the experiment with irrigation by drip lines were measured pre-dawn at 4:00 and continously each half of hour from 7:00 to 17:30. For flooding irrigation trial Ψ_{stem} was measured 4 times during the day (04:00; 10:00; 12:00; 16:00 UTC+1) using a pressure chamber with the same method used for the experiment 1. Five leaves per each treatment were sampled. Gas exchange were measured right after Ψ_{stem} measurement, in the same way of experiment 1.

Soil moisture volume (SMV)

To measure the SMV for both treatments without disturbing the root system of the experimental trees, the assessment was conducted away from the plants. The dripline was temporarily moved 2 m from the tree row, and excavations were performed in an adjacent, undisturbed soil strip free of roots. This procedure ensured that the measurements did not modify the soil–root environment or influence subsequent water uptake of the monitored trees. The measurements were made by digging to various depths from the surface and measuring the diameter of the soil moisture 40 minutes after the start of irrigation (irrigation time for split irrigation treatment) and after 1 hour and 20 minutes (irrigation time for single irrigation treatment). The 3D shape (Fig. 1) was recreated from the measurements, and the volume was calculated. Soil moisture volume was estimated as an inverted stepped cone, with bases positioned at different depths where diameters were measured, starting from the deepest level upward. The single irrigation treatment had an SMV of 34.42 L, and the split irrigation treatment had an SMV of 18.33 L. To assess the percentage of the root apparatus reached by irrigation, the root-system volume of second-year trees was determined by excavating five plants and measuring their longitudinal extension—which corresponded to the canopy ground projection (Gilman, 1988)—and their rooting depth (20–30 cm). The mean root-system volume was 25.53 ± 3.97 L (n = 5). When relating root volume to the SMV, the wetted soil volume corresponded to 135% of the root-zone volume in the single-irrigation treatment and 72% in the split-irrigation treatment.

Statistic analysis

Data are reported as mean ± SE. Means were compared by t-student test for $p<0.05$. Statistical analyses were conducted using IBM SPSS Statistics (IBM, Armonk, NY, USA). Plots were drawn by SigmaPlot 10.0.

2.3. Results

Experiment 1

Predawn stem water potential (ψ_{stem}) was similar in both treatments and was -0.54 and -0.56 MPa in single irrigation and split irrigation treatment, respectively. At 10:00 split irrigation trees had lower Ψ_{stem} than single irrigation trees: the gap was about -0.24 MPa. Immediately after the irrigation provided at 12:00 there was a significant increase of Ψ_{stem} for the split irrigation treatment and split irrigation had significantly higher Ψ_{stem} than single irrigation at 12:30 once the irrigation shift was ended. At the afternoon (16:00) Ψ_{stem} increased for both treatment without significant differences. The effect of Ψ_{stem} was reflected on P_n, g_s and E. Leaf photosynthesis at 10:00 and 12:00 were higher in single irrigation trees than in split irrigation trees. After the irrigation shift at noon, leaf photosynthesis for the split irrigation turn increased by 8% and there were not significant differences between the two treatments. P_n similar trend was observed for g_s; at 10:00, the single irrigation treatment showed significantly higher g_s values than the split irrigation treatment. At 12:30, after irrigation, g_s

in split-irrigated trees was significantly higher than in single-irrigated trees. Leaf transpiration (E) was higher in split irrigation treatment after noon irrigation but it was similar between the two treatments at 10:00 and 16:00; at 12:00 and 12:30 E in split irrigation trees was higher by approximately 28% amd 24% compared to single irrigation trees respectively (Fig. 2.2).

During 2024 (Fig. 2.3) from day of the year (DOY) 182 to 303, were taken four measurement in different dates between 11:00 and 13:00 of Ψ_{stem} , P_n, g_s , E, ETR. Throughout the season, Ψ_{stem} values were consistently higher in the split irrigation treatment compared to the single irrigation treatment, with significant differences observed at DOY 189 and 246. The general trend of Ψ_{stem} resulted increasing along the season. Meanwhile, general trand for P_n was opposite, decreasing along the season with a peak at DOY 205. In DOY 189, 205 and 246, net photosynthesis recorded higher values (from 5% to 13%) for split irrigation than single irrigation with no significant statistical difference. P_n similar trend was detected for E where for DOY 189 nad 205 were found higher values for the single irrigation (24% and 10% respectively) and at DOY 246 and 303 higher values for the split irrigation (19% and 13% respectively). Regarding g_s the differences in values were similar to E but the general trend showed a peak in DOY 205 and then a decrease until 246 and after that an increase. In the last two dates of measurements the split irrigation had significant higher values than single irrigation (22% at DOY 246 and 16% at DOY 303). No difference was detected between the treatments along the season regard ETR where followed a trend similar to P_n.

In 2023 (Table 2.1), TCSA, weight of pruned suckers, length of current year shoot, current year shoot number and number of female flower were all singnificatly larger for split irrigation than single irrigation, rispectively 30%, 85%, 23% 69% and 150%. In 2024 only TCSA resulted48% larger for split irrigation than single. Senescence index, the length of courrent year shoot and weight of pruned suckers were higher for single irrigation treatment (11%, 16%, 11% rispectively).

Experiment 2

The same experiment design of the first experiment was replicated on hazelnut trees at the 5th leaf (Fig 2.4) irrigated by drip irrigation system. During the day the two treatments had the same trend: single irrigated trees had higher Ψ_{stem} than the split irrigation turn. At 16:00 the two treatments had the same values of Ψ_{stem}. Consequently, P_n was higher for the single irrigation turn thesis exepted the measurement at 10:00 where there was no difference. There were no significant differences in the other parameters (g_s and E).

In the same experiment replicated on the same trees using flood irrigation system, at 12:30 Ψ_{stem} was significantly higher in the split irrigation than single irrigation (Fig 2.5). At 10:00, P_n was higher in the single irrigation turn treatment, for the rest of the day there were no difference between treatments. g_s trend was similar to P_n trend. E increased after irrigation; at 12:30 the split irrigation had higher values than the single.

2.4. Discussion

Experiment 1

Water potential is one of the major factors influencing shoot growth; in other tree species such as peach, shoot growth rate is larger after midday and it reaches its maximum in the late afternoon (18:00) and then decrease during the night (Berman and DeJong, 1997). In our experiments, the midday irrigation had the aim to boost this increase of growth rate by increasing the water stem potential during the afternoon. Indeed, experiment 1, carried out on second leaf trees, water potential increased after midday irrigation as well as transpiration rate (E) after midday irrigation, but later in the afternoon it was similar across the two treatments. This daily trend was mirrored by the seasonal trend of midday stem water potential

(Ψ_{stem}) that in split irrigation treatment was higher than in single irrigation treatment for most of the season. At the end of the season, split irrigation trees had higher vegetative growth, as pointed out by the larger TCSA (+30%), mean one-year old shoots (+23%) and the weight of pruned suckers (+85%), than single irrigation.

The positive effect of split irrigation on vegetative growth can be interpreted in light of the temporal dynamics of shoot and cambial activity in tree species. Diurnal studies in peach and other fruit trees show that stem extension rates typically peak in the afternoon, when rising temperatures and adequate turgor promote cell expansion (Berman and DeJong, 1997). By supplying water precisely during this critical window, the midday irrigation pulse likely increased Ψ_{stem} and prevented the typical midday decline in turgor, thereby enhancing cell enlargement and sustaining both shoot elongation and cambial activity (Cabon et al., 2020). This mechanism is consistent with the Lockhart growth model, which states that irreversible cell expansion occurs only when turgor pressure exceeds the yield threshold of the cell wall (Lockhart, 1965), highlighting the tight dependence of growth processes on plant water status. The greater shoot length observed after the 2024 growing season can therefore be attributed to improved daytime turgor conditions under split irrigation.

Additionally, the higher vigor and larger number of suckers in the split-irrigated plants may have contributed to a more extensive root system, further supporting the increased growth of one-year shoots. Although the increase of the amount of pruned suckers causes an increase of the labor needed for pruning, it points out an increase of the total tree biomass above and below ground. Indeed root biomass, that was not measured in this experiment, is usually related to the above ground biomass (Cairns et al., 1997) and this is particularly important in young developing trees since the increase of the biomass of the root apparatus can promote a faster tree growth and a consequent advance of tree fruit yield (Bevington and Castle, 1985). In 2023, treatments affected reproductive activity too: split irrigation trees had 150%

more female flowers than single irrigation. Indeed, the yield in split irrigation was 47% larger than in single irrigation. The absolute number of nuts per plant did not economically justify the harvest, but it was the result of the significant increase of the number of female flowers because of the split irrigation treatment. These results indicated that split irrigation can advance the first crop. Indeed, if in 2023 the yield per tree was negligible (kg/ha), the larger size of the plant plus the repetition of the same irrigation schedule in 2024 caused an even more evident increase of yield. The increase in yield was coupled with larger vegetative growth. Looking at the seasonal trend in 2024, the split irrigation caused a moderate increase of Ψ_{stem}, like that observed in 2023. These results further support the indication that split irrigation can be a suitable technique in young orchard to promote vegetative growth and advance plant bearing.

Experiment 2

In order to test the effectiveness of the split irrigation in influencing the daily pattern of Ψ_{stem}, the experiment was replicated on fifth leaf trees, which were already bearing a crop. Surprisingly, the first attempt using drip irrigation system was not effective in producing an increase of stem water potential after the midday irrigation. Previous studies highlighted the effect of different growth and kernel development stages at variable wet soil volume, showing that a soil wet volume lower than 33% of the total volume explored by tree roots causes a reduced effectiveness of water uptake by filbert trees (Gispert et al., 2015). According to these data, we carried out a second attempt using a simulation of a flood irrigation system using a bucket, pouring the water over all the rootzone area, with the same water volume distributed by drip irrigation following the same schedule of the previous experiments. In this second attempt split irrigation treatment had higher stem water potential than single irrigation after midday irrigation. In both irrigation systems there was not a difference during the day of the photosynthetic rate but an increase of E, as in second leaf trial. These results indicate that a crucial role is played by the amount of soil wet by irrigation. Indeed, splitting the irrigation caused a reduction of the wet soil of 87.76%. This is not an issue in trees when they are still small and the root apparatus explores a limited soil volume that is compatible with the volume wetted by the dripper, but once the tree grows, as pointed out by Gispert et al. (2015), the relatively small volume of soil wet by the drippers can pose significant limitation to the absorption of water by the root apparatus. Furthermore the assessment of the distribution of the wetted soil volume at different depth pointed out that, even in a silty clay loamy soil, the irrigation for 1.2 h (needed to meet the calculated water requirement for the two year old tree) with a 4l/h dripper can wet soil layers deeper than 50 cm, while most of the root apparatus is located above 50 cm (Fregoni and Zioni, 1962). Indeed, in the first experiment drippers wetted the majority of the root; this explains the different results obtained in experiment 1 and in the first part of experiment 2. Most of the filbert orchards are drip irrigated using a design that is constant over the years. These data indicate it is fundamental to consider the number of emitters to the size of the root mass and as it can influence the irrigation effectiveness over the orchard life.

Economic and practical considerations

Split irrigation had a positive effect on the growth of young filbert trees and increased the number of flowers per plant. When comparing the costs of the two irrigation strategies, no differences emerged: the total water volume applied was identical, as were the total irrigation hours and the amount of electrical energy required to activate the pump. This makes split irrigation a practical option to enhance growth, especially in young orchards, where its effect on vegetative development and physiological performance appears more pronounced.

With respect to irrigation system configuration, several solutions are possible. For example, the setup used in our experimental orchard—one 4 L h^{-1} emitter per plant, positioned at the center of the row—proved effective and simplifies monitoring of potential system failures.

In adult orchards, however, the type of irrigation system can influence the efficacy of split irrigation. Using drip irrigation on mature filbert trees did not affect midday stem water potential, likely due to the spatial distribution of soil moisture, which tends to concentrate water in a small surface area and deeper soil layers.

For this reason, applying split irrigation in adult orchards may require systems capable of wetting larger soil volume—such as sprinklers or dual sub-surface drip lines (one on each side)—compared with a single drip line. In such configurations, irrigation efficiency may exceed that achievable with flood irrigation. In young trees, which have a smaller root apparatus, drip irrigation combined with split irrigation can enhance growth without increasing overall costs.

An ideal irrigation system should start with a single 4 L h^{-1} emitter per plant, with the number of emitters increasing progressively as the tree grows and eventually transitioning to sprinklers. This transition does not necessarily imply higher water use: drip emitters can be replaced with low-flow sprinklers delivering 14–20 L h^{-1}. However, from the very first installation, the irrigation system must be designed to carry sufficient flow capacity to supply the required water volume per hectare as orchard water demand increases over time.

2.5. Conclusions

Splitting the irrigation shift improved the growth of young filbert trees by increasing stem water potential during the hours of the day when most shoot elongation occurs in tree species. This enhancement in plant water status also promoted the formation of reproductive buds and increased fruit yield, effectively shortening the unproductive juvenile period of young orchards.

In adult trees, the physiological response was similar: midday stem water potential rose immediately after the irrigation pulse and remained higher throughout the afternoon compared with a single daily irrigation. However, for mature orchards, the effectiveness of split irrigation depends strongly on concentrating the soil moisture volume within the active root zone. This requires wetting a sufficiently wide soil surface to avoid deep percolation losses. As discussed earlier, adopting irrigation systems that increase the wetted area—such as higher-flow emitters or, preferably, low-flow sprinklers—can enhance the efficacy of split irrigation in adult trees.

A key outcome of this study is that split irrigation represents a cost-neutral practice: it does not require additional water, energy, or irrigation time, yet it can substantially enhance growth and productivity, particularly during the establishment phase. The efficiency of this technique should nevertheless be tested across different environments, especially with varying soil textures. In more free-draining soils, additional splits beyond two daily applications may be necessary to maintain soil moisture close to the root apparatus throughout the day, thereby sustaining higher stem water potential, photosynthesis, and seasonal growth.

In adult orchards, upgrading the irrigation layout to systems capable of wetting a larger soil volume may be essential to fully exploit the benefits of split irrigation. Naturally, as with any irrigation strategy, the feasibility of this approach depends on the water availability of the area. Yet, even under reduced water supply or deficit-irrigation conditions, split irrigation remains a promising, zero-cost strategy to improve plant water status and enhance growth.

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Table 2.1 - Vegetative indices measured at the end of the growing season of 2023 and 2024. Trunk cross section area (TCSA) is expressed in cm^2, the weight of pruned suckers in kilograms, the length of current year shoot in centimeters. Shoot growth ratio, current year shoot number and female flowers number are expressed in absolute numbers. Each value is the mean ± SE (n=5). For each index was reported the standard error. Points marked by different letters were different per $p<0.05$ (t-student test).

Year		Split Irrigation		Single Irrigation	
2023	TCSA (cm^2)	60.60 ± 7.82	a	46.65 ± 4.43	b
	Weight of pruned suckers (kg)	0.45 ± 0.04	a	0.24 ± 0.03	b
	Length of current year shoot (cm)	69.17 ± 3.69	a	56.36 ± 3.91	b
	Senescence ratio	1.29 ± 0.14	a	1.51 ± 0.25	a
	Current year shoot number	23.89 ± 2.95	a	14.17 ± 0.95	b
	Female flowers number	20.00 ± 3.89	a	8.00 ± 1.81	b
2024	TCSA (cm^2)	194.46 ± 22.56	a	131.34 ± 12.64	b
	Weight of pruned suckers (kg)	1.09 ± 0.10	a	1.23 ± 0.05	a
	Length of current year shoot (cm)	58.30 ± 6.31	a	69.80 ± 5.06	a
	Senescence ratio	0.99 ± 0.15	a	1.11 ± 0.08	a

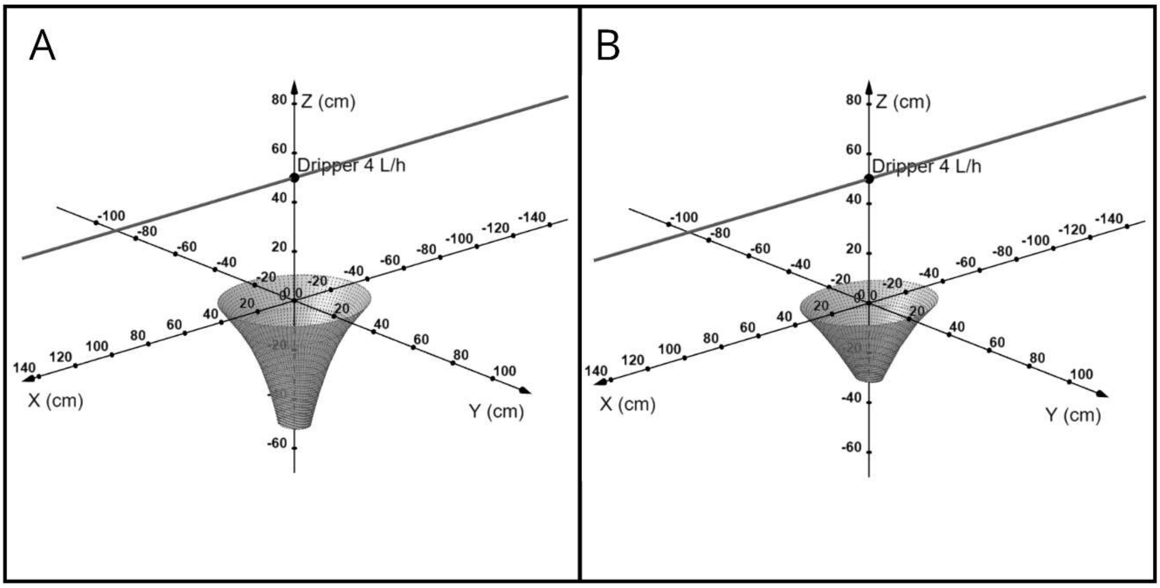

Fig. 2.1. 3D representation of soil moisture volume in two different irrigation duration: 1 hour and 20 minutes for single irrigation treatment and 40 minutes for split irrigation (34.42 L for single irrigation and 18.33 for split irrigation). To simplify the representation, the geometric forms were assumed to take the form of inverted coness. The deepest levels reached were 50 cm for the single irrigation and 30 cm for split irrigation.

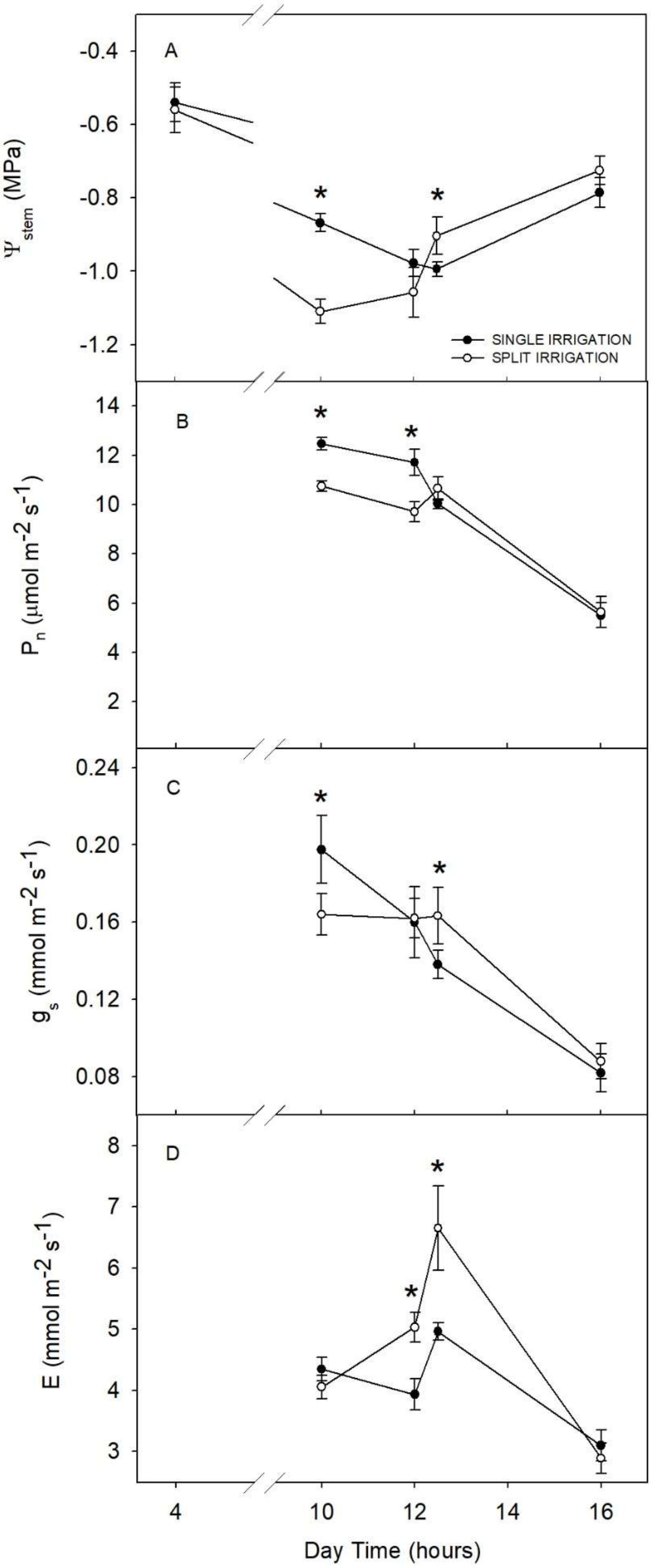

Fig. 2.2 Daily trend of stem water potential (Ψ_{stem}) expressend in MPa (box A); net photosyntesis (A) expressed in µmol m^{-2} s^{-1} (box B); stomata conductance (g_s) expressed n mmol m^{-2} s^{-1} (box C) and transpiration rate (E) expressed n mmol m^{-2} s^{-1} (box D), of second leaf hazelnut trees.Each value is the mean ± SE (n=5). Points marked by asterisk were different per $p<0.05$ (t-student test).

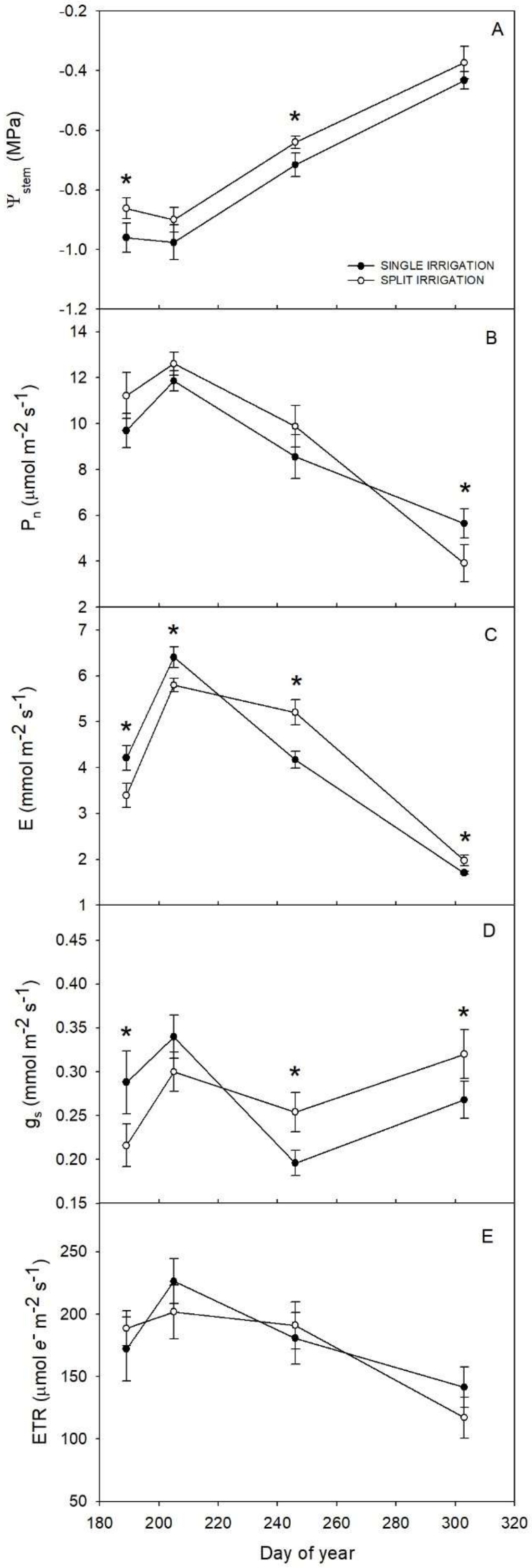

Fig. 2.3. 2024 seasonal trend of second leaf hazelnut trees, stem water potential (Ψ_{stem}) expressed in MPa (box A); net photosyntesis (A) expressed in μmol m^{-2} s^{-1} (box B); stomata conductance (g_s) expressed n mmol m^{-2} s^{-1} (box C); transpiration rate (E) expressed n mmol m^{-2} s^{-1} (box D); electron transport rate (ETR) expressed in μmol e^- m^{-2} s^{-1}, of second leaf hazelnut trees. Each value is the mean ± SE (n=5). Points marked by asterisk were different per $p<0.05$ (t-student test).

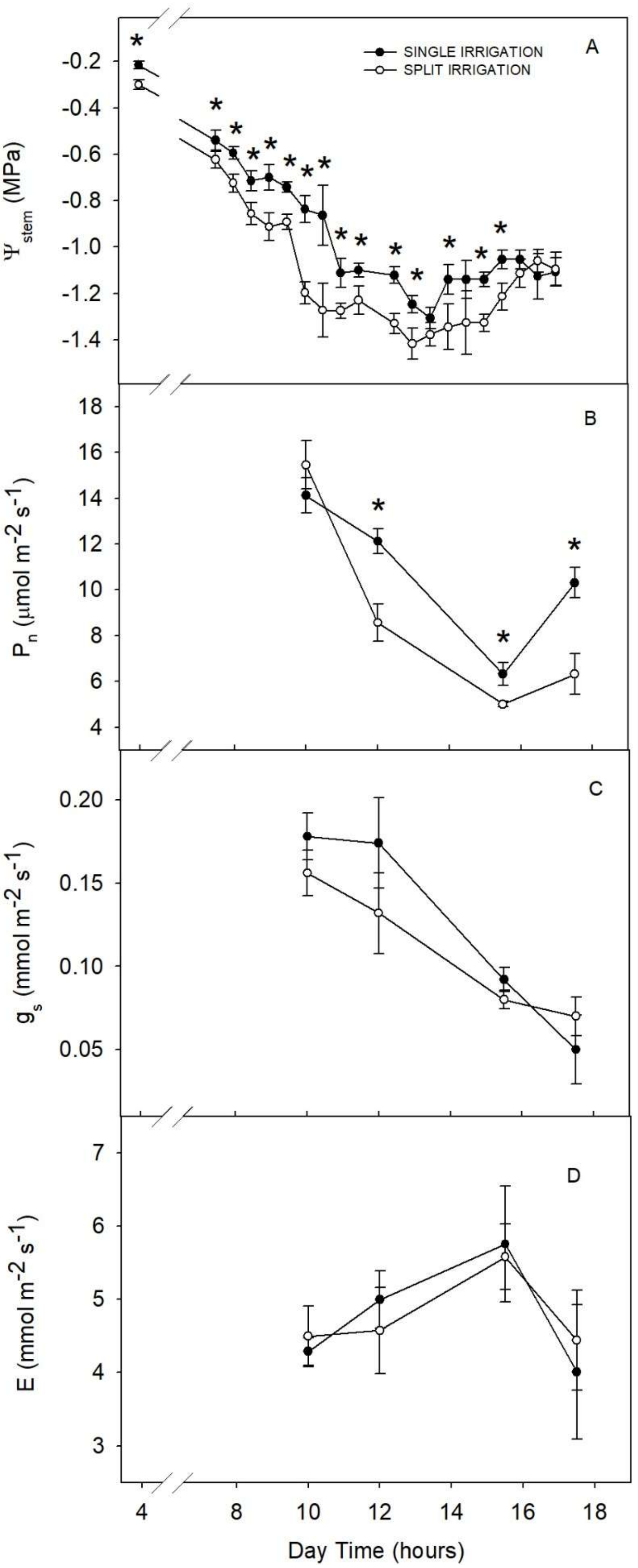

Fig. 2.4. Daily trend of fifth leaf hazelnut trees drip irrigated, stem water potential (Ψ_{stem}) expressend in MPa (box A); net photosyntesis (A) expressed in µmol m^{-2} s^{-1} (box B); stomata conductance (g_s) expressed n mmol m^{-2} s^{-1} (box C) and transpiration rate (E) expressed n mmol m^{-2} s^{-1} (box D), of second leaf hazelnut trees. Each value is the mean ± SE (n=5). Points marked by asterisk were different per $p<0.05$ (t-student test).

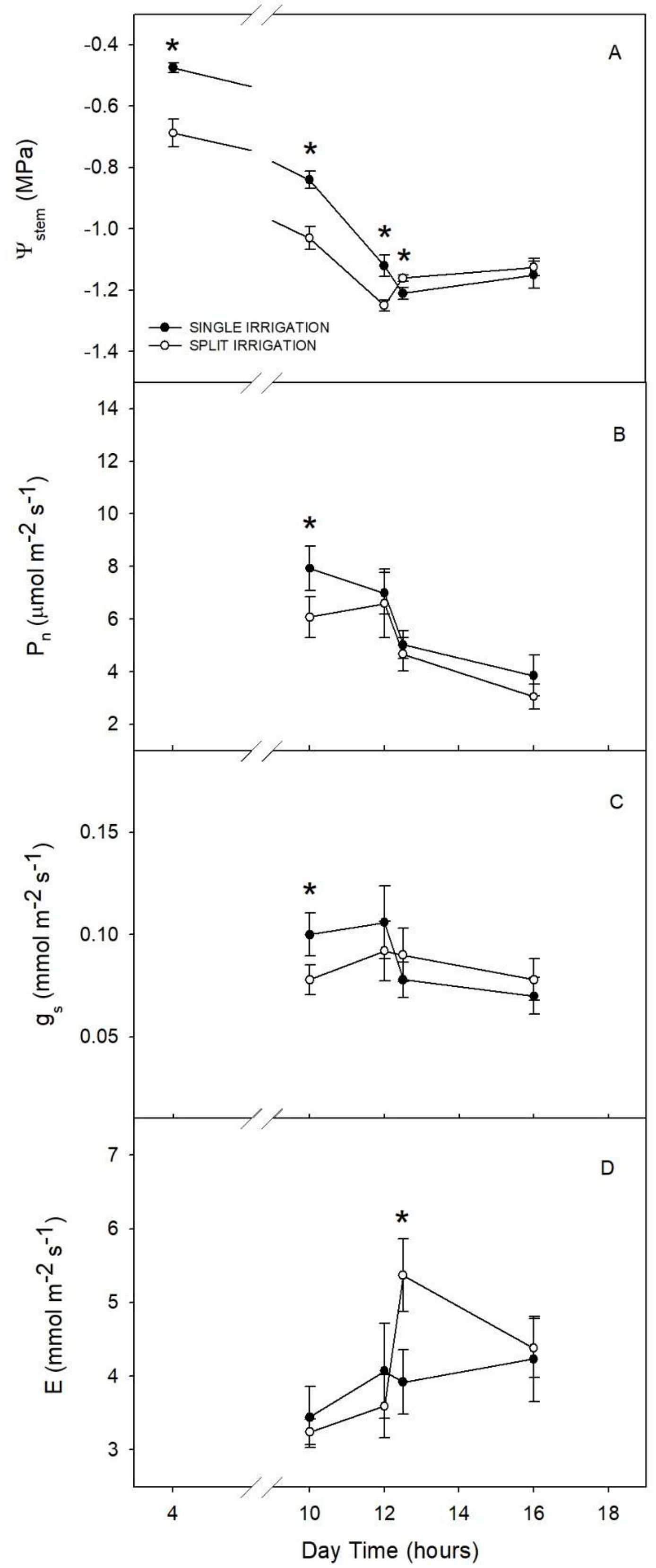

Fig. 2.5. Daily trend of fifth leaf hazelnut trees irrigated with flood system. Stem water potential (Ψ_{stem}) expressend in MPa (box A); net photosyntesis (A) expressed in µmol m^{-2} s^{-1} (box B); stomata conductance (g_s) expressed n mmol m^{-2} s^{-1} (box C) and transpiration rate (E) expressed n mmol m^{-2} s^{-1} (box D), of second leaf hazelnut trees. Each value is the mean ± SE (n=5). Points marked by asterisk were different per p<0.05 (t-student test).

CHAPTER 3

Establishing Filbert Stem Water Potential Baseline to Improve Water Management

Abstract

Irrigation management in modern filbert (Corylus avellana L.) orchards is becoming increasingly important due to climate change, with rising temperatures and more frequent arid periods occurring across many hazelnut-growing regions. While irrigation is essential to sustain productivity, water scarcity in several areas highlights the need for efficient and sustainable irrigation strategies. Stem water potential (Ψ_{stem}) is one of the most reliable indicators for assessing plant water status, yet no species-specific baseline has been defined for filbert under non-limiting soil moisture conditions. This study aimed to establish an Ψ_{stem} baseline for filbert, following approaches previously developed for olive and Prunus species. Vapor pressure deficit (VPD) was used as the environmental driver defining Ψ_{stem} variability under well-watered conditions. A large dataset of Ψ_{stem}–VPD pairs was collected during the 2024 growing season in two major hazelnut-producing countries, Italy (Piacenza) and Oregon (USA), and supplemented with measurements from previous trials. The resulting baseline, derived from the upper 0.07 fraction of Ψ_{stem} values within VPD classes, revealed a stable and linear relationship between Ψ_{stem} and VPD. This baseline functions as an operational reference: Ψ_{stem} values close to the baseline indicate non-limiting soil water conditions, negative deviations reflect increasing water stress, whereas values exceeding the baseline may signal excessive soil moisture. Overall, the proposed Ψ_{stem} baseline provides a plant-based threshold that can be directly applied in field irrigation management to optimize timing and amount of water application and can be integrated with other plant-based indicators, such as baseline deviations or CWSI, within threshold-based or advanced irrigation decision-support frameworks, supporting more sustainable water use under increasingly variable climatic conditions.

3.1. Introduction

In modern horticulture, irrigation provides a series of proven benefits. Hazelnut orchards are historically not irrigated, but in recent years with the increase of temperature in summer, irrigation systems are commonly adopted all over the world. Irrigation significantly influences the physiological processes of hazelnut trees (Corylus avellana L.), impacting aspects such as photosynthesis, water relations, and overall plant health. Adequate water supply enhances leaf gas exchange parameters, including net photosynthesis rate (A), stomatal conductance (g_s), and internal CO_2 concentration (C_i) (Tombesi, 1994). This improvement supports better growth and productivity. Conversely, water stress can lead to reduced chlorophyll content and lower levels of photosynthetic pigments, adversely affecting plant vitality (Dias et al., 2005). Past studies have shown that irrigation strongly improves hazelnut growth and yield compared with non-irrigated conditions; however, increasing irrigation beyond crop evapotranspiration requirements does not result in further yield benefits. For example, Girona et al. (1994) reported clear differences between irrigated and non-irrigated treatments, but only marginal or negligible yield responses when irrigation exceeded optimal levels. In addition to the lack of productive advantages, excessive irrigation in hazelnut orchards has been associated with agronomic and physiological risks, particularly in soils with limited drainage capacity. Rowe and Beardsell (1973) reported that waterlogging in fruit trees reduces soil oxygen availability and impairs root function, leading to reduced growth and physiological performance. Experimental evidence in woody species further indicates that tolerance to waterlogging is closely linked to the capacity for internal oxygen transport from aerial tissues to submerged roots, a mechanism that is poorly developed in flood-intolerant species (Philipson and Coutts, 1978). These findings support the concept that excessive irrigation may promote transient root-zone waterlogging and oxygen limitation in tree crops. In the context of climate change, where water availability is expected to become increasingly constrained during the hottest periods of the growing season, improving irrigation management strategies is therefore essential not only to avoid water deficits, but also to prevent the negative consequences associated with excessive water application (Sabir, 2024). To identify conditions of over-irrigation, it is necessary to define the physiological thresholds beyond which irrigation water is no longer limiting for plant processes. To determinate the water status of the plant, midday stem water potential (Ψ_{stem}) is a standard tool for plant-based irrigation management in many woody perennial crops (Shackel et al., 2021). In a well-watered system, the only variable factors that can modify Ψ_{stem} during the vegetative season are the atmospheric features like temperature and humidity, that can be evaluated by the vapor pressure deficit (VPD) (Shakel et al., 2021). In addition, as for Ψ_{stem}, stomata conductance responds to different VPD conditions, affecting the water use efficiency and the carbon assimilation (Ocheltree et al., 2014). Cincera et al. 2018 documented intra-specific variability in stomatal sensitivity to VPD. The study showed that different genotypes of C. avellana respond differently to different VPD conditions, probably caused by genetic differences. For this reason, for this work it was projected to collect data in different part of the world on different varieties of filbert.

The experiment hypothesis is that stem water potential under non-limiting water availability in the soil is defined by VPD. Ψ_{stem} vs VPD relationship define the maximum Ψ_{stem} that can be reached at the specific weather conditions.

The aim of this study is to create a hazelnut stem water potential baseline to prevent excess irrigation.

3.2. Materials & Methods

To develop a robust stem water potential (Ψ_{stem}) baseline representative of non-limiting soil water conditions across a wide range of atmospheric demand, data were collected from hazelnut orchards differing in climate, cultivar, and irrigation management. The inclusion of geographically distinct sites was intentionally aimed at expanding the variability of vapor pressure deficit (VPD) conditions under which Ψ_{stem} was measured, while ensuring that all measurements were conducted on fully irrigated trees. As the Ψ_{stem} baseline is defined as the upper envelope of the Ψ_{stem}–VPD relationship under non-water-limiting conditions, site-specific differences in climate and management were considered functional to baseline construction rather than confounding factors. The experiment was carried out in Piacenza, Italy and Corvallis, Oregon.

Experimental design

Irrigation management and definition of non-limiting soil water conditions.

To ensure non-limiting soil water conditions, irrigation was scheduled to fully replace crop evapotranspiration (ETc), calculated on a daily basis assuming non-limiting soil water availability. Actual evapotranspiration was estimated as $ETc = ET_0 \times Kc \times Kr$, where reference evapotranspiration (ET_0) was calculated using the FAO Penman–Monteith equation (Allen et al., 1998). The crop coefficient (Kc) was set to 0.8 throughout the growing season (April–October), according to lysimetric measurements on hazelnut (Mingeau and Rousseau, 1994), while the reduction coefficient (Kr) accounted for changes in effective ground cover following FAO-56 guidelines. Kr was calculated as a function of canopy ground cover fraction (fc), which was estimated geometrically from canopy projection on the soil and progressively increased with tree growth. Irrigation volumes were intentionally set to meet or slightly exceed estimated ETc, in order to avoid transient soil water deficits. Under these conditions, irrigation management was used as an operational criterion to define non-limiting soil water conditions for Ψ_{stem} baseline determination.

Piacenza, Italy

The experiment was carried out at the experimental hazelnut orchard of the Università Cattolica del Sacro Cuore (45°02'03.2"N 9°43'51.7"E; 61 m a.s.l.) in 2024. The orchard (cv Tonda di Giffoni) was drip irrigated. Piacenza is in the south-central part of the Po Valley where the climate features are between the Mediterranean climate and the continental/oceanic one of Central and Western Europe (Nistor, 2016). In 2024 between bud break and leaf senescence (from April to November) the daily average temperature varied between 10 and 27°C and a cumulate annual precipitation of 1200 mm. The soil was silty clay loam texture based on USDA soil classification (20% sand, 43% silt and 37% clay). Hazelnut trees were irrigated daily, with irrigation volumes calculated to fully replace or slightly exceed crop evapotranspiration (ETc), in order to avoid soil water limitation throughout the measurement period. The cultivar used was Tonda di Giffoni, the plants used for taking measurements were half of them were self-rooted and the other half were grafted on Corylus Colurna. The measurement period lasts from May to October. The measurements were conducted weekly between 12:00 and 14:00 local time, before taking the measurement, in order to equilibrate the leaf to stem water potential, leaves were wrapped in an aluminum foil that prevented leaf transpiration. After 30 minutes, leaves were taken from the tree and measured with a Scholander chamber (model 3005H07G4P40, Soil Moisture Equipment, Santa Barbara, CA, USA). Fully mature and healthy leaves located in the middle of the current-year shoot were sampled. The leaves were cut and immediately placed in the chamber. Stomatal conductance (g_s), leaf transpiration (E), and net photosynthesis (A) were measured during the leaf equilibration period using a portable gas analyzer (LCpro T, ADC BioScientific, Hoddeston, UK) on fully expanded, healthy leaves located in close proximity to the wrapped leaf, with similar age, canopy position, and light exposure. All measurements were performed following the manufacturer's calibration procedures prior to each measurement campaign. Gas exchange data were used to support physiological interpretation under non-limiting soil water conditions and were not intended for direct quantitative comparison across sites.

Corvallis, Oregon

Experiments were carried out in different commercial hazelnut orchards in the Willamette Valley (44°26'46.9"N 123°18'15.6"W; 44°26'08.3"N 123°13'26.6"W), near the city of Corvallis, in Benton County, Oregon (USA), between May and August 2024. 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 commercial orchards taken in examination were planted with McDonald and Jefferson varieties both at 5th leaf. In each orchard, trees were trained on single stem and planted 6 m between row and 3 m on the row, with a density of 555 trees per ha− 1 and North-South row orientation. The irrigation was applied from June to August, with a sub irrigation system with drippers 60 cm spaced with a flow rate of 2 liters per hour. The irrigation shifts lasted 12 hours in June and 24 hours in July and August, every day. Irrigation scheduling and duration were designed to ensure full restitution of estimated crop evapotranspiration (ET_c), thereby maintaining non-limiting soil water conditions during all Ψ_{stem} measurements. Considering tree size, the water volume applied per day was between 140 and 280 liters depending on irrigation duration. All Ψ_{stem} measurements were conducted within the same midday time window (12:00–14:00 local time) and following the same leaf selection and equilibration protocol adopted at the Italian site. The same Scholander-type pressure chamber model was used for all measurements (model 3005H07G4P40, Soil Moisture Equipment, Santa Barbara, CA, USA). During the leaf equilibration period, gas-exchange measurements (g_s and E) were taken during the leaf equilibration period using a porometer (LI-600, LI-COR Biosciences, Lincoln, NE, USA) on fully expanded, healthy leaves located in close proximity to the wrapped leaf, with similar age, canopy position, and light exposure. All measurements were performed following the manufacturer's calibration procedures prior to each measurement campaign. Gas exchange data were used to support physiological interpretation under non-limiting soil water conditions and were not intended for direct quantitative comparison across sites.

Baseline regression

The baseline relationship between midday stem water potential (Ψ_{stem}) and vapor pressure deficit (VPD) was calculated following the method described by Shackel et al. (2021). The full dataset of Ψ_{stem}–VPD pairs was divided into 0.5 kPa VPD classes. Within each class, the fraction upper 0.07 of Ψ_{stem} values (i.e., the least negative) were selected, assuming they represent non-soil-water-limited conditions. Average Ψ_{stem} and VPD values from these subsets were used to perform linear regression. The choice of the 0.07 fraction was based on a sensitivity analysis reported by Shackel et al. (2021), in which upper Ψ_{stem} fractions ranging from 0.02 to 0.16 were evaluated. Among the tested fractions, 0.07 yielded the highest R^2 and the lowest p-value, and was therefore considered the most robust and appropriate estimate of the Ψ_{stem} baseline under non-soil-water-limiting conditions. To enrich dataset were added past measurements used for past trials of irrigated and rain-fed orchards of McDonald and Jefferson.

3.3. Results

Midday stem water potential baseline

Figure 3.1 shows the negative relation between Ψ_{stem} vs VPD. The data set used to obtain the baseline had a range of VPD from 0.2 to 5 kPa which was quite similar for both locations.

Regarding Ψ_{stem} the range was from -0.05 MPa and -1.4 MPa including all varieties irrigated and rain-fed. The upper 0.07 envelop used for calculating baseline regression had a VPD range between 0.2 - 3.5 kPa and a Ψ_{stem} range between -0.22 MPa and 0.55 MPa. Dataset included well-water and rain-fed trees of different varieties. The regression of fraction upper 0.07 was linear and had equation

$$\Psi_{stem}\ (\mathrm{MPa}) = -0.09 \times \mathrm{VPD} - 0.18$$

$R^2=0.80$ and a significance $P<0.0001$.

In Figure 3.1 to continue the baseline was added a dotted line which was the continuation of baseline regression..

Leaf transpiration vs VPD

The relation between E and VPD (Figure 3.2) resulted in a positive relation with higher growth between 0.5 and 2 kPa then tended to flatter and decrease the rise. For this graph, only data taken during 2024 season of McDonald, Jefferson and Tonda di Giffoni when uniform and non-limiting irrigation ensured homogeneous field conditions across cultivars. The regression had equations

$$E\ (\mathrm{mmol\ s^{-1}\ m^{-2}}) = 10.05 \times (1 - e^{-0.38 \times \mathrm{VPD}})$$

with a $R^2=0.18$ and $P<0.0001$

The variability depended by varieties and water source was high but maximum level was reached in well-watered conditions. Highest E values observed were 11 mmol s^{-1} m^{-2} and lowest 2 mmol s^{-1} m^{-2}.

g_s *vs* Ψ_{stem}

The relation was not linear and tended to saturate after -0.8 MPa which was the flex point, as shown in Figure 3. At -1.4 MPa, g_s was close to complete stomata closure, from this point it increased reaching its maximum at -0.45 MPa after this point, and the trend showed a slight decrease until -0.2 MPa. The regression had equation

$$g_s\ (\text{mmol s}^{-1}\ \text{m}^{-2}) = 0.12-0.05\times\Psi_{stem}-0.008\times(\Psi_{stem})^2-0.0002\times(\Psi_{stem})^3$$

$R^2=0.06$ and a significance of $P=0.0018$.

As for Figure 2, the data set used concerned only data acquired in 2024. Also, in this case the variability per variety and source of water was high but looking to the single treatment trends seemed coherent with the regression of the whole dataset. Well-watered orchards (McDonald and Tonda di Giffoni) reached higher values between 0.55 and 0.65 mmol s^{-1} m^{-2} around -0.6 MPa.

3.4. Discussion

Ψ_{stem} baseline definition and response to atmospheric demand in hazelnut

The main objective of this experiment was to establish a reference relationship between midday stem water potential (Ψ_{stem}) and atmospheric demand under non-limiting soil water conditions, providing a practical tool for irrigation management in hazelnut orchards and helping to avoid over-irrigation. Following the conceptual framework proposed by Shackel et al. (2021), the Ψ_{stem} baseline represents plant water status under adequate soil moisture availability rather than a non-stressed physiological condition. This distinction is particularly relevant for hazelnut, as similar Ψ_{stem} values may occur either under high vapor pressure deficit (VPD) and well-watered soil or under low VPD combined with soil water limitation.

In this context, Ψ_{stem} values close to the baseline indicate that irrigation is not limiting plant water uptake and transpiration, whereas deviations below the baseline reflect increasing soil or hydraulic limitations. Conversely, Ψ_{stem} values exceeding the baseline may suggest excessive soil moisture, potentially leading to transient hypoxic conditions and impaired root functioning.

In the present study, the Ψ_{stem}–VPD baseline relationship in hazelnut was linear, with a slope of −0.09 and an intercept of −0.18 MPa. These values fall within the range reported for other woody crops, such as olive (−0.18, −0.34 MPa; Shackel et al., 2021) and Prunus spp. (−0.12, −0.41 MPa; McCutchan and Shackel, 1992). Compared with these species, hazelnut exhibited a less steep baseline slope, indicating a smaller decline in Ψ_{stem} per unit increase in atmospheric demand under non-limiting soil water conditions. This suggests a relatively buffered Ψ_{stem} response to increasing VPD when soil water supply is adequate.

Importantly, the slope of the Ψ_{stem} baseline should not be interpreted as a direct indicator of drought tolerance or isohydric behavior. In hazelnut, conservative water-use strategies and high sensitivity to water stress are primarily reflected in the rapid reduction of stomatal conductance and the narrow functional range of Ψ_{stem} observed under declining soil water availability. As shown by the g_s–Ψ_{stem} relationship, stomatal closure occurs at relatively high Ψ_{stem} values compared with more anisohydric species, supporting the classification of hazelnut as an isohydric species.

Overall, the Ψ_{stem} baseline defined in this study provides a robust physiological reference for distinguishing atmospheric from soil-driven reductions in plant water status and represents a valuable component for the integration of plant-based indicators into irrigation decision-making frameworks for hazelnut.

Inclusion of irrigated and rain-fed data in baseline construction

The Ψ_{stem} and VPD relationship presented in this study includes measurements collected under both irrigated and rain-fed conditions, as data were intentionally pooled to cover a wide range of plant water status and atmospheric demand. However, the baseline was not derived from the entire dataset, but was calculated following the upper envelope approach proposed by Shackel et al. (2021). By dividing the dataset into VPD classes and selecting the upper 0.07 fraction of Ψ_{stem} values within each class, the analysis isolated measurements representative of non-soil-water-limited conditions, independently of irrigation regime, site, or year.

Under this framework, measurements collected under rain-fed or water-limited conditions remain part of the overall Ψ_{stem} and VPD domain but do not influence the baseline regression, as they consistently fall below the upper envelope. The inclusion of such data therefore does not compromise the definition of a unified baseline; rather, it reinforces its physiological meaning by clearly distinguishing non-limiting conditions from progressive soil water limitations across contrasting environments.

Baseline range and interpretation of deviations as indicators of soil water limitation

It is noteworthy that the range of Ψ_{stem} values corresponding to the hazelnut baseline is relatively narrow (from approximately −0.28 to −0.67 MPa between VPD values of 1 and 5 kPa), while observed Ψ_{stem} values in the field extended to −1.4 MPa. This indicates that the baseline serves primarily as a stable upper boundary for plant water status, against which deviations can be interpreted as evidence of soil water limitation. The relatively limited baseline range compared to the broader physiological range observed in the orchard highlights its robustness as a reference line but also underscores the importance of monitoring actual Ψ_{stem} values over time.

Effect of grafting on plant water status and Ψ_{stem} baseline interpretation

The differences observed between grafted and own-rooted plants in terms of stomatal conductance, net photosynthesis, and, at specific times of the season, stem water potential, can be interpreted considering the distinct root system architecture associated with grafting onto Corylus colurna. Previous studies have demonstrated that grafted hazelnut trees develop deeper and more structured root systems compared to own-rooted plants, enabling access to deeper and more stable soil water reserves and promoting different water uptake strategies (Portarena et al., 2021; Vinci et al., 2023).

Portarena et al. (2021) showed that grafted hazelnut plants exhibit distinct carbon allocation patterns and deeper water uptake compared to own-rooted trees, resulting in differences in whole-plant hydraulic functioning and physiological regulation. Such traits may enhance the buffering capacity of grafted plants against short-term fluctuations in atmospheric demand, particularly under conditions of high vapor pressure deficit. In this context, a deeper rooting depth may allow grafted plants to sustain relatively high stomatal conductance and radiation interception during the early and mid-season phases without inducing more negative stem water potential values.

The effect of grafting is therefore relevant not only for plant physiological performance but also for irrigation-related parameters, including crop coefficients and the interpretation of plant-based water status indicators. Vinci et al. (2023) reported lower midseason crop coefficient values for grafted hazelnut orchards compared to those commonly reported for own-rooted systems, despite higher planting densities. This suggests a greater efficiency in water use and a modified relationship between canopy development, radiation interception, and transpiration in grafted trees.

In the present study, no statistically significant differences were detected in the Ψ_{stem}–VPD relationship between grafted and own-rooted plants, supporting the use of a single non-water-stressed baseline for both materials under well-watered conditions. However, the distinct rooting depth and water uptake dynamics associated with grafting may contribute to subtle differences in plant hydraulic regulation that are not fully captured under non-limiting soil moisture conditions. Under more heterogeneous soil water availability or during prolonged periods of high evaporative demand, these differences could potentially influence the stability or slope of the Ψ_{stem} baseline. Consequently, grafting should be considered a potential source of variability when applying plant-based irrigation indicators, and further targeted studies are required to assess its role in shaping baseline relationships under contrasting soil water regimes.

Stomatal regulation, isohydric behavior and physiological limitations in hazelnut

Regarding the relation between Ψ_{stem} and g_s, the relation showed a decline with decreasing Ψ_{stem}, with values in optimal conditions around 0.2–0.6 mmol m^{-2} s^{-1} at approximately −0.4 MPa and approaching complete stomatal closure at about −1.4 MPa. The narrow range of optimal stomata conductance suggests the high susceptibility of filbert to heat stress and his tendency to have better performance in well irrigated conditions. Compared to olive tree and Prunus, complete stomata closure happens respectively at -7 and -3/-2.5 MPa, more negative pressure than hazelnut (-1.4 MPa),confirming the conservative hydraulic strategy of this species. This behavior is consistent with the isohydric or "water-saving" strategy described for hazelnut, whereby stomatal closure is rapidly induced to preserve xylem integrity and avoid excessive declines in plant water potential (Marsal et al., 1997; Pasqualotto et al., 2018; Altieri et al., 2024).

Recent evidence further supports this interpretation by highlighting the high physiological sensitivity of hazelnut to water stress, which is associated with limited stomatal regulation capacity and a typically shallow root system (Rius-Garcia et al., 2025). The same study also reported significant genotypic differences, with cultivars such as 'Tonda di Giffoni' showing greater ionic homeostasis and photosynthetic resilience under stress compared to more sensitive genotypes like 'Tonda Gentile Romana', reinforcing the concept that isohydric behavior in hazelnut is modulated by cultivar-specific traits rather than being a uniform species-level response.

Within this physiological framework, the steeper Ψ_{stem}–VPD relationship observed in hazelnut reflects a strong sensitivity to atmospheric demand rather than to soil water availability.

Recent studies indicate that this response is driven by early stomatal closure associated with limited stomatal regulation capacity and a relatively shallow root system, resulting in rapid physiological downregulation even when soil water is not limiting (Cincera et al., 2019; Altieri et al., 2024; Rius-Garcia et al., 2025).

The low explanatory power of the g_s–Ψ_{stem} relationship observed in this study is consistent with this isohydric behavior, as stomatal conductance in hazelnut is rapidly downregulated even under mild water stress to maintain relatively stable stem water potential (McCauley et al., 2024). Under these conditions, large variations in g_s can occur within a narrow Ψ_{stem} range, resulting in weak statistical coupling between the two variables and reinforcing the role of atmospheric demand as the primary physiological constraint. Interestingly, as shown in Figure 3, the observed decline of g_s at relatively high Ψ_{stem} values (−0.3 to −0.2 MPa) may indicate a possible limitation caused by transient waterlogging conditions. Similar short-term reductions in stomatal conductance under waterlogged conditions have been reported in other woody species, where hypoxic stress at the root level can rapidly constrain gas exchange (Levinsson et al., 2023).

Integration of plant-based water status indicators and irrigation cut-off thresholds into irrigation decision frameworks

Recent studies have emphasized the value of integrating plant-based water status indicators into advanced irrigation decision-making frameworks. In this context, diagnostic indices such as deviations from a reference baseline or the Crop Water Stress Index (CWSI) provide a physiological interpretation of crop water status that is directly linked to stomatal regulation and transpiration.

For hazelnut, McCauley et al. (2024) recently established a CWSI framework showing that stem water potential values above approximately −0.6 MPa correspond to low CWSI values (<0.2), representative of an unstressed physiological condition associated with stomatal conductance thresholds around 0.2 mmol m^{-2} s^{-1}. These findings are consistent with the Ψ_{stem} ranges identified in the present study as indicative of non-limiting soil water conditions and active stomatal function.

In addition to their diagnostic value, plant-based water status indicators can be directly linked to irrigation cut-off (ICO) strategies aimed at improving water productivity without compromising yield. Ortega-Farías et al. (2020) demonstrated that, for the cultivar 'Tonda di Giffoni', maintaining midday stem water potential around −1.0 MPa allowed irrigation water savings of approximately 19% without significant reductions in stomatal conductance, net assimilation rate, or kernel weight. Conversely, when Ψ_{stem} declined to more negative thresholds (−1.3 to −1.6 MPa), marked reductions in gas exchange and kernel weight were observed. These results support the interpretation of deviations below the Ψ_{stem} baseline as indicators of soil water limitation and identify −1.0 MPa as a physiologically safe lower boundary for regulated deficit irrigation, whereas larger deviations should be regarded as entering a water stress zone associated with functional and productive penalties.

Beyond their diagnostic role, plant-based indicators such as Ψ_{stem} baselines and CWSI can also be integrated into multi-objective irrigation frameworks that aim to jointly optimize yield, quality, and water productivity under limited water availability. Recent optimization-based approaches have demonstrated how crop water status or response functions can act as constraints or objective variables within such models. Within this perspective, the Ψ_{stem} baseline proposed here represents a robust physiological reference that can support both threshold-based irrigation scheduling—such as irrigation cut-off strategies—and its integration into more advanced optimization-driven decision-support systems.

3.5. Conclusions

This study provides the first definition of a Ψ_{stem} baseline for filbert under non-limiting soil water conditions, developed across different environments and cultivars. The baseline, obtained from a large and heterogeneous dataset, showed a stable and linear relationship with VPD, since atmospheric demand is the principal driver of Ψ_{stem} when irrigation fully meets plant water requirements. The narrow Ψ_{stem} range defining the baseline, compared with the much wider range observed in field conditions, highlights its robustness as an upper physiological limit and reinforces its usefulness as a diagnostic tool for irrigation management.

Although the Ψ_{stem}–VPD baseline of filbert was less steep than that reported for other woody crops such as olive and Prunus spp., it provides a robust reference for interpreting plant water status under non-limiting soil moisture conditions. The pronounced sensitivity of filbert to water stress is instead reflected in the rapid decline of stomatal conductance at relatively high Ψ_{stem} values, supporting its classification as an isohydric species and highlighting its dependence on adequate soil water availability to sustain optimal gas-exchange performance. Furthermore, the observed reduction in stomatal conductance at high Ψ_{stem} values suggests that transient waterlogging may also impair plant functioning, emphasizing the need to avoid both water deficit and excessive irrigation. Overall, the Ψ_{stem} baseline developed in this work represents a practical and physiologically grounded reference for irrigation scheduling in hazelnut orchards. Using this baseline, growers can better identify conditions in which soil water availability is optimal and avoid unnecessary irrigation inputs that may reduce root efficiency or induce waterlogging stress. Future research should expand the dataset across additional cultivars, training systems, rootstock and soil types, and evaluate the integration of Ψ_{stem} baseline monitoring with real-time irrigation decision tools. Such developments would enhance the sustainability and resilience of hazelnut production under increasingly variable climatic conditions.

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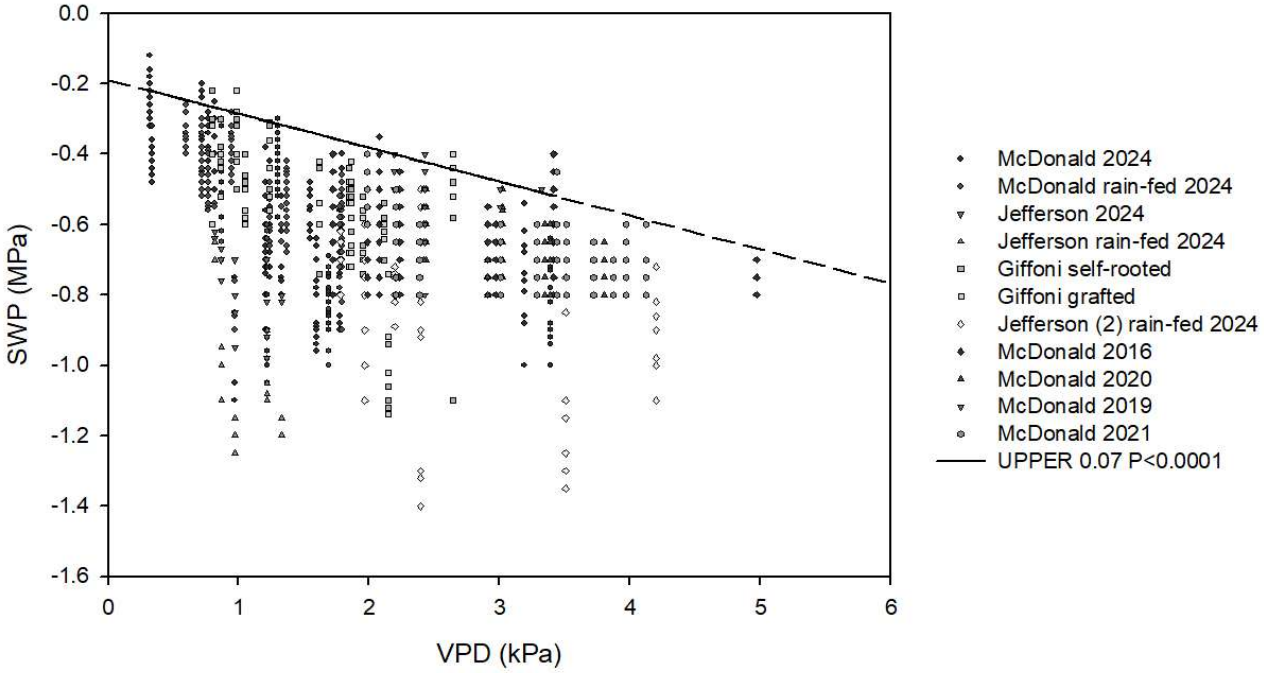

Fig 3.1- All measured data of stem water potential (Ψ_{stem}, MPa) in relation to midday vapor pressure deficit (VPD, kPa) for different cultivars at the two selected sites. Each point represents an individual measurement, and vertically aligned points indicate values collected at the same site and time. The solid black line represents the regression fitted to the upper 0.07 fraction of the dataset ($P < 0.0001$), while the dotted line shows the projection of the remaining baseline. The resulting equation was Ψ_{stem} (MPa) = $-0.09 \times VPD - 0.18$, with a R^2 of 0.80.

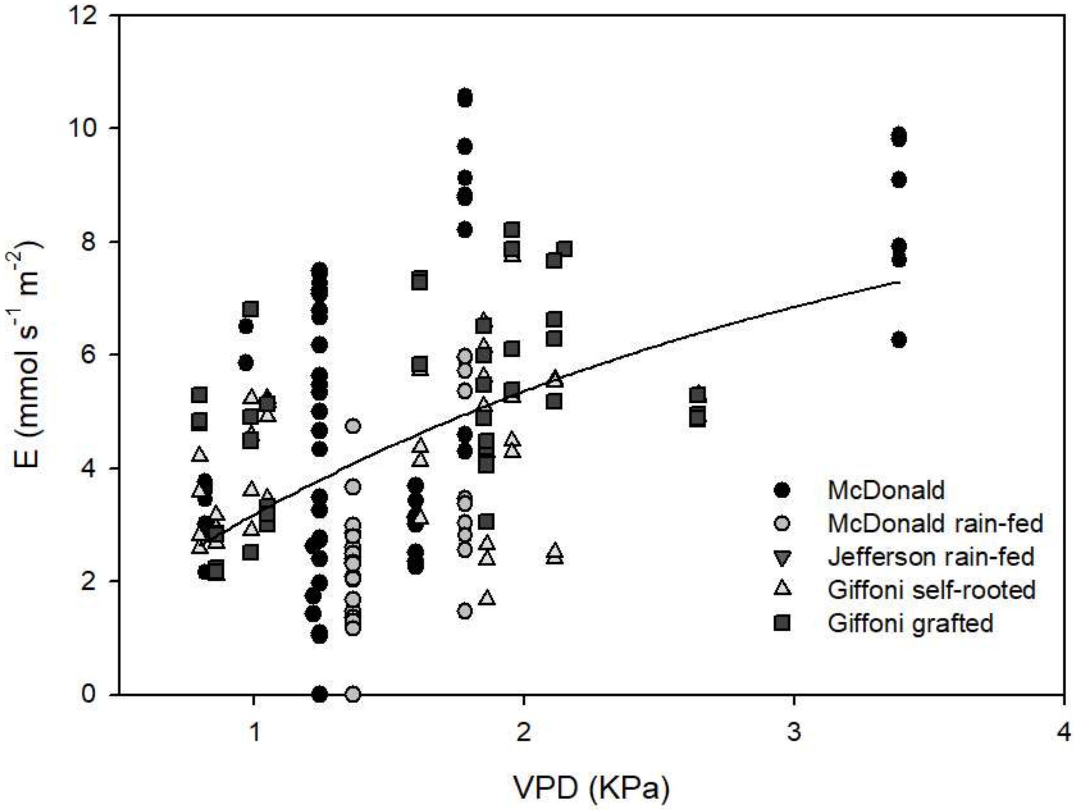

Fig 3.2 – Relationship between transpiration rate (E, mmol m^{-2} s^{-1}) and vapor pressure deficit (VPD, kPa). Each point represents an individual measurement, and vertically aligned points indicate values collected at the same site and time. A nonlinear regression model was fitted to the data and was significant ($P < 0.0001$). The resulting equation was E (mmol m^{-2} s^{-1}) = $10.05 \times (1 - e^{-0.38} \times VPD)$, with a R^2 of 0.18.

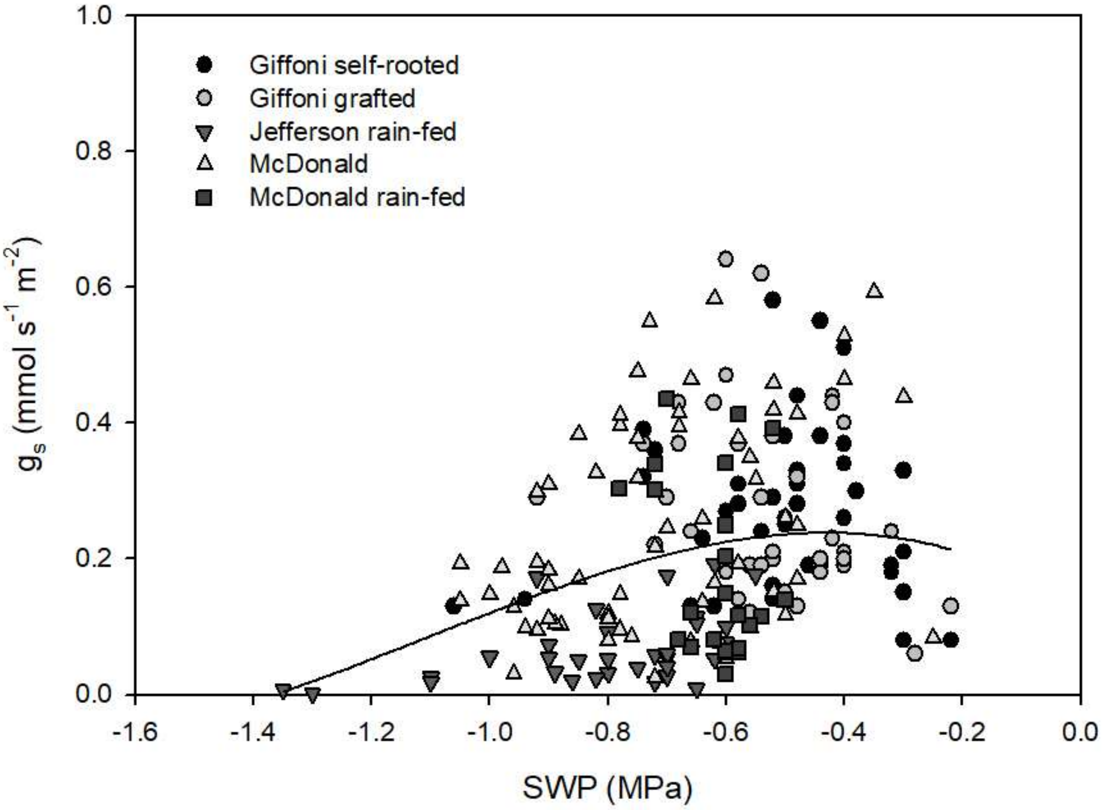

Fig 3.3 – Relationship between stomatal conductance (g_s, mmol m^{-2} s^{-1}) and stem water potential (Ψ_{stem}, MPa). Each point represents an individual measurement. The solid line shows the third-degree (cubic) polynomial regression, which was significant ($P = 0.0018$). The resulting equation was g_s (mmol m^{-2} s^{-1}) $= 0.12 - 0.05 \times \Psi_{stem} - 0.008 \times \Psi_{stem}{}^2 - 0.0002 \times \Psi_{stem}{}^3$, with a R^2 of 0.06.

CHAPTER 4

Impact of Soil Management Techniques on the Development of Young Hazelnut Orchards

Abstract

This study evaluated the effects of different soil management practices on the physiological performance, vegetative growth, and economic sustainability of young hazelnut (*Corylus avellana* L.) orchards during the establishment phase. Four under-row treatments were compared: mechanical tillage, herbicide strip, bioplastic film mulch, and field bean (*Vicia faba*) mulch. Physiological parameters such as photosynthetic rate, stomatal conductance, and stem water potential showed only minor variations among treatments, indicating a limited influence of tested soil management on plant physiology under adequate irrigation. In contrast, clear differences were observed in vegetative growth, with organic mulching promoting greater development compared with mechanical or chemical control. The bioplastic film mulch proved ineffective in weed suppression and degraded rapidly, while field bean mulch improved plant growth but involved higher management costs. Overall, mechanical tillage emerged as the most economically sustainable and practical solution for orchard establishment, whereas field bean mulch may serve as an environment-friendly alternative for farms pursuing regenerative or low-input management strategies.

4.1 Introduction

Competition between weeds and perennial fruit crops has long been recognized as a major factor limiting growth and yield, particularly during the early stages of orchard establishment. Herbaceous weeds are generally more efficient in absorbing water and nutrients from the soil compared with woody plants, resulting in strong competitive pressure on young trees (Swanton et al., 2015; Pedroso and Moretti, 2022). For this reason, modern orchard systems rely on several soil management techniques aimed at suppressing weed growth and minimizing interference. These include chemical control with herbicides, mechanical tillage, mowing, mulching, and the use of cover crops, each presenting distinct effects on weed suppression, cost, and soil quality (Fracchiolla et al., 2015).

In hazelnut, weed control is particularly critical during the first years after planting, when the canopy does not yet shade the inter-row surface. In this period, the combination of irrigation and fertilization creates favorable conditions for vigorous weed development, while trees are still physiologically vulnerable to competition for soil resources (Mennan et al., 2020). Early and effective weed suppression therefore contributes directly to canopy expansion and to the acceleration of bearing onset (Pedroso and Moretti, 2022). During the establishment phase, hazelnut orchards generate only costs and no economic return until they become productive from the sixth year onwards (Coppola et al., 2020), consequently, identifying efficient and cost-effective weed management strategies becomes essential to sustain orchard profitability and long-term sustainability.

Chemical weed control remains the predominant practice in many hazelnut-producing regions. The use of pre- and post-emergence herbicides ensures rapid and wide-spectrum control, but it raises environmental and regulatory concerns, as well as the risk of herbicide resistance. In Oregon, for instance, repeated glyphosate and clethodim applications have selected resistant biotypes of Italian ryegrass (*Lolium perenne ssp. multiflorum*), now among the most problematic weeds in young orchards in Oregon (Bobadilla et al., 2021). However, the dependency on chemical control alone is increasingly questioned because of its limited contribution to soil health and biodiversity.

Alternative approaches have been evaluated in hazelnut and related nut crops. Mennan and Ngouajio (2012) found that hazelnut husk mulch applied at 10 cm thickness reduced weed biomass by 83 % and that brassica cover crops (e.g. *Brassica juncea*) further suppressed weed emergence, highlighting the dual benefit of organic residues as weed control and soil amendment. Mulching improves water retention and organic matter content, and may enhance root growth and soil biological activity, contributing to orchard resilience (Lodolini et al., 2024). Similar effects have been observed in almond (*Prunus dulcis* (Mill.) D.A.Webb) orchards, where synthetic mulching materials completely prevented weed emergence and enhanced plant height and trunk diameter compared with flaming or untreated controls (Kitiş and İbrişim, 2024). In olive (*Olea europaea* L.), synthetic mulching also outperformed mechanical hoeing in maintaining soil moisture and promoting early yield (Lodolini et al., 2024).

Long-term comparisons of soil management practices in Mediterranean almond orchards provide additional insight into the ecological implications of different techniques. Fracchiolla et al. (2015) observed that decades of residual herbicide applications drastically reduced weed flora richness and seed bank diversity, whereas mowing, post-emergence herbicides, and green-manured cover crops promoted more balanced ground-flora communities that may deliver ecological services such as nitrogen uptake, organic matter input, and erosion control.

In this context, the evaluation of alternative weed management strategies for hazelnut orchards is necessary to identify efficient, sustainable, and economically viable options for both early establishment and long-term orchard maintenance.

The present study therefore aims to compare different under-row management techniques—including chemical, mechanical, and mulching practices—in terms of their efficacy in controlling weeds, their effects on plant growth, and their implications for the sustainability of hazelnut orchard systems.

4.2 Material & methods

The experiment was carried out in northern Italy, in Piacenza, at the experimental hazelnut orchard of the Università Cattolica del Sacro Cuore (45°02'03.2"N, 9°43'51.7"E; 61 m a.s.l.). The trial lasted three years (2023–2025). The orchard (*cv.* Tonda di Giffoni) was drip-irrigated using a single drip line per row. In 2023 and 2024, each tree was supplied with one emitter (4 L h^{-1}), whereas in 2025 two emitters (4 L h^{-1} each) were installed per tree to increase the soil wetted area in response to canopy development. Emitters were positioned 50 cm above the soil surface, aligned with the tree trunk.

Piacenza is in the south-central part of the Po Valley, where the climate transitions between Mediterranean and continental/oceanic conditions typical of Central and Western Europe (Nistor, 2016). Between bud break and leaf senescence (April to November), the daily average air temperature ranged from 10°C to 27°C, with a total annual precipitation of about 400 mm.

The soil had a silty clay loam texture according to the USDA soil classification (20% sand, 43% silt, 37% clay). The orchard was established in January 2022 with a spacing of 4 × 4 m (625 trees ha^{-1}) and trained to a single-stem system.

Irrigation was scheduled to replenish 100% of the actual evapotranspiration ($ETa = ET_0 \times Kc \times Kr$), where ET_0 represents the reference evapotranspiration (mm day^{-1}), Kc the crop coefficient (dimensionless), and Kr the ground canopy coverage factor (dimensionless), from April (bud break) to October (leaf fall). ET_0 was estimated using the Penman–Monteith equation, based on air temperature (Ta), relative humidity (RH), solar radiation (Rs), and wind speed (Ws) (Allen et al., 1998). A weather station (Netsens s.r.l., Calenzano, Italy) installed within the experimental orchard continuously recorded Ta, RH, Rs, Ws, and precipitation (Pp). A constant Kc value of 0.8 was used from April to October. Detailed monthly ETc values and the corresponding daily irrigation supply per plant (L $plant^{-1}$ d^{-1}) are reported in Table S1 of the Supplementary Materials

The experimental design included four weed management treatments applied along the tree row: (i) inter-row tillage, (ii) bioplastic film mulch, (iii) strip herbicide spray, and (iv) field bean (*Vicia faba*) mulching.

Inter-row tilling

The inter-row tillage treatment was performed using an in-row weeding machine (Turbo Evo, Rinieri, Forlì, Italy). The operation consisted of two passes, one per side of the tree row. The disc cultivator alternately moved the soil toward and away from the tree base, thereby removing and uprooting weeds. Per year the operation was replicated 3 times per year.

Herbicides

This treatment consisted of applying glyphosate-based herbicide (Roundup Gold®, Monsanto) at 3.5 L ha^{-1} at the beginning of the growing season (April–May). When necessary, a second application was carried out in June or July.

Bioplastic film mulch

For this treatment, two 100-m reels of black biodegradable soil mulching film made of MATER-BI biopolymer (Novamont S.p.A., Italy). The film had a thickness of 15 µm and a width of 100 cm. Before placing the film, a ridging was made using a disk cultivator moving the soil toward the mid of the row. The film was placed by hand along both sides of the tree row, covering most of the area with a strip approximately 1.50 m wide. The irrigation dripline was positioned near the trunk collar, leaving a small, uncovered area (≈ 20 cm^2) to allow localized water delivery. This configuration enabled both irrigation and nutrient supply beneath the mulch.

Field bean mulch

For this treatment, field bean (*Vicia faba*) was sown at a rate of 180 kg ha^{-1} in late September or early October as a winter cover crop, aiming to produce about 4 t ha^{-1} of fresh biomass. The cover crop was terminated at full pod stage in May, mowed, and windrowed onto the tree row to form an organic mulch layer.

Physiological measures

Physiological measurements were carried out at midday on the same days across all treatments during the growing season. Midday stem water potential (Ψ_{stem}) was determined using a pressure chamber (Model 3005H07G4P40, Soil Moisture Equipment, Santa Barbara, CA, USA). Stomatal conductance (g_s), transpiration rate (E) and net photosynthetic rate (P_n) were simultaneously measured using a portable gas analyzer (LCpro T, ADC BioScientific, Hoddesdon, UK). In addition, the electron transport rate (ETR) and the effective quantum efficiency of photosystem II (Y(II)) were assessed with a portable fluorometer (OS5p+, Opti-Science, Hudson, NH, USA). Measurements were repeated every 15–20 days throughout the vegetative period, always under clear-sky conditions to ensure consistent light availability.

Experimental design

Each treatment was applied to a separate row, and ten representative trees per row were selected at the beginning of the first year to serve as experimental units for physiological and growth measurements. On these ten trees per treatment, physiological parameters were recorded throughout the study, while morphological traits were assessed at the beginning (April) and at the end (November) of each growing season (2023, 2024, 2025).

The measured variables included trunk cross-sectional area (TCSA, cm^2), recorded before bud break and after leaf fall; total weight of pruned suckers produced during the current season (kg); length of the longest shoot of both the previous and current years (cm); number of current-year shoots; and number of female flowers, recorded in December 2023 and December 2024. The senescence index was calculated as the ratio between the length of the longest current-year shoot produced on an apical two-year-old shoot and the length of that same two-year-old shoot.

Leaf nitrogen concentration

Leaf samples were collected in August of each year from fully expanded leaves and freeze-dried to constant weight. The samples were then finely ground, and total nitrogen concentration was determined using the Kjeldahl method. Lyophilized leaf tissue (0.5 g) was weighed into digestion tubes, to which 7 g of potassium sulfate (K_2SO_4) were added as a digestion catalyst. Under a fume hood, 12 mL of a mixed concentrated sulfuric–phosphoric acid solution (H_2SO_4/H_3PO_4) were carefully added, followed by 7 mL of 30% hydrogen peroxide (H_2O_2). After gentle mixing, a Kjeldahl catalyst tablet was introduced. Samples were placed in a digestion block (SpeedDigester K-425, Büchi, Switzerland) at 390 °C for 15 minutes to control initial foaming, then the temperature was increased to 700 °C and maintained for approximately 40 minutes, until the digestate turned emerald green. After cooling, the digested solution was distilled in an alkaline medium (30% NaOH) using a distillation unit (K-355, Büchi, Switzerland), and the released ammonia was captured in 25 mL of 4% boric acid (H_3BO_3) containing methyl red indicator. The absorbed ammonia was then titrated with 0.1 N sulfuric acid (H_2SO_4) to quantify total nitrogen.

Statistical analysis

Statistical analyses were conducted using IBM SPSS Statistics (IBM, Armonk, NY, USA). All data are expressed as mean ± SE. Treatment effects were evaluated by one-way ANOVA performed separately for each sampling date, with the significance level set at $\alpha = 0.05$. When significant, means were separated using Tukey's multiple comparison test (Sokal and Rohlf, 1969). Graphs were generated using SigmaPlot 10.0 (Systat Software, Inc., San Jose, CA, USA).

4.3 Results

Gas exchange and photosynthetic performance

In 2023 (Fig. 4.1), seasonal mean P_n differed significantly among treatments (one-way ANOVA, $F_{3,36} = 4.65$, $P = 0.0076$). The Field Bean Mulch treatment showed the highest P_n, exceeding Tilled and Herbicide by approximately 31% and 38%, respectively. E and g_s followed a similar trend, suggesting that the presence of organic mulch promoted greater gas exchange activity. However, chlorophyll fluorescence parameters Y(II) and F_v/F_m showed comparable values across treatments, suggesting that photochemical efficiency was not affected by soil management.

In 2024 (Fig. 4.2), seasonal mean P_n differed among treatments ($F_{3,12} = 5.63$, $P = 0.012$), although the magnitude of the differences was smaller than in 2023. In 2025 (Fig. 4.3), only Tilled, Herbicide, and Field Bean Mulch treatments were monitored. Seasonal mean P_n differed among treatments (one-way ANOVA, $F_{2,15} = 4.02$, $P = 0.039$), with Herbicide and Field

Bean Mulch showing higher values than Tilled by approximately +26.8% and +26.3%, respectively.

Stem water potential (Ψ_{stem})

In 2024 (Fig. 4.4 panel A), midday Ψ_{stem} reached its minimum around DOY 206 (one-way ANOVA, $F_{3,16} = 10.42$, $P = 0.0004$), when Tilled trees showed the most negative values (–9.8 MPa). At the same date, Field Bean Mulch and Herbicide plots maintained significantly less negative potentials (–7.8 MPa and –8.3 MPa), corresponding to improvements of about +20% and +15%, respectively, while Bioplastic Film Mulch (–9.6 MPa) remained close to the Tilled treatment.

In 2025 (Fig. 4.4 panel B), midday Ψ_{stem} reached its lowest seasonal values around DOY 182 (one-way ANOVA, $F_{2,12} = 8.27$, $P = 0.0054$), with –9.4 MPa in Tilled, –9.6 MPa in Herbicide, and –10.6 MPa in Field Bean Mulch. At this stage, Field Bean Mulch trees experienced about 14% more negative potentials than Tilled, while Herbicide showed only a slight additional reduction (–3%).

Trunk Cross-Section Area

Trunk cross-sectional area (TCSA) increased steadily from 2022 to 2025 across all treatments (Fig. 4.5).

Treatment effects on TCSA were significant from 2023 onward (one-way ANOVA, $P < 0.05$), whereas no differences were detected in 2022 ($F_{3,36} = 1.71$, $P = 0.181$), indicating that trees had comparable initial vigor at the onset of the experiment.

In 2023, Bioplastic Film Mulch maintained the lowest TCSA values, significantly smaller than the other treatments, while Tilled, Herbicide, and Field Bean Mulch showed comparable growth.

In 2024, differences among treatments became more pronounced. Field Bean Mulch recorded the largest TCSA (200 cm^2), significantly higher than Tilled (+53%) and Herbicide (+61%), and more than twice that of Bioplastic Film Mulch.

In 2025, Field Bean Mulch maintained the highest TCSA (472 cm^2), significantly greater than Herbicide (332 cm^2, –30%) and slightly higher than Tilled (425 cm^2). Tilled and Field Bean Mulch did not differ statistically, while Herbicide showed a smaller cross-section area.

Overall, TCSA dynamics indicate that trunk growth was generally consistent across years, with Field Bean Mulch achieving the greatest expansion during the most vigorous growth phase (2024–2025).

Yield

Yield per plant increased sharply from 2024 to 2025 (Fig. 4.6), reflecting the transition from the juvenile to the early productive phase. The increase ranged from approximately +2300% in Tilled to +8800% in Field Bean Mulch. Yield did not differ significantly among treatments in 2025 (one-way ANOVA, $P > 0.05$), averaging 443 g plant^{-1} in Tilled, 440 g in Field Bean Mulch, and 345 g in Herbicide. Despite Herbicide showing a 22% lower yield than Tilled, differences were not statistically significant due to high variability within treatments.

Leaf nitrogen concentration

Leaf nitrogen concentration is reported in Fig. 4.7. No significant differences were detected among soil management treatments in any year. Foliar N levels slightly decreased from 2023 (~21g kg^{-1}) to 2025 (~18 g kg^{-1}). Both mulch treatments had nitrogen contents in the leaves comparable to tilled and herbicide strips.

Vegetative parameters

Soil management significantly affected several vegetative parameters in 2023 and 2024 (one-way ANOVA, $P \leq 0.05$), while no consistent treatment effect was detected in 2022.

Measurements in 2022 were used as baseline values to assess subsequent growth responses. At planting, Field Bean Mulch trees showed slightly greater initial shoot length compared with Bioplastic Film Mulch, while Tilled and Herbicide plots exhibited intermediate and comparable values, confirming a homogeneous starting point across treatments (Tab 1).

In 2023, soil management significantly affected apical shoot length, sucker biomass, the number of one-year shoots, and the senescence ratio. Tilled trees displayed the greatest shoot elongation and the highest sucker biomass, about five to six times higher than Bioplastic Film Mulch. Conversely, Bioplastic Film Mulch produced more one-year old shoots than Herbicide and showed the lowest senescence ratio, indicating reduced annual elongation relative to the previous season. Field Bean Mulch maintained intermediate values, while no significant differences were found in the number of female flowers.

In 2024, differences among treatments were significant for sucker biomass and senescence ratio. Tilled trees accumulated the highest sucker biomass, followed by Field Bean Mulch, while Herbicide and Bioplastic Film Mulch had lower values. The senescence ratio was highest in Herbicide and Bioplastic Film Mulch, suggesting that these treatments promoted greater shoot elongation compared with the previous year, whereas Tilled maintained a more stable annual growth pattern. Apical shoot length did not differ significantly among treatments.

In 2025, both apical shoot length and senescence ratio were affected by soil management. Herbicide and Field Bean Mulch trees developed longer shoots than Tilled and maintained higher senescence ratios (> 1). In contrast, Tilled and Bioplastic Film Mulch showed lower ratios, indicating slower relative elongation and reduced annual vigor.

4.4 Discussion

The aim of this study was to assess the impact of different weed control practices on the growth efficiency of hazelnut trees and to evaluate the economic sustainability of the various treatments.

Significant differences were observed in growth, measured by TCSA, for the treatment with field bean mulch, which showed higher values after second year of application (TCSA = 200.4 ± 29.6 cm^2, compared to 131.3 ± 12.6 cm^2 in the tilled treatment, 124.2 ± 8.7 cm^2 in the herbicide treatment and 90.6 ± 13.4 cm^2). This is probably due to the higher P_n measured during the years, even though no major differences in P_n were found among treatments. This likely suggests a limited impact of soil management on physiological parameters, especially under non-limiting irrigation conditions.

Regarding weed pressure, the bioplastic film mulch was not effective in controlling weeds (Fig. 4.9). A few months after laying the film, weeds began to break through the bioplastic, creating openings for new weed growth. After the second year, weed pressure was no longer controlled, which is why this treatment was excluded in the third year.

For the field bean mulch (Fig 4.11 and Fig 4.12), weed control was less effective than herbicide (Fig. 4.13) or tilled (Fig. 4.10) treatments but still acceptable, considering that no further soil disturbance occurred after mulching. The efficiency of weed control by field bean mulch depends on the amount of biomass produced in spring before mowing, which in turn depends mainly on sowing timing. Sowing must occur within a narrow window in the second half of October; however, this period is often rainy, making it difficult to complete sowing before November. Delayed sowing can cause late germination and reduced vigor at vegetative growth resumption. The optimal fresh biomass tested ranged between 3.5 and 4.0 kg m^{-2}.

In any case, the cost of sowing field bean is higher than those of herbicide or inter-row tillage, even with a similar number of field operations and working hours. This is explained by the cost of seeds, which is not present in the other treatments and by the cost of different field operation (sowing, mowing and mulching). The estimated annual cost was approximately €470 ha^{-1} for field bean (including cost of seeds €66 ha^{-1} for 200 kg of seed, €250 ha^{-1} cost of mechanical sowing, €150 ha^{-1} cost of mowing and mulching), compared to €180 ha^{-1} for inter-row tillage, €220 ha^{-1} (including mechanical operation and cost of products for one application) for herbicide application and €320 ha^{-1} for bioplastic film mulch (including €150 ha^{-1} cost of the material, €100 ha^{-1} for bed forming and €70 ha^{-1} for laying the film). All the costs are calculated per hectare per year in juvenile phases, most of these operations are not useful at maturity. Nevertheless, field bean mulching is a valuable practice for enriching the soil with microbiological organisms and improving soil health, as reported by several studies (Novara et al., 2020). Field bean can contribute substantial amounts of biologically fixed nitrogen. Under Mediterranean conditions, values of N_2 fixation in the aboveground biomass have been reported to range from approximately 120 kg N ha^{-1} at flowering to about 180 kg N ha^{-1} at maturity, depending on soil management and environmental conditions (Tedone et al., 2023). Combined with its significant effect on tree growth increase (+20.8% TCSA increase compared to tillage at the end of the experiment, not significant), this suggests that field bean mulch is an environmentally sustainable practice, particularly suitable for farms adopting regenerative agriculture approaches.

From a cost-effectiveness perspective, inter-row tillage and herbicide treatments were less expensive per year in terms of field operations, with inter-row tillage being the cheapest. In addition, herbicide application may have a slight impact on young plants at their second leaf stage. Although no statistically significant differences in growth or yield were found between tillage and herbicide treatments (443 ± 90.8 g tree^{-1} for tillage and 440 ± 152 g tree^{-1} for herbicide), the herbicide treatment consistently showed the lowest average TCSA at the end of the trial 331.7 ± 27.7 cm^2.

Another factor suggesting a potential mild toxicity effect of herbicide on plants is the lower sucker production recorded in the second and third years (–51% in 2024 and -70.8% in 2025 compared to tilled). While sucker production is not a desired outcome, it reflects the vigour and energy status of the plant. In the early, non-productive years, suckers contribute to photosynthesis and carbohydrate accumulation, supporting root system growth. When suckers are pruned during winter, the plant may benefit from a stronger and more developed root apparatus as a result of this temporary photosynthetic contribution.

4.5 Conclusions

In conclusion, soil management practices showed limited effects on the physiological performance of hazelnut trees, confirming that, under adequate irrigation, plant water status and photosynthetic activity remain stable across treatments. Nevertheless, field bean mulch promoted greater vegetative growth compared to other treatments, while the bioplastic film was ineffective in weed suppression and agronomically unsustainable in the medium term. From an economic perspective, mechanical inter-row tillage represented the most cost-effective practice, combining low operational costs with satisfactory plant growth. Overall, these findings suggest that mechanical tillage is the most practical and sustainable solution during the establishment phase of hazelnut orchards, whereas field bean mulch may serve as an alternative option within regenerative systems.

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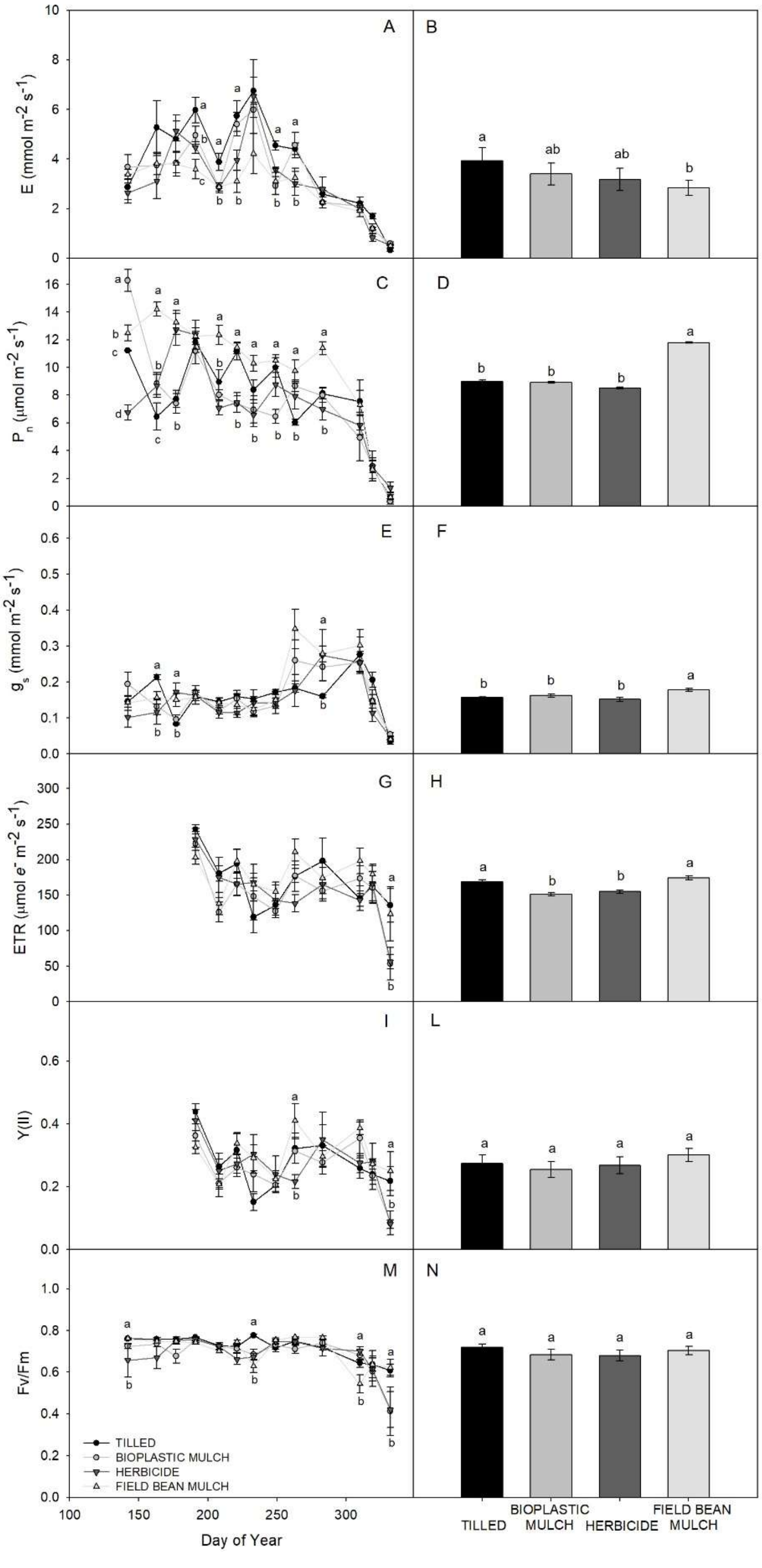

Fig. 4.1 - Seasonal trends (Panels A, C, E, G, I, M) and seasonal means (Panels B, D, F, H, L, N) in 2023. A–B: Leaf transpiration E (mmol m $^{-2}$ s $^{-1}$); C–D: Net photosynthesis P_n (μmol m $^{-2}$ s $^{-1}$); E–F: Stomata conductance g_s (mmol m $^{-2}$ s $^{-1}$); G–H: Electron Transport Rate ETR (μmol e $^{-}$ m $^{-2}$ s $^{-1}$); I–L: Effective quantum yield of Photosystem II photochemistry Y(II) (–); M–N: Maximum quantum efficiency of Photosystem II F_v/F_m (–). Values are means ± SE (n=5). Different letters indicate significant differences among treatments according to Tukey's HSD test ($p < 0.05$); when letters are not present, differences are not significant.

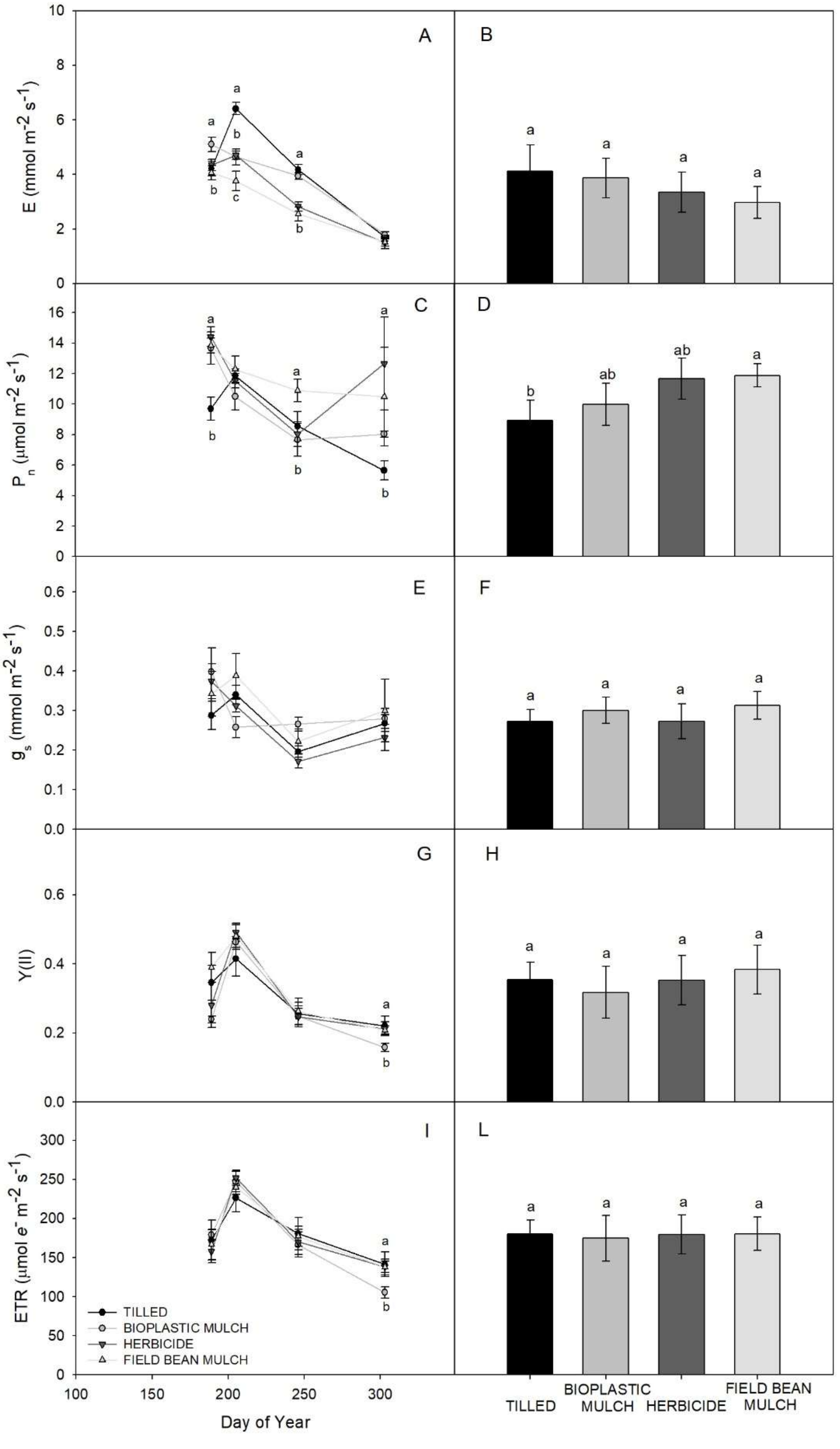

Fig. 4.2 – Seasonal trends (Panels A, C, E, G, I) and seasonal means (Panels B, D, F, H, L) in 2024. A–B: Leaf transpiration E (mmol m $^{-2}$ s $^{-1}$); C–D: Net photosynthesis P_n (µmol m $^{-2}$ s $^{-1}$); E–F: Stomata conductance g_s (mmol m $^{-2}$ s $^{-1}$); G–H: Electron Transport Rate ETR (µmol e $^{-}$ m $^{-2}$ s $^{-1}$); I–L: Effective quantum yield of Photosystem II photochemistry Y(II) (–). Values are means ± SE (n=5). Different letters indicate significant differences among treatments according to Tukey's HSD test ($p < 0.05$); when letters are not present, differences are not significant.

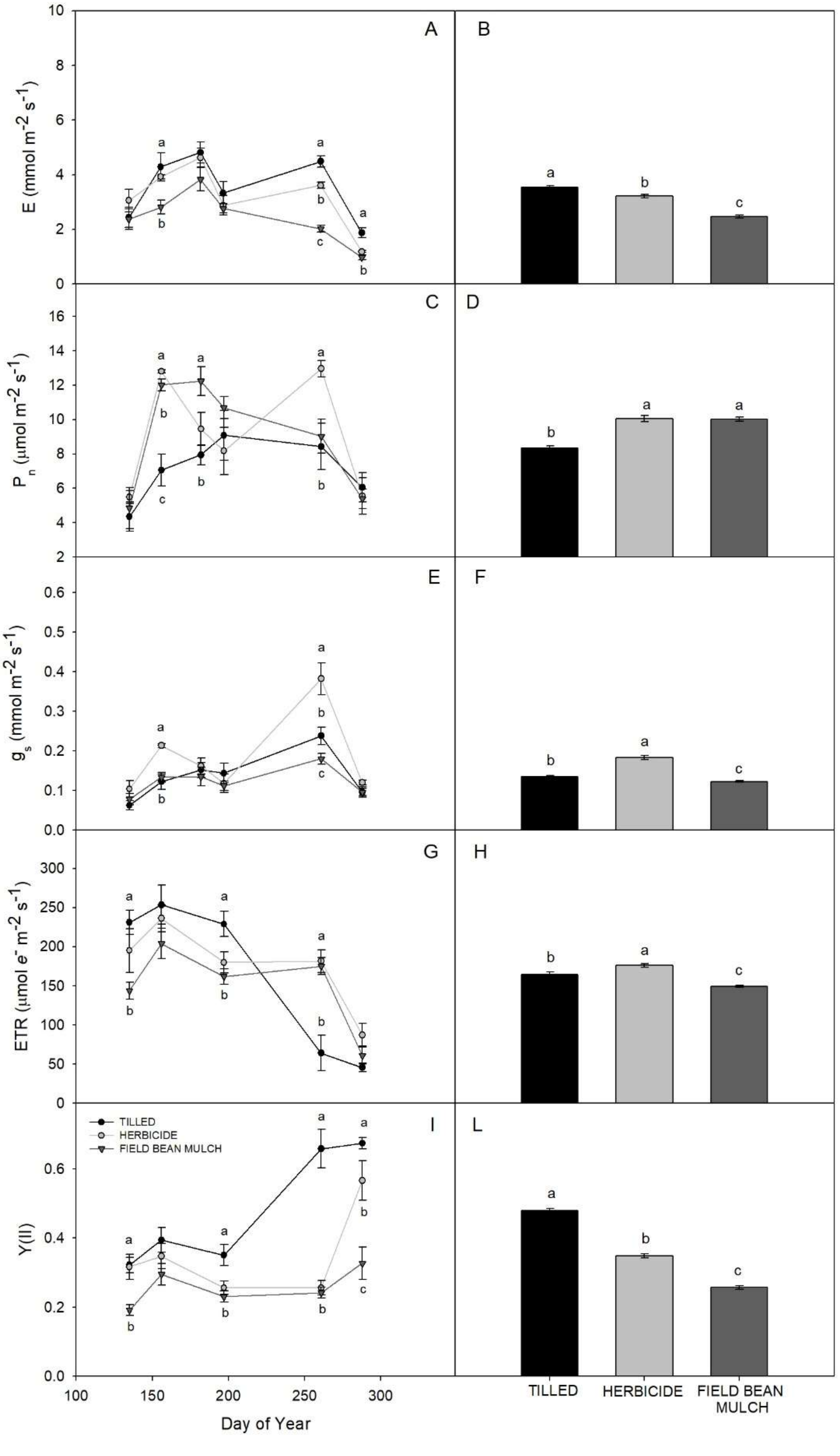

Fig. 4.3 - Seasonal trends (Panels A, C, E, G, I) and seasonal means (Panels B, D, F, H, L) in 2025. A–B: Leaf transpiration E (mmol m $^{-2}$ s $^{-1}$); C–D: Net photosynthesis P_n (µmol m $^{-2}$ s $^{-1}$); E–F: Stomata conductance g_s (mmol m $^{-2}$ s $^{-1}$); G–H: Electron Transport Rate ETR (µmol e $^{-}$ m $^{-2}$ s $^{-1}$); I–L: Effective quantum yield of Photosystem II photochemistry Y(II) (–). Values are means ± SE (n=5). Different letters indicate significant differences among treatments according to Tukey's HSD test ($p < 0.05$); when letters are not present, differences are not significant.

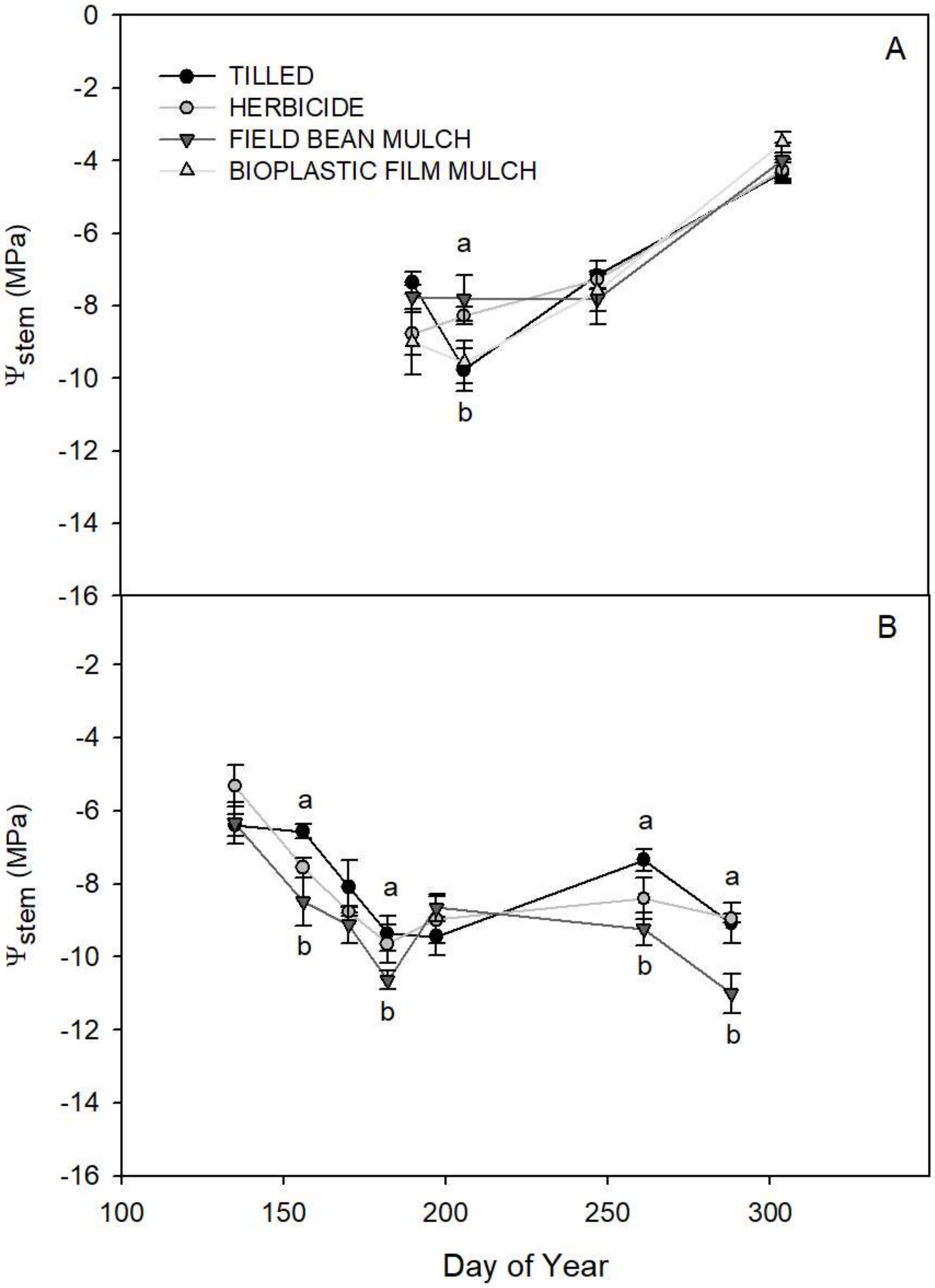

Fig. 4.4. – Seasonal variation of midday stem water potential (Ψ_{stem}) of hazelnut trees under different soil management treatments from 2023 to 2025. Values are means ± SE (n=5). Different letters indicate significant differences among treatments according to Tukey's HSD test ($p < 0.05$); when letters are not present, differences are not significant.

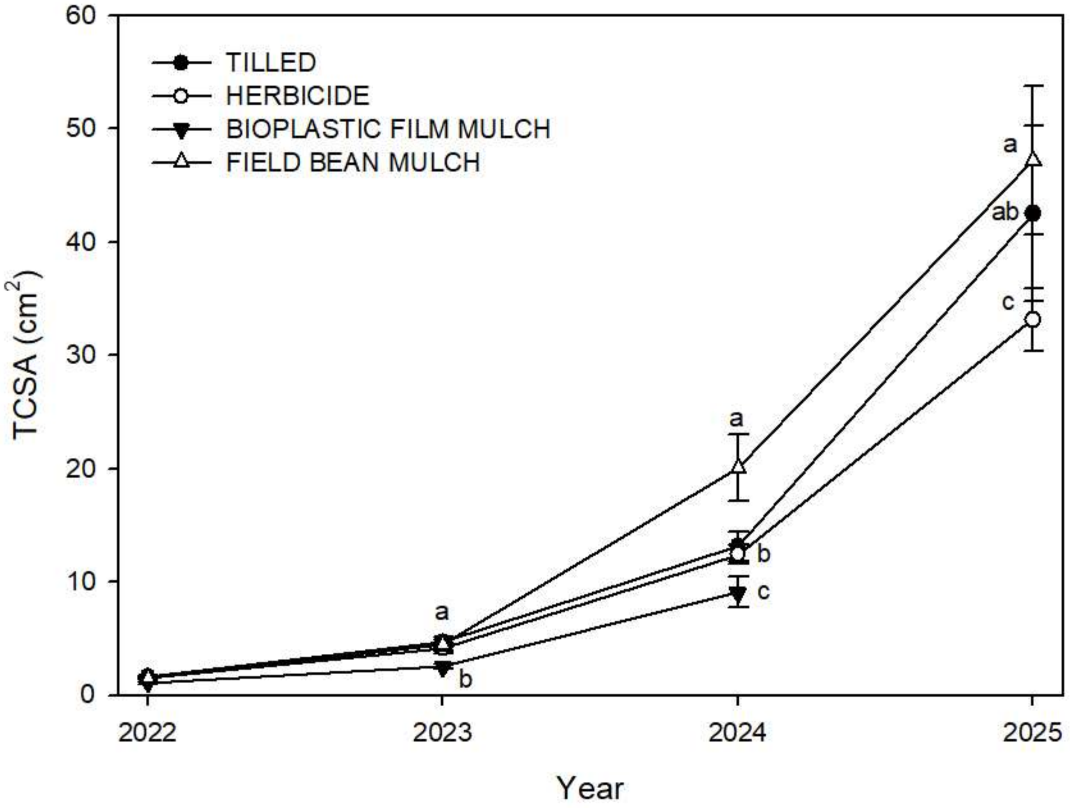

Fig. 4.5 – Annual trend of Truk Cross Section Area TCSA of hazelnut trees from 2022 to 2025 under different N doses and application frequencies. Mean ± SE (n = 5). Different letters indicate significant differences among treatments according to Tukey's HSD test ($p < 0.05$); when letters are not present, differences are not significant.

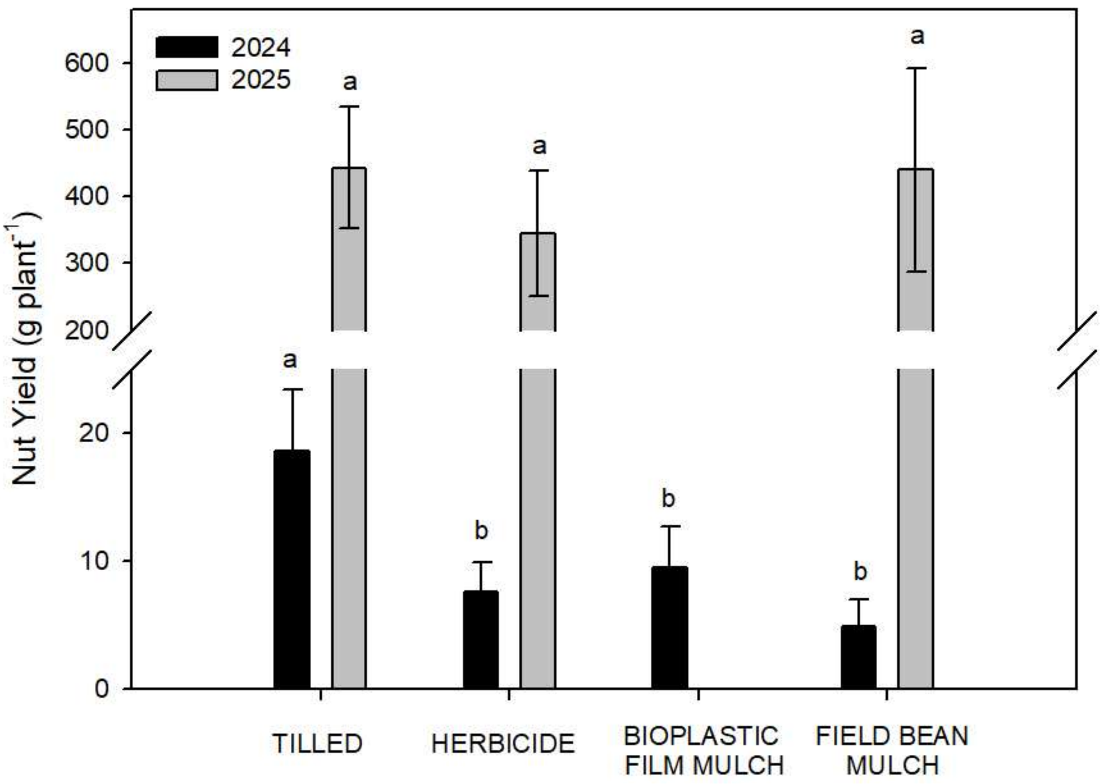

Fig. 4.6 – Yield per plant (g) of hazelnut trees under different soil management systems in 2024 and 2025. Bars represent means ± SE (n=5). Different letters indicate significant differences among treatments according to Tukey's HSD test (p < 0.05); when letters are not present, differences are not significant.

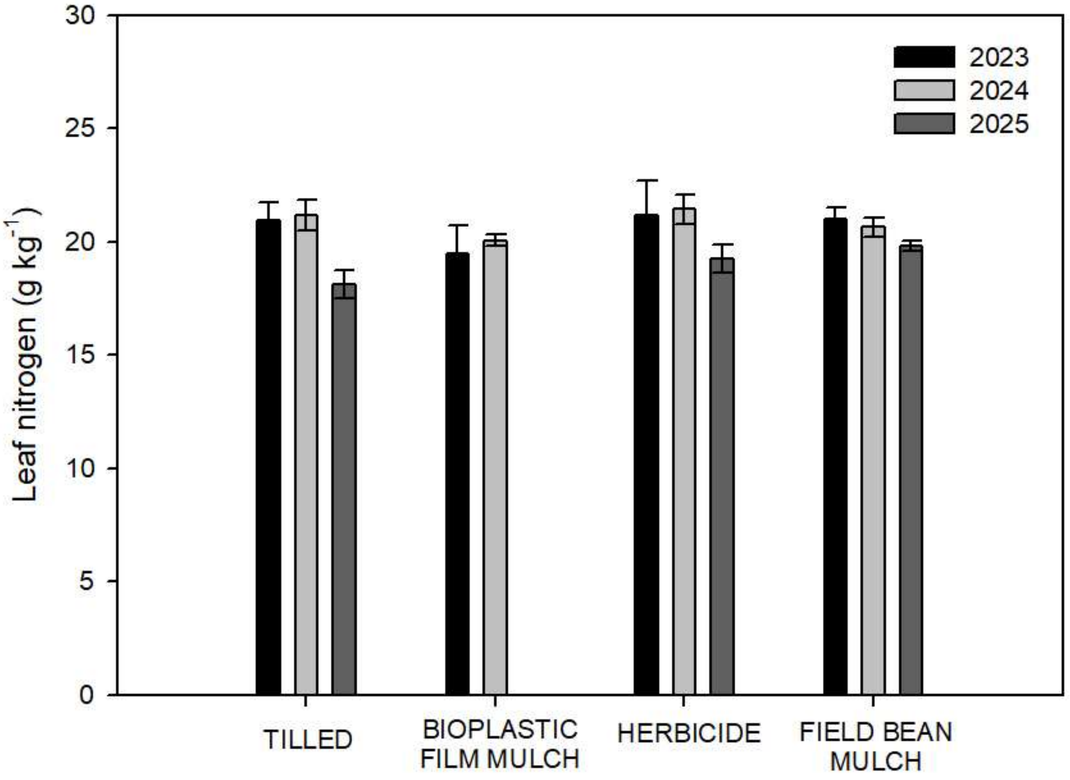

Fig. 4.7 – Leaf nitrogen concentration (%) of hazelnut trees under different soil management systems from 2023 to 2025. Values are means ± SE (n=5).

Tab. 4.1 - Vegetative parameters of hazelnut trees under different soil management systems from 2022 to 2025. Data include apical shoot length, sucker biomass, number of one-year shoots, senescence ratio (ratio between current-year and previous-year shoot length), and number of female flowers. Values are means ± SE (n=5). Different letters indicate significant differences among treatments according to Tukey's HSD test ($p < 0.05$); when letters are not present, differences are not significant.

2022	Soil Management	Length apical shoot (cm)	Weight pruned suckers (g)	One year shoot (n)	Senescence ratio	Female flowers (n)
	Tilled	48.33 ± 3.98 a	-	-	-	-
	Herbicide	43.22 ± 3.94 a	-	-	-	-
	Bioplastic film mulch	30.63 ± 6.50 b	-	-	-	-
	Field bean mulch	53.56 ± 4.86 a	-	-	-	-
2023						
	Tilled	56.36 ± 3.91 a	243.39 ± 30.33 a	14.17 ± 0.95 a	1.51 ± 0.25 a	8.00 ± 1.81 a
	Herbicide	42.71 ± 6.27 b	119.16 ± 19.46 b	11.50 ± 1.54 b	1.18 ± 0.24 a	5.20 ± 1.69 a
	Bioplastic film mulch	41.00 ± 4.33 b	37.02 ± 4.37 c	16.80 ± 2.42 a	0.29 ± 0.06 b	6.11 ± 1.27 a
	Field bean mulch	46.43 ± 3.54 b	151.24 ± 21.55 b	13.33 ± 1.80 ab	0.94 ± 0.10 a	5.60 ± 1.66 a
2024						
	Tilled	69.80 ± 5.06 a	1226.00 ± 52.20 a	-	1.11 ± 0.08 b	-
	Herbicide	76.10 ± 6.10 a	357.57 ± 28.66 c	-	1.87 ± 0.25 a	-
	Bioplastic film mulch	72.70 ± 4.35 a	225.83 ± 22.71 d	-	1.91 ± 0.19 a	-
	Field bean mulch	66.20 ± 5.53 a	553.00 ± 71.82 b	-	1.51 ± 0.12 a	-
2025						
	Tilled	31.55 ± 1.11 b	-	-	0.48 ± 0.04 b	-
	Herbicide	42.25 ± 5.32 a	-	-	0.99 ± 0.13 a	-
	Bioplastic film mulch	-	-	-	-	-
	Field bean mulch	38.10 ± 2.94 a	-	-	0.58 ± 0.07 b	-

Fig. 4.8 – Bioplastic mulch treatment right after placed.

Fig. 4.9 – Weed pressure after one year of bioplastic mulch treatment.

Fig.4.10 – Inter-row tilled treatment (2023)

Fig. 4.11 – Field Bean mulch right after shred and windrowed.

Fig. 4.12 – Field Bean mulch at the end of the season (2023)

Fig. 4.13 – Herbicide treatment (2023)

CHAPTER 5

Response of Young Hazelnut Trees to Different Nitrogen Fertilization Rates

Abstract

Nitrogen (N) plays a central role in supporting photosynthesis, vegetative growth, and early productivity in fruit crops. For hazelnut (Corylus avellana L.), Italian regional guidelines recommend relatively low N inputs during the establishment phase, particularly under non-irrigated conditions. However, information on optimal N requirements for young, irrigated hazelnut orchards remains limited. This study aimed to identify the optimal N rate for young, irrigated hazelnut orchards and to relate N supply to leaf N concentration, gas exchange, vegetative growth, and early yield. A three-year experiment (2023–2025) was conducted in an irrigated 'Tonda di Giffoni' orchard in northern Italy. Four fertilization regimes combining two N doses and two application frequencies were compared with an unfertilized control. Leaf N concentration, gas exchange parameters, vegetative growth, and yield were monitored throughout the study. N supply had limited influence on seasonal physiological patterns, while leaf N concentration showed a clear dose–response relationship. Maximum photosynthetic rates were associated with leaf N concentrations between 20 and 22 g kg-1 dry weight. Growth and yield responses indicated that intermediate–high N applications (approximately 75–100 kg N ha^{-1} at the 2nd–3rd year) resulted in the greatest trunk growth and highest yield at the 4th year. In the final year, despite fertilizer rates exceeding current recommendations, leaf N concentrations remained below the optimal threshold, suggesting a dilution effect associated with increasing canopy size and structural biomass. The results indicate that young hazelnut trees require higher N inputs than those commonly recommended by regional guidelines. However, increasing N supply beyond the optimal range does not proportionally enhance photosynthesis, vegetative growth, or early yield.

5.1 Introduction

Nitrogen (N) is one of the most important essential elements for plant growth, being a fundamental constituent of chlorophyll, amino acids, and proteins (Hawkesford et al., 2012; Taiz et al., 2015). Its availability directly influences photosynthetic efficiency, canopy development, and yield potential. In fruit trees, adequate N supply promotes leaf expansion, shoot elongation, and the establishment of a well-balanced canopy, while both deficiency and excess can lead to metabolic and structural imbalances affecting productivity and environmental sustainability (Weinbaum et al., 1992; Sun et al., 2017). Leaf N concentration is one of the most reliable indicators of photosynthetic capacity in C_3 plants, as it directly reflects the biochemical investment in the photosynthetic apparatus. Across a wide range of woody and herbaceous species, up to 60–70% of total leaf N is allocated to photosynthetic proteins—mainly Rubisco, thylakoid membrane complexes, and electron transport enzymes—which collectively determine the maximum carboxylation and assimilation rates (Reich et al., 1999; Evans and Clarke, 2019; Dong et al., 2022). Consequently, a strong linear relationship has been consistently observed between foliar N concentration and photosynthetic performance, largely independent of species or environment. Under N deficiency, chlorophyll concentration and photosynthetic rate decline rapidly, leading to reduced specific leaf area, limited carbon assimilation, and lower biomass accumulation (Peng et al., 1995; Zhao et al., 2005). Maintaining leaf N concentration within the physiological sufficiency range is therefore essential to sustain optimal photosynthetic activity, canopy development, and vegetative growth.

In perennial crops such as hazelnut, N plays an even more complex physiological role because it is not only required for current growth but is also stored and remobilized between seasons. Based on long-term field studies conducted in Oregon, hazelnut trees were shown to rely strongly on internal N reserves, which are remobilized during spring bud break and early leaf emergence before new uptake occurs from the soil. Isotopic tracer experiments reported in these studies indicated that only about 28% of applied N fertilizer is recovered by the tree, while a substantial fraction of absorbed N is stored in perennial woody tissues to support subsequent growth cycles. Within the same experimental framework, a reference range for foliar N concentration of 2.2–2.5% (dry weight), based on August leaf sampling, was established as the threshold below which clear N deficiency symptoms occur (Olsen, 1997).

Subsequent studies conducted in different hazelnut-growing regions have reported foliar N concentrations that closely align with the range proposed by Olsen (1997), despite substantial differences in climate, cultivar, and soil conditions. In the US Upper Midwest, research on hybrid hazelnuts (C. avellana × C. americana) highlighted relatively low N requirements. In establishment trials, Braun et al. (2011a, 2011b) found that plant survival and growth decreased with increasing N rate and that satisfactory foliar N concentrations (~2.2%) could be achieved with moderate fertilization, particularly on soils rich in organic matter. Later synthesis confirmed that exceeding this level does not further enhance growth but rather reduces N use efficiency (Braun et al., 2024).

Comparable values have been reported in other traditional, non-irrigated hazelnut production systems. In Chile, recent work on high-yielding orchards of cv. ‘Barcelona’ managed under non-irrigated conditions confirmed that mid-summer leaf N concentrations of 2.3–2.4% correspond to optimal conditions for growth and productivity, with a progressive seasonal decline observed towards autumn (Hirzel and Mejias-Barrera, 2025). Controlled-environment experiments with juvenile C. avellana ‘Tonda di Giffoni’ further demonstrated that a 50% reduction in N supply was sufficient to cause visible chlorosis and reduced biomass accumulation, confirming the crop’s sensitivity to sub-optimal N availability (Voogt et al., 2023). Additional field evidence supports the existence of an optimal N rate beyond which growth efficiency declines. In northeastern China, one-year-old C. avellana × C. heterophylla seedlings exhibited maximum root biomass, shoot elongation, and photosynthetic capacity at 22 g N plant^{-1}, whereas higher rates reduced root activity and growth (Li et al., 2019). Although this rate cannot be directly translated into a field-scale recommendation, it corresponds to a moderate nitrogen supply when expressed on an area basis, depending on planting density, and is of the same order of magnitude as tens to low hundreds of kg N ha^{-1}. Similarly, in Turkey, subsurface application of urea divided into two equal doses significantly increased yield, kernel ratio, and leaf N concentration compared with surface or single-dose applications, demonstrating that timing and placement are as important as the total rate for improving N use efficiency (Özkutlu et al., 2024).

Taken together, these studies indicate that, although recommended N application rates vary widely among regions and production systems, the foliar N concentration associated with optimal physiological performance remains relatively consistent, generally clustering around 22–24 g kg-1. Similar convergence of foliar sufficiency ranges has been reported across perennial woody crops and is widely adopted as a diagnostic threshold in plant nutritional assessment (Olsen, 1997; Bryson et al., 2014; Carranca et al., 2018).

Notably, much of the experimental evidence underlying these ranges originates from non-irrigated or traditionally managed orchard systems, suggesting that foliar N concentration is constrained by intrinsic physiological limits rather than by fertilizer input alone. This interpretation is consistent with the concept of biological limits to nitrogen use efficiency, whereby increases in N supply beyond a critical threshold do not result in proportional gains in photosynthesis or vegetative growth (Rotundo & Cipriotti, 2017; Tagliavini et al., 2025). Only recently have studies begun to investigate hazelnut N dynamics under modern irrigated systems. Wiman et al. (2023) demonstrated that fertigation substantially improved N partitioning and yield compared with traditional dryland orchards. Irrigated trees showed higher

^{15}N enrichment in all organs and greater cumulative production, highlighting the need to reassess N management strategies and reference thresholds originally developed under non-irrigated conditions.

Despite the physiological importance of N, fertilization guidelines for hazelnut vary widely among regions. In Italy, disciplinary standards for integrated production recommend around 70 kg N ha^{-1} at the third year after planting, while agronomic handbooks suggest contrasting rates—100 kg N ha^{-1} (Tombesi, 1985) and 56 kg N ha^{-1} (Botta, 2018) for the same developmental stage. Long-term monitoring of nutrient removal in Piedmont orchards showed that N is the element most extracted by the crop, with average annual removal of 23–26 kg N ha^{-1} in producing orchards (Roversi, 2014).

Based on this evidence, our hypothesis is that hazelnut responds positively to moderate N supply, whereas excessive fertilization does not proportionally enhance growth or yield and may reduce N use efficiency.

The aim of this experiment was therefore to determine the optimal N dose during the first years after planting that maximizes photosynthetic performance, vegetative growth, and early yield efficiency under irrigated orchard conditions.

5.2 Materials & methods

Site description and orchard management

The experiment was carried out in northern Italy, within the experimental hazelnut orchard of the Università Cattolica del Sacro Cuore, located in Piacenza (45°02′03.2″ N, 9°43′51.7″ E; 61 m a.s.l.). Piacenza lies in the south-central sector of the Po Valley, an area characterized by a transitional climate between Mediterranean and continental/oceanic regimes typical of Central and Western Europe (Nistor, 2016). During the vegetative period (from April to November), average daily air temperatures varied between 10 °C and 27 °C, and the total annual rainfall was approximately 400 mm.

The topsoil layer (0–50 cm), corresponding to the main root zone, was classified as silty clay loam according to the USDA system, with 20% sand, 43% silt, and 37% clay, and was characterized by a neutral pH (7.6), an organic carbon content of 1.45% (≈2.5% organic matter), a total nitrogen content of approximately 0.12%. The orchard was established in January 2022, with trees spaced 4 × 4 m apart (625 plants ha^{-1}) and trained to a single-stem structure. The trial covered three growing seasons (2023–2025). The orchard, cv. Tonda di Giffoni, was managed under drip irrigation, with seasonal irrigation volumes of 5, 10, and 16 L $plant^{-1}$ day^{-1} in 2023, 2024, and 2025, respectively. These irrigation volumes were determined based on crop evapotranspiration requirements, as described below.

Irrigation scheduling was based on the restoration of 100% of actual evapotranspiration (ETa = $ET_0 \times Kc \times Kr$), where ET_0 is the reference evapotranspiration (mm day^{-1}), Kc is the crop coefficient, and Kr represents the ground canopy coverage factor. Irrigation was applied from bud break (April) to leaf fall (October). ET_0 was calculated using the FAO Penman–Monteith method (Allen et al., 1998) from measurements of air temperature (Ta), relative humidity (RH), solar radiation (Rs), and wind speed (Ws). These meteorological parameters, together with precipitation (Pp), were continuously monitored by a weather station (Netsens s.r.l., Calenzano, Italy) installed within the orchard. A constant Kc value of 0.8 was adopted throughout the irrigation period. Detailed monthly ETc values and the corresponding daily irrigation supply per plant (L $plant^{-1}$ d^{-1}) are reported in Table S1 of the Supplementary Materials

Experimental design and treatments

The experiment was conducted in a single row of the orchard, where each group of five consecutive trees constituted one experimental unit, receiving the same fertilization treatment. Four nitrogen fertilization treatments were applied, in addition to an unfertilized control. Treatments combined two nitrogen dose levels (Low and High, defined as nitrogen dose per application) with two application frequencies (weekly and bi-weekly), resulting in four fertilization treatments: (i) low dose applied every two weeks (Low Bi-Weekly Dose, LBWD), (ii) low dose applied weekly (Low Weekly Dose, LWD), (iii) high dose applied every two weeks (High Bi-Weekly Dose, HBWD), and (iv) high dose applied weekly (High Weekly Dose, HWD). For each growing season, two nitrogen dose levels (Low and High) were defined, and each dose level was applied using the two application frequencies. The terms Low and High therefore indicate relative nitrogen dose levels within each year, whereas Weekly and Bi-weekly describe the application frequency. As a consequence of this factorial design, treatments LWD and HBWD received the same total annual nitrogen input, while differing in nitrogen dose per application and temporal distribution. Annual nitrogen rates for each treatment are reported in Table 1. Treatments were arranged in order of increasing nitrogen supply per hectare, considering a planting density of 625 plants ha^{-1}. The experiment was carried out during the 2023, 2024, and 2025 growing seasons. Nitrogen fertilization treatments started after bud break, with the first application performed in late April of each growing season. Doses applied per treatment and year are reported in Table 1.

For each plant, the required amount of fertilizer was weighed and placed in a separate container. The fertilizer was evenly distributed over the soil surface corresponding to the root zone, which was estimated as the canopy projection area on the ground.

Physiological measurements

Gas exchange and stem water potential

Physiological measurements were conducted at midday (11:30–14:30 solar time) during the 2023, 2024, and 2025 growing seasons. Measurements were intentionally performed at midday to ensure high and comparable atmospheric demand among sampling dates, a condition that enhances the sensitivity of gas exchange parameters to treatment effects under field conditions. Measurements were carried out from late April/May to late October–early

November, covering the entire vegetative period, with at least five measurement campaigns per season. On each measurement date, all treatments were assessed within the same day to ensure comparability under similar environmental conditions.

Midday stem water potential (Ψ_{stem}) was determined using a pressure chamber (Model 3005H07G4P40, Soil Moisture Equipment, Santa Barbara, CA, USA). Fully expanded, mature leaves located on shoots close to the main stem were selected and bagged in aluminum foil at least 30 min prior to measurement.

Stomatal conductance (g_s), transpiration rate (E), and net photosynthetic rate (P_n) were measured simultaneously using a portable gas analyzer (LCpro T, ADC BioScientific, Hoddesdon, UK). Leaf gas exchange measurements were conducted under ambient field conditions during midday and under clear-sky conditions. During measurements, photosynthetic photon flux density (PPFD) at the leaf level typically ranged between 1200 and 1800 μmol m^{-2} s^{-1}, air temperature between 28 and 35 °C, and vapor pressure deficit (VPD) between 2.0 and 3.5 kPa, depending on the measurement date. Measurements were performed within a relatively narrow time window to minimize environmental variability among treatments and under ambient CO_2 concentrations, which ranged between 430 and 450 ppm.

Chlorophyll fluorescence

Chlorophyll fluorescence measurements were performed on fully expanded, sun-exposed leaves using a portable fluorometer (OS5p+, Opti-Science, Hudson, NH, USA). Measurements were conducted under field conditions during midday, on the same leaves used for gas exchange measurements. During the first experimental season, the maximum quantum efficiency of PSII (Fv/Fm) was assessed on dark-adapted leaves. Leaves were dark-adapted for approximately 30 minutes using leaf clips to ensure full oxidation of QA and opening of PSII reaction centers. Minimum fluorescence (Fo) was recorded under weak modulated light, while maximum fluorescence (Fm) was induced by a saturating light pulse. The Fv/Fm ratio was calculated as (Fm − Fo)/Fm. In subsequent measurements, chlorophyll fluorescence was assessed under light-adapted conditions, focusing on the effective quantum yield of PSII (Y(II)) and electron transport rate (ETR). Steady-state fluorescence (Fs) and maximum fluorescence in the light-adapted state (F′m) were determined using saturating pulses, and Y(II) was calculated as (F′m − Fs)/F′m. Electron transport rate was estimated as $ETR = Y(II) \times PPFD \times 0.5 \times \alpha$, where PPFD is the incident photosynthetic photon flux density, 0.5 accounts for equal energy partitioning between photosystems, and leaf absorptance (α) was assumed to be 0.84. Calculation and interpretation of fluorescence-derived parameters followed standard ecophysiological approaches (Jones, 2014), while instrument settings and measurement protocols followed the manufacturer’s guidelines (Opti-Sciences, 2013). Preliminary measurements in the second experimental season confirmed that Fv/Fm showed limited sensitivity under the experimental conditions; therefore, subsequent analyses focused on light-adapted fluorescence parameters (Y(II) and ETR), which are more responsive indicators of photosynthetic regulation under moderate nutritional treatments. Measurements were performed on five replicate plants per treatment ($n = 5$), using one leaf per plant, and the same individuals were monitored throughout the experimental period. In 2023, net photosynthesis (P_n) progressively declined during the season despite relatively stable or slightly increasing intercellular CO_2 concentration (Ci) across treatments (Supplementary Table Sx). This pattern indicates that the seasonal reduction in P_n was not primarily driven by stomatal limitations, but rather by non-stomatal factors.

Vegetative and reproductive measurements

The measured variables included trunk cross-sectional area (TCSA), recorded before bud break and after leaf fall; total weight of pruned suckers produced during the current season; length of the longest shoot of both the previous and current years; number of current-year shoots; and number of female flowers. All vegetative and reproductive measurements were performed at complete leaf fall at the end of each growing season, specifically at the end of 2022 (baseline), 2023, 2024, and 2025, depending on the variable considered. Female flower counts were conducted in December 2023 and December 2024. The senescence index was calculated as the ratio between the length of the longest current-year shoot produced on an apical two-year-old shoot and the length of that same two-year-old shoot. Measurements were performed on five replicate plants per treatment ($n = 5$), using the same individuals monitored for physiological measurements throughout the experimental period.

Leaf N analysis

Leaf samples were collected in August of each growing season (2023, 2024, and 2025) from fully expanded leaves and freeze-dried to constant weight. The samples were then finely ground, and total N concentration was determined using the Kjeldahl method. Lyophilized leaf tissue (0.5 g) was weighed into digestion tubes, to which 7 g of potassium sulfate (K_2SO_4) were added as a digestion catalyst. Under a fume hood, 12 mL of a mixed concentrated sulfuric–phosphoric acid solution (H_2SO_4/H_3PO_4) were carefully added, followed by 7 mL of 30% hydrogen peroxide (H_2O_2). After gentle mixing, a Kjeldahl catalyst tablet was introduced. Samples were placed in a digestion block (SpeedDigester K-425, Büchi, Switzerland) at 390 °C for 15 minutes to control initial foaming, then the temperature was increased to 700 °C and maintained for approximately 40 minutes, until the digestate turned emerald green. After cooling, the digested solution was distilled in an alkaline medium (30% NaOH) using a distillation unit (K-355, Büchi, Switzerland), and the released ammonia was captured in 25 mL of 4% boric acid (H_3BO_3) containing methyl red indicator. The absorbed ammonia was then titrated with 0.1 N sulfuric acid (H_2SO_4) to quantify total N.

Statistical analysis

Statistical analyses were conducted using IBM SPSS Statistics (IBM, Armonk, NY, USA). All data are expressed as mean ± SE. Differences among treatments were evaluated using one-way ANOVA model with significance level set at 0.05. Means were separated by Tuckey's w-procedure at P=0.05 (Sokal and Rohlf, 1969). Graphs were generated using SigmaPlot 10.0 (Systat Software, Inc., San Jose, CA, USA).

5.3 Results

Gas exchange and photosynthetic performance

For all growing seasons considered in this study (2023–2025), there were no evident and constant differences among treatments in the seasonal trends of E, P_n, g_s, ETR and Y(II). Concerning P_n, the most representative pattern was observed in 2023 (Fig. 1, panel C), where fluctuations occurred throughout the season, followed by a consistent decrease reaching the minimum at DOY 332. Seasonal mean Y(II) differed among treatments in 2023 and 2024 (Figs. 1–2), with the unfertilized control showing higher values than some fertilized treatments. Fv/Fm was assessed during the first experimental season and did not show significant differences among treatments. Preliminary measurements in the second season confirmed a limited sensitivity of this parameter under the experimental conditions; therefore, subsequent analyses focused on light-adapted fluorescence parameters (Y(II) and ETR), which are more responsive to treatment effects.

In 2025 (Fig. 3, panel D), differences among treatments emerged for the seasonal average of P_n. The HWD and HBWD treatments showed significantly higher values compared to the others. Specifically, HWD was +12.18% higher than the Control, +11% than the LBWD, and +4.51% than the LWD. Similarly, HBWD was +14.30% higher than the Control,

+13.10% than LBWD, and +6.49% than LWD. In the same year, HBWD also showed the best performance in E, g_s, and Y(II) compared to the other treatments.

Regarding stem water potential (Fig. 4), significant differences among treatments were detected at specific sampling dates, although no consistent treatment effect was observed across the season. The lowest values were recorded in 2025 at DOY 197 (–11.44 MPa for Control) and in 2024 at DOY 206 (–12.96 MPa for LBWD).

Vegetative indices and yields

At the end of 2025, differences in growth rate among treatments were detected. The TCSA (Fig. 5) of LWD was significantly higher than the others, specifically +68.30% compared to Control, +36.18% to LBWD, +17.06% to HBWD, and +34.92% to HWD.

Regarding apical shoot length (Table 2), after the 2024 season, the HBWD treatment had longer shoots compared to other treatments, with a senescence ratio of 1.35, second only to the Control (1.63). After the 2025 season, no significant differences among treatments were observed in shoot length, and LBWD exhibited the highest senescence ratio.

The number of current-year shoots and the number of female flowers were assessed only during the first experimental season (2023) as early indicators of vegetative and reproductive potential. These measurements were not repeated in subsequent years due to the increasing structural complexity of the canopy and the limited additional information provided relative to the substantial sampling effort required.

Regarding yield (Fig. 6), at 3rd leaf stage (2024), no differences among treatments were observed. However, in 2025 (4th leaf stage), HBWD and LWD produced the highest yields, both significantly higher than the Control.

Leaf N concentration

Leaf nitrogen concentration increased with N supply in all years (Fig. 7), although the intensity of the response varied across seasons. In 2023 and 2024, leaf N concentration displayed a clear quadratic response to increasing N rate, reaching a maximum at intermediate inputs and slightly decreasing at higher rates. In contrast, in 2025 the response was less pronounced, with overall lower leaf N values and a more gradual increase across treatments. The control consistently showed the lowest leaf N concentration, while fertilized treatments ranged between 18 and 24 g kg^{-1}, depending on the year.

A significant relationship was found between leaf N concentration and P_n (Fig. 8) during July and August, with peak photosynthetic rates occurring at approximately 22 g kg^{-1} leaf N, corresponding to an applied nitrogen rate of about 100 kg N ha^{-1}. As observed in Fig. 7, Fig. 8 also highlights the differences in leaf N concentration between 2023, 2024 and 2025, which are reflected in the photosynthetic performance.

5.4 Discussion

The primary objective of this study was to identify optimal nitrogen application rates during the establishment phase of irrigated hazelnut orchards under commercial field conditions. Despite nitrogen inputs reaching up to three times the rates recommended for integrated crop management in Italy (Regione Lazio, 2025) and exceeding those suggested in technical handbooks for hazelnut cultivation (Tombesi, 1985; Botta, 2018), measured leaf nitrogen concentrations consistently remained near or only slightly above the minimum threshold of the optimal sufficiency range reported in the literature (Olsen, 1997; Bryson et al., 2014). This apparent discrepancy between fertilizer input and foliar nitrogen status highlights a critical limitation of broadcast fertilization during orchard establishment: as trees develop, maintaining adequate leaf nitrogen concentrations requires progressively higher fertilizer inputs, raising both economic and environmental concerns. These findings indicate that, although irrigation modifies nitrogen availability at the soil–root interface, intrinsic physiological constraints and growth-related dilution effects impose upper limits on achievable foliar nitrogen concentrations regardless of nitrogen supply.

The relationship between nitrogen supply and leaf nitrogen concentration followed a non-linear pattern during the first two seasons, consistent with previous studies reporting a maximum attainable foliar nitrogen concentration of approximately 22 g kg^{-1} in hazelnut (Braun et al., 2011a, 2011b). In contrast, this saturation response was not observed in the third season, when foliar nitrogen concentrations remained below 20 g kg^{-1} despite relatively high nitrogen inputs. This deviation can be attributed to the progressive expansion of canopy and root systems, leading to a dilution of nitrogen across increasing structural biomass. The so-called nitrogen dilution effect is well documented in perennial crops, where biomass accumulation outpaces nitrogen uptake, resulting in declining tissue nitrogen concentrations even under sustained fertilization (Evans, 1989; Greenwood et al., 1990). The progressive decline in foliar nitrogen concentration observed across years in this study may therefore reflect the combined effects of canopy and root system expansion and associated changes in soil nitrogen distribution. As the root system explores an increasing soil volume, the effective fertilizer nitrogen available per unit of root biomass may decrease, reducing apparent nitrogen uptake efficiency despite sustained or increased nitrogen inputs (Greenwood et al., 1990; Marschner, 2012).

Seasonal patterns in leaf gas exchange provided insight into the physiological regulation of photosynthetic performance under irrigated conditions. In 2023, the progressive decline in net photosynthesis was not accompanied by a corresponding decrease in intercellular CO_2 concentration, indicating that photosynthetic limitations were predominantly non-stomatal in nature. This pattern—characterized by stable or increasing Ci values concurrent with declining CO_2 assimilation—is widely interpreted as evidence for increasing contributions of non-stomatal limitations under field conditions (Flexas and Medrano, 2002; Lawlor and Tezara, 2009). Such limitations may include reductions in biochemical capacity for CO_2 fixation, constraints on electron transport, and increasing importance of mesophyll conductance limitations under high atmospheric demand and elevated temperatures (Grassi and Magnani, 2005). Although Ci alone does not allow quantitative partitioning among stomatal, mesophyll, and biochemical limitations without additional analyses such as A/Ci response curves (Deans et al., 2019), the consistency of this response across measurement dates strongly suggests that internal physiological processes exerted primary control over photosynthetic performance during the latter portion of the growing season.

Inter-annual differences in stomatal conductance and electron transport rate between 2023 and 2024 likely reflect a combination of climatic variability and plant developmental progression. Higher values of g_s and ETR in 2024 suggest enhanced photochemical capacity under more favorable environmental conditions and greater physiological acclimation as trees aged. Similar year-to-year variability in stomatal behavior and fluorescence-based parameters has been widely reported in perennial woody species under field conditions and is commonly attributed to inter-annual variability in climate and seasonal acclimation processes (Grassi and Magnani, 2005; Flexas and Medrano, 2002). These findings emphasize the importance of multi-year field trials to correctly interpret nitrogen effects on photosynthetic performance under variable climatic conditions.

A central outcome of this study is the identification of a clear functional relationship between leaf nitrogen concentration and net photosynthesis in field-grown hazelnut, with peak photosynthetic rates occurring at approximately 20–22 g kg^{-1} leaf nitrogen. This represents one of the first field-based demonstrations directly linking foliar nitrogen status to photosynthetic capacity in hazelnut orchards. The strong correlation observed supports the well-established biochemical role of nitrogen in determining photosynthetic capacity in C_3 plants (Evans, 1989; Evans and Clarke, 2019), where nitrogen is a major constituent of Rubisco and components of the electron transport chain. The observed plateau in photosynthetic response beyond this threshold aligns with the concept of diminishing returns in nitrogen fertilization, whereby nitrogen use efficiency declines once photosynthetic machinery approaches saturation (Evans and Clarke, 2019; Niinemets et al., 2015). From a practical standpoint, this threshold provides a physiologically meaningful target range for leaf analysis and nitrogen management decisions in hazelnut.

Treatment effects on vegetative growth and early yield corroborated the physiological responses. Intermediate nitrogen treatments (HBWD and LWD), corresponding to approximately 75 and 100 kg N ha^{-1} in the second and third years, respectively, produced the largest trunk cross-sectional area and the highest early yield while maintaining leaf nitrogen concentrations within the identified optimal range. These nitrogen rates exceed traditional recommendations for hazelnut under Mediterranean conditions (Tombesi, 1985; Botta, 2018), reflecting the increased nitrogen demand of irrigated orchards where enhanced water availability accelerates growth. The stronger response of trunk growth compared to apical shoot length suggests preferential allocation of nitrogen-derived resources to structural development, which may have long-term implications for orchard productivity.

The progressive reduction in treatment responsiveness observed over successive years may also be linked to changes in soil nitrogen distribution and root system architecture. As root systems expanded into deeper and wider soil volumes, the effective fertilizer concentration per unit of root biomass likely declined, reducing apparent uptake efficiency despite increasing total inputs. Soil nitrogen dynamics in orchards are influenced by mineralization–immobilization processes, leaching losses, spatial heterogeneity of nutrient distribution, and irrigation-induced redistribution of nitrogen within the soil profile (Havlin et al., 2014; Marschner, 2012). Under these conditions, broadcast fertilization becomes increasingly inefficient as trees mature, highlighting the importance of integrating soil and plant-based diagnostics when designing nitrogen management strategies for perennial crops.

5.5 Conclusions

This study establishes, for the first time under field conditions, a direct quantitative relationship between leaf nitrogen concentration and photosynthetic performance in hazelnut, identifying 20 to 22 g kg^{-1} as the functional optimum that maximizes carbon assimilation. This physiologically meaningful target transforms leaf tissue analysis from a descriptive indicator into a mechanistic tool for nitrogen management decisions. To achieve this optimal range during orchard establishment, nitrogen application rates of 75 and 100 kg N ha^{-1} in the second and third years after planting are required under irrigated conditions—substantially exceeding standard agronomic recommendations but necessary to overcome growth-related dilution effects as trees develop. However, the economic reality is sobering: fertilizer costs at these rates exceed 200 euros per hectare annually by the third year, representing a significant operational expense, while broadcast application becomes progressively less efficient as canopy size increases and nitrogen becomes distributed across expanding root systems and structural biomass. This pattern of diminishing returns reveals a fundamental limitation of conventional fertilization strategies in intensive hazelnut production. The broader implication is clear: irrigation fundamentally alters nitrogen dynamics in orchard systems, creating both opportunities and challenges that demand rethinking traditional nutrient management approaches. Fertigation emerges as the critical next step, offering the potential to synchronize nitrogen delivery with plant demand, improve uptake efficiency, reduce total inputs and costs, and minimize environmental losses—transforming what is currently an expensive and inefficient practice into a sustainable production strategy. Beyond the immediate practical applications, this work demonstrates that understanding the mechanistic linkage between nutrient supply, tissue concentration, and physiological function provides the foundation for evidence-based management systems applicable across perennial crop production, where the challenge of maintaining optimal nutrition during rapid vegetative growth phases remains a universal constraint on establishment success and long-term productivity.

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Tab. 5.1 – Experimental scheme of nitrogen fertilization treatments, including application frequency, fertilizer nitrogen content, applied nitrogen rate, and estimated cost per hectare (average fertilizer price: 380 € t^{-1}). Treatment codes are defined as follows: LBWD, low nitrogen dose with biweekly application; LWD, low nitrogen dose with weekly application; HBWD, high nitrogen dose with biweekly application; and HWD, high nitrogen dose with weekly application. Estimated costs refer exclusively to fertilizer cost and do not include labor, irrigation, or other operational expenses. Treatments differed in nitrogen dose per application and application frequency; equal annual N rates may result from different dose–frequency combinations.

Year	Dose	Frequence	Treatment code	Fertilizer	N content (%)	Number of Application	g plant^{-1}	kg N ha^{-1}
2023	Low	Weekly	LWD	NO_3NH_4	27%	24	20	75
	High	Weekly	HWD	NO_3NH_4	27%	24	40	150
	Low	Bi-weekly	LBWD	NO_3NH_4	27%	12	20	40
	High	Bi-weekly	HBWD	NO_3NH_4	27%	12	40	75
2024	Low	Weekly	LWD	NO_3NH_4	27%	24	25	100
	High	Weekly	HWD	NO_3NH_4	27%	24	50	200
	Low	Bi-weekly	LBWD	NO_3NH_4	27%	12	25	60
	High	Bi-weekly	HBWD	NO_3NH_4	27%	12	50	100
2025	Low	Weekly	LWD	NO_3NH_4	27%	17	50	130
	High	Weekly	HWD	NO_3NH_4	27%	17	90	250
	Low	Bi-weekly	LBWD	NO_3NH_4	27%	9	50	70
	High	Bi-weekly	HBWD	NO_3NH_4	27%	9	90	130

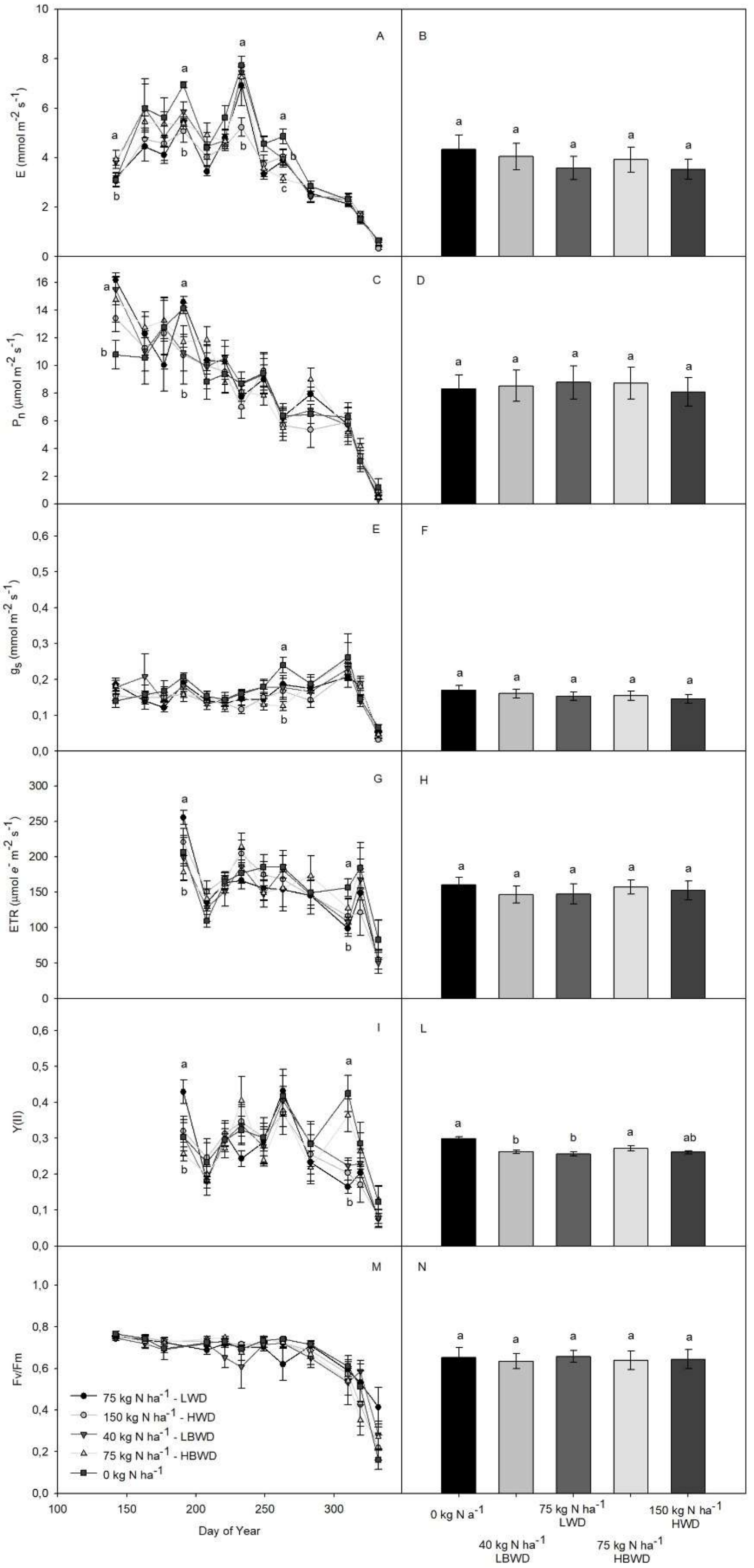
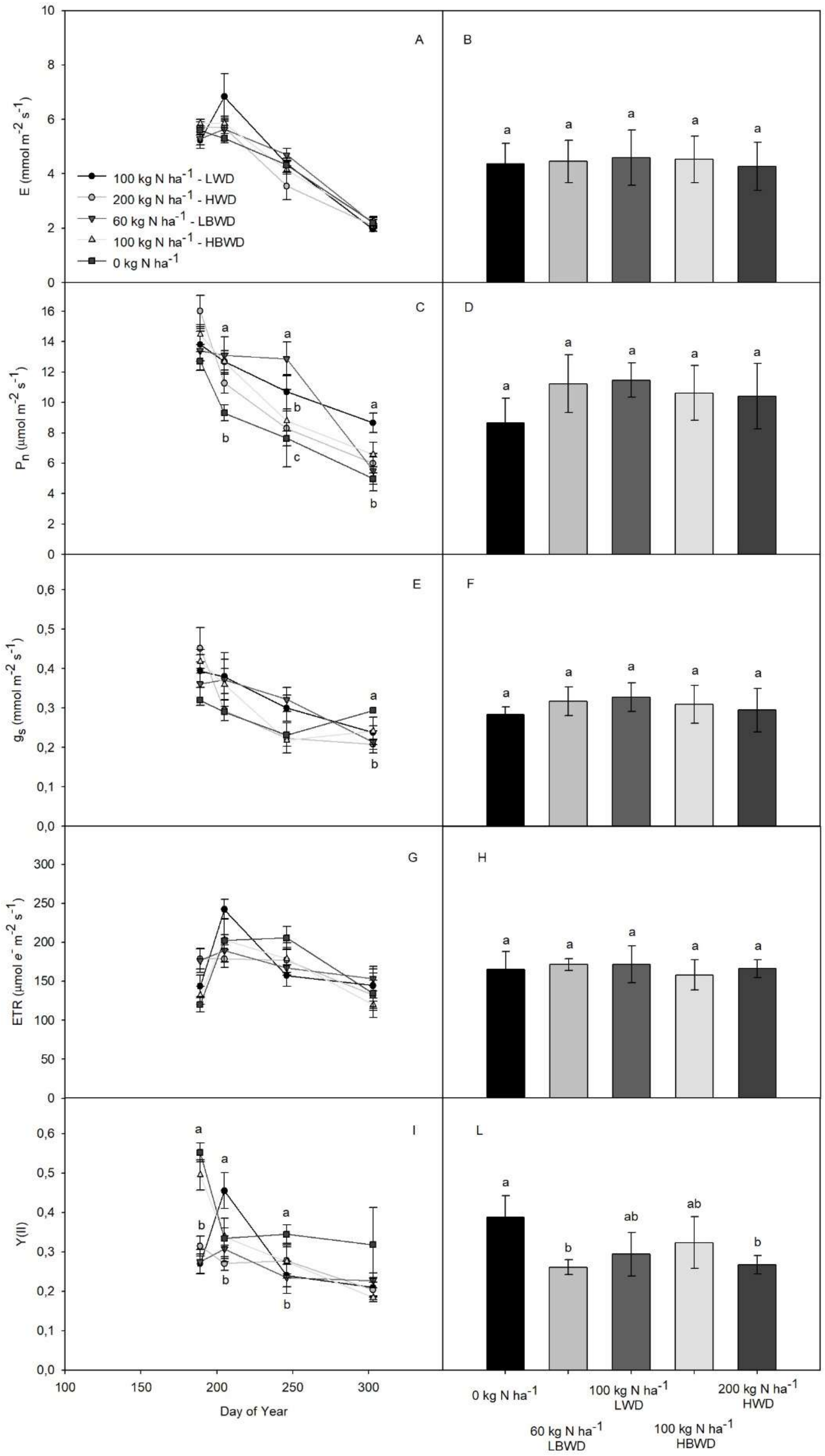


Fig. 5.1 – Seasonal trends (Panels A, C, E, G, I, M) and seasonal means (Panels B, D, F, H, L, N) of leaf physiological parameters measured in 2023. A–B: leaf transpiration (E); C–D: net photosynthesis (P_n); E–F: stomatal conductance (g_s); G–H: electron transport rate (ETR); I–L: effective quantum yield of PSII photochemistry (Y(II)); M–N: maximum quantum efficiency of PSII (F_v/F_m). Treatments were Control (0 kg N ha⁻¹), low nitrogen dose weekly (LWD), high nitrogen dose weekly (HWD), low nitrogen dose biweekly (LBWD), and high nitrogen dose biweekly (HBWD). Values are means ± SE (n = 5). Different letters indicate significant differences among treatments within the same sampling date or seasonal mean (P < 0.05); absence of letters indicates no significant differences.



Fi. 5.2 - Seasonal trends (Panels A, C, E, G, I) and seasonal means (Panels B, D, F, H, L) of leaf physiological parameters measured in 2024. A–B: leaf transpiration (E); C–D: net photosynthesis (P_n); E–F: stomatal conductance (g_s); G–H: electron transport rate (ETR); I–L: effective quantum yield of PSII photochemistry (Y(II)). Treatments were Control (0 kg N ha^{-1}), low nitrogen dose weekly (LWD), high nitrogen dose weekly (HWD), low nitrogen dose biweekly (LBWD), and high nitrogen dose biweekly (HBWD). Values are means ± SE (n = 5). Different letters indicate significant differences among treatments ($P < 0.05$).

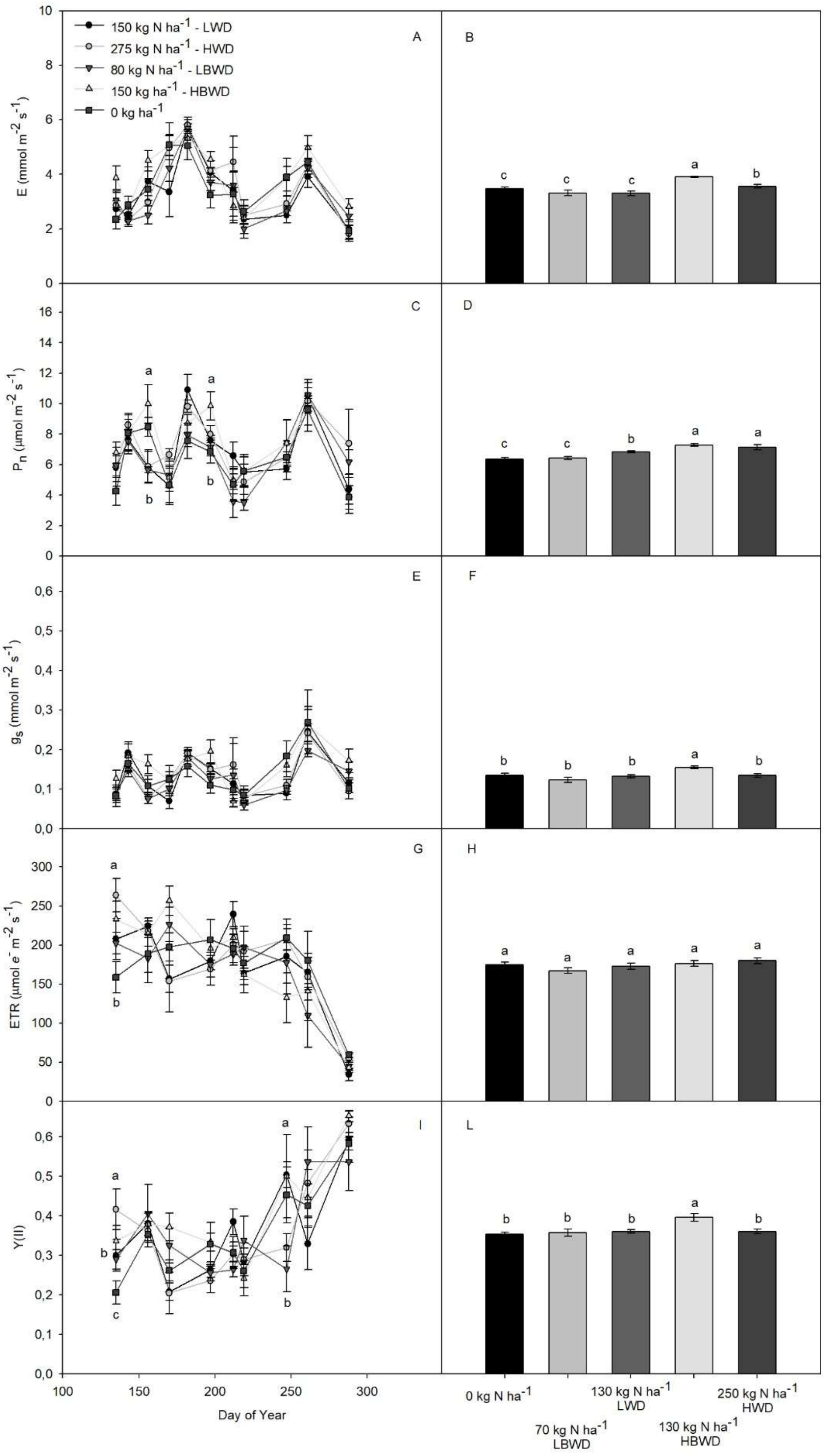


Fig. 5.3 – Seasonal trends (Panels A, C, E, G, I) and seasonal means (Panels B, D, F, H, L) of leaf physiological parameters measured in 2025. A–B: leaf transpiration (E); C–D: net photosynthesis (P_n); E–F: stomatal conductance (g_s); G–H: electron transport rate (ETR); I–L: effective quantum yield of PSII photochemistry (Y(II)). Treatments were Control (0 kg N ha^{-1}), low nitrogen dose weekly (LWD), high nitrogen dose weekly (HWD), low nitrogen dose biweekly (LBWD), and high nitrogen dose biweekly (HBWD). Values are means ± SE (n = 5). Different letters indicate significant differences among treatments ($P < 0.05$).

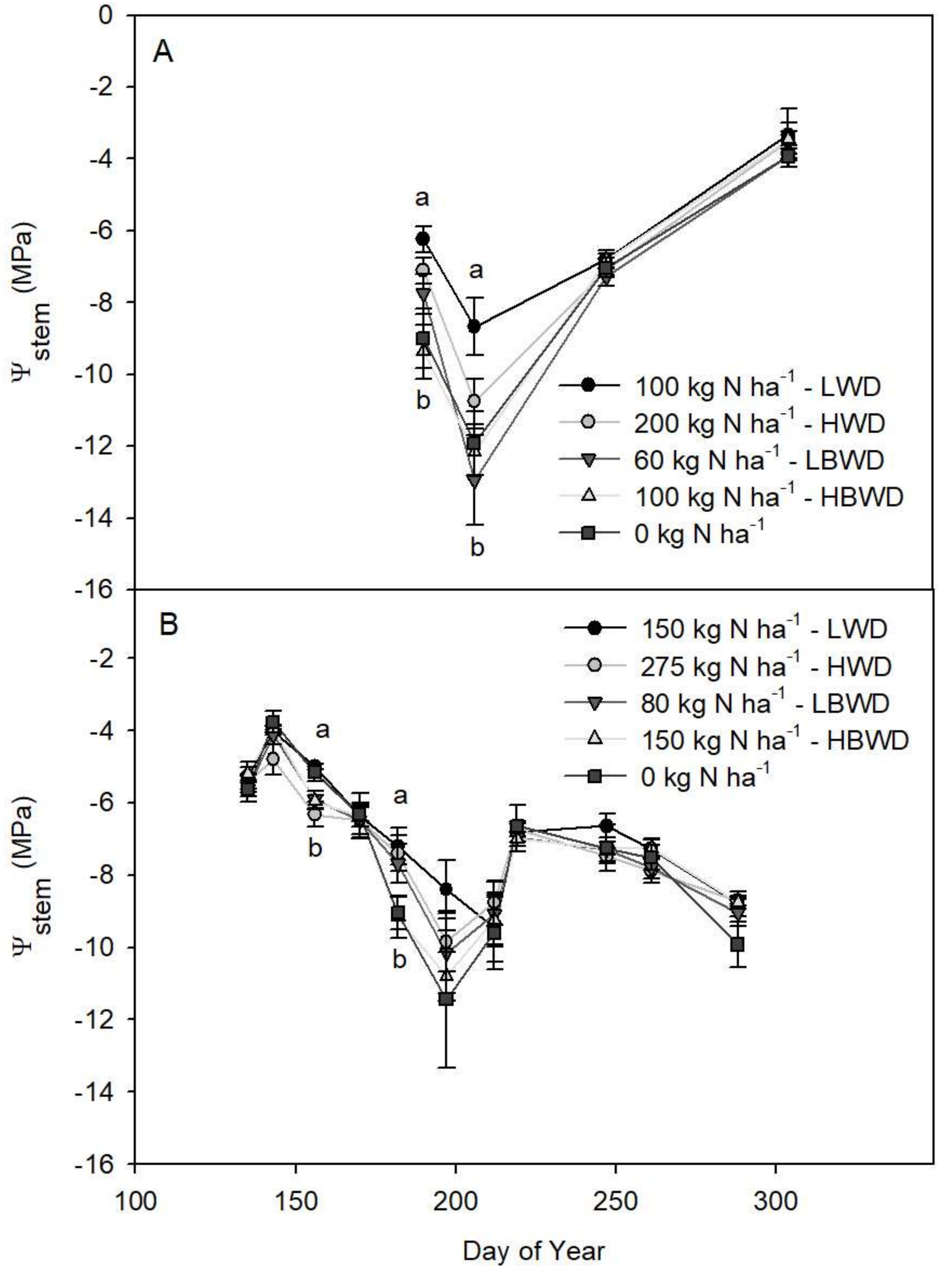


Fig. 5.4 – Seasonal trends of midday stem water potential (Ψ_{stem}) in hazelnut trees under different nitrogen rates and application frequencies during 2024 (A) and 2025 (B). Treatments were Control (0 kg N ha^{-1}), low nitrogen dose weekly (LWD), high nitrogen dose weekly (HWD), low nitrogen dose biweekly (LBWD), and high nitrogen dose biweekly (HBWD). Values are means ± SE (n = 5). Different letters indicate significant differences among treatments at the same sampling date ($P < 0.05$).

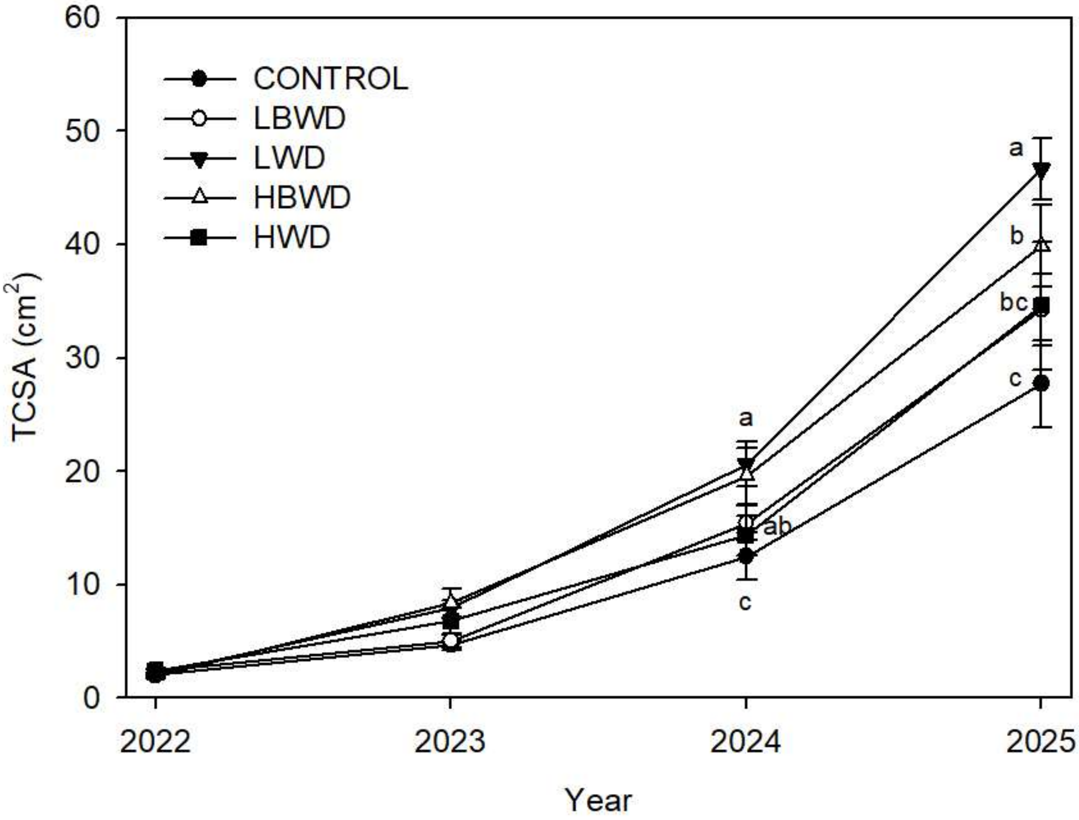


Fig. 5.5 – Annual trend of trunk cross-sectional area (TCSA) of hazelnut trees from 2022 to 2025 under different nitrogen rates and application frequencies. Treatments were Control (0 kg N ha^{-1}), low nitrogen dose weekly (LWD), high nitrogen dose weekly (HWD), low nitrogen dose biweekly (LBWD), and high nitrogen dose biweekly (HBWD). Values are means ± SE (n = 5). Different letters indicate significant differences among treatments within the same year ($P < 0.05$).

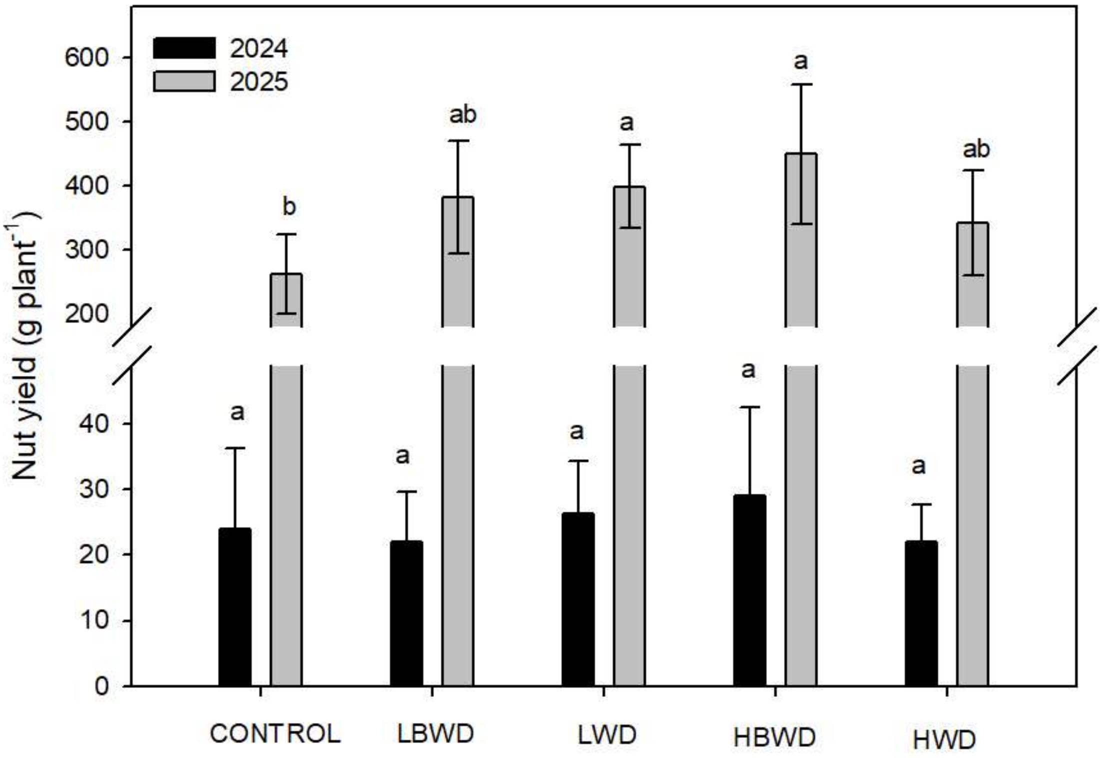


Fig. 5.6 – Nut yield per plant in 2024 and 2025 as affected by nitrogen rate and application frequency. Treatments were Control (0 kg N ha^{-1}), low nitrogen dose weekly (LWD), high nitrogen dose weekly (HWD), low nitrogen dose biweekly (LBWD), and high nitrogen dose biweekly (HBWD). Values are means ± SE (n = 5). Different letters indicate significant differences among treatments within each year ($P < 0.05$).

Tab. 5.2 – Effect of nitrogen (N) fertilization rate and application frequency on vegetative and reproductive parameters of hazelnut trees during 2022–2025. In 2022, all trees received a uniform nitrogen application (25 kg N ha⁻¹) prior to the initiation of fertilization treatments, and these data represent pre-treatment baseline measurements. Values are mean ± SE (n = 5). Different letters indicate significant differences among treatments within each year (P < 0.05).

Treatment	N (kg ha⁻¹)	Length apical shoot (cm)	Weight pruned suckers (g)	Number one-year shoots	Senescence ratio	Female flowers (n)
Control	25	43.40 ± 10.56 b	-	-	-	-
LBWD	25	51.40 ± 5.12 b	-	-	-	-
LWD	25	65.20 ± 5.99 a	-	-	-	-
HBWD	25	52.50 ± 2.14 b	-	-	-	-
HWD	25	64.00 ± 4.75 a	-	-	-	-
Treatment	N (kg ha⁻¹)					
Control	0	43.10 ± 4.61 b	354.88 ± 19.56 b	26.50 ± 5.39 ab	0.35 ± 0.02 b	6.60 ± 3.66 d
LBWD	40	50.00 ± 4.11 ab	370.31 ± 41.78 b	26.25 ± 1.11 b	0.37 ± 0.04 b	14.00 ± 2.08 b
LWD	75	55.90 ± 3.65 a	220.86 ± 15.41 c	15.67 ± 0.67 c	0.22 ± 0.02 c	22.00 ± 1.53 c
HBWD	75	52.10 ± 4.48 ab	727.06 ± 123.40 a	25.00 ± 5.22 ab	0.73 ± 0.12 a	34.33 ± 9.70 a
HWD	150	54.80 ± 7.93 ab	451.18 ± 110.87 b	29.50 ± 1.04 a	0.45 ± 0.11 b	7.67 ± 1.67 d
Treatment	N (kg ha⁻¹)					
Control	0	47.33 ± 3.53 c	718.00 ± 127.13 bc	-	1.63 ± 0.39 a	-
LBWD	60	42.80 ± 5.42 c	1290.00 ± 56.79 a	-	0.91 ± 0.19 b	-
LWD	100	57.25 ± 1.89 b	781.25 ± 91.43 bc	-	1.12 ± 0.09 b	-
HBWD	100	69.00 ± 7.76 a	975.83 ± 146.55 b	-	1.35 ± 0.15 ab	-
HWD	200	47.00 ± 8.19 c	718.33 ± 28.92 c	-	1.15 ± 0.33 ab	-
Treatment	N (kg ha⁻¹)					
Control	0	29.10 ± 0.91 a	-	-	0.55 ± 0.12 ab	-
LBWD	70	32.00 ± 3.51 a	-	-	0.78 ± 0.09 a	-
LWD	130	26.70 ± 2.17 a	-	-	0.48 ± 0.04 b	-
HBWD	130	30.42 ± 3.54 a	-	-	0.41 ± 0.02 b	-
HWD	250	26.70 ± 2.17 a	-	-	0.55 ± 0.09 b	-

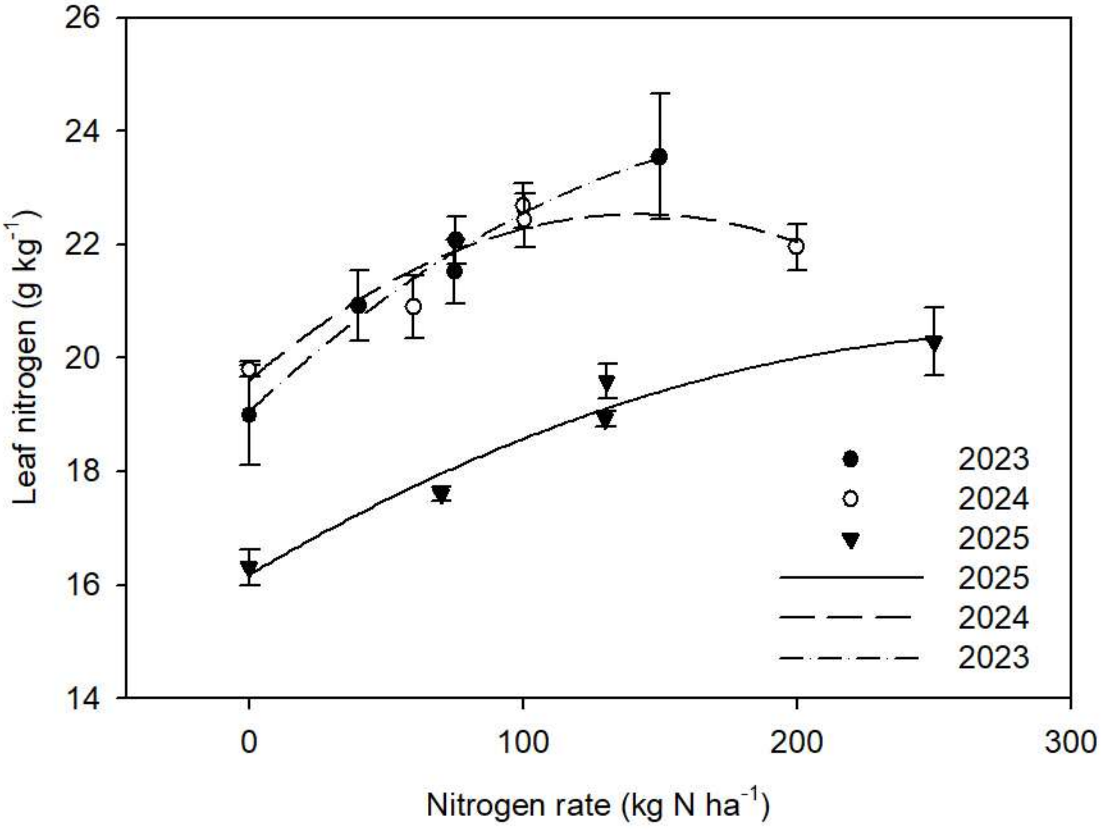


Fig. 5.7 – Relationship between nitrogen rate and leaf nitrogen concentration in 2023, 2024, and 2025. Each point represents the mean ± SE (n = 5). Quadratic regression curves are shown for each year. The fitted models were significant ($P < 0.05$), with coefficients of determination of 0.98, 0.88, and 0.96 for 2023, 2024, and 2025, respectively. The regression equations were: 2023: $y = 1.9064 + 0.0045x - 1.0400 \times 10^{-5}x^2$; 2024: $y = 1.9612 + 0.0041x - 1.4538 \times 10^{-5}x^2$; 2025: $y = 1.6180 + 0.0029x - 4.8729 \times 10^{-6}x^2$.

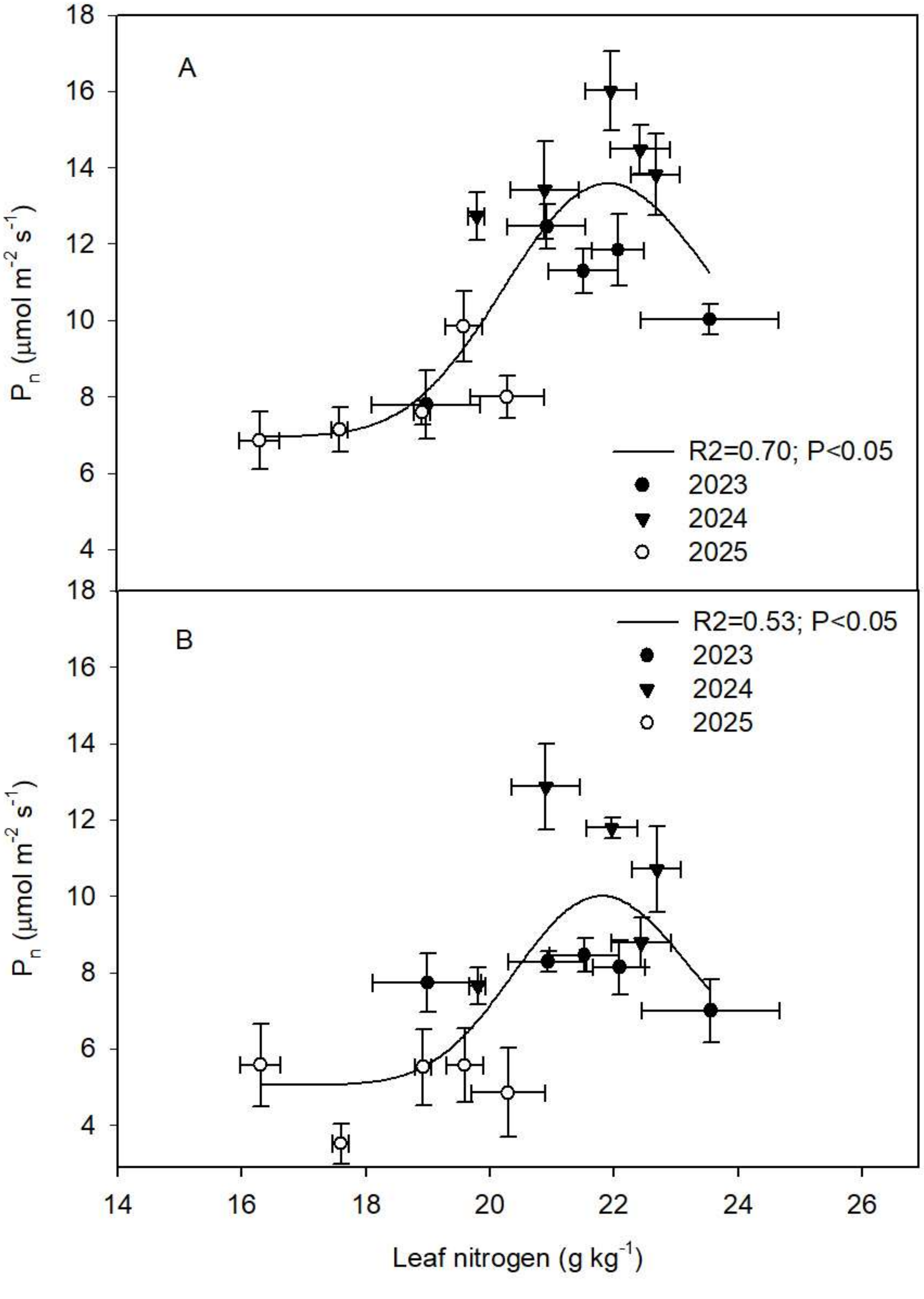


Fig. 5.8 – Relationship between leaf nitrogen concentration and net photosynthesis (P_n) in hazelnut leaves measured in July (A) and August (B) across three growing seasons (2023–2025). Each point represents the mean ± SE (n = 5). Nonlinear regression curves were significant at $P < 0.05$.

CHAPTER 6

Final conclusions

Classical agronomic practices considered—irrigation, soil management, and nitrogen fertilization—play different roles in supporting the early growth of young hazelnut orchards. Among these, irrigation emerged as the factor with the greatest influence on vegetative performance.

In the irrigation trial, the split-irrigation schedule resulted in the most pronounced increase in growth after only one year of application, without any additional operational cost compared with the single daily turn. This finding, combined with the definition of a species-specific stem water potential baseline, highlighted the strong sensitivity of hazelnut to atmospheric demand and climatic variability. Maintaining plant water status within optimal physiological ranges therefore appears to be the most critical condition for sustaining growth during the establishment phase.

When the results from irrigation were compared with those from the fertilization and soil-management experiments, it became clear that even higher inputs of nitrogen or alternative under-row management practices did not generate growth responses comparable to those obtained through improved irrigation scheduling. These outcomes confirm that, although all three operations are essential for the successful establishment of a new orchard, irrigation represents the most decisive and impactful agronomic input in determining early tree performance.

In summary, this doctoral research demonstrates that careful water management—supported by physiological indicators such as stem water potential—should be prioritized as the primary driver of vigorous and uniform growth in young hazelnut orchards, while fertilization and soil management play complementary but comparatively less influential roles.

Supplementary materials

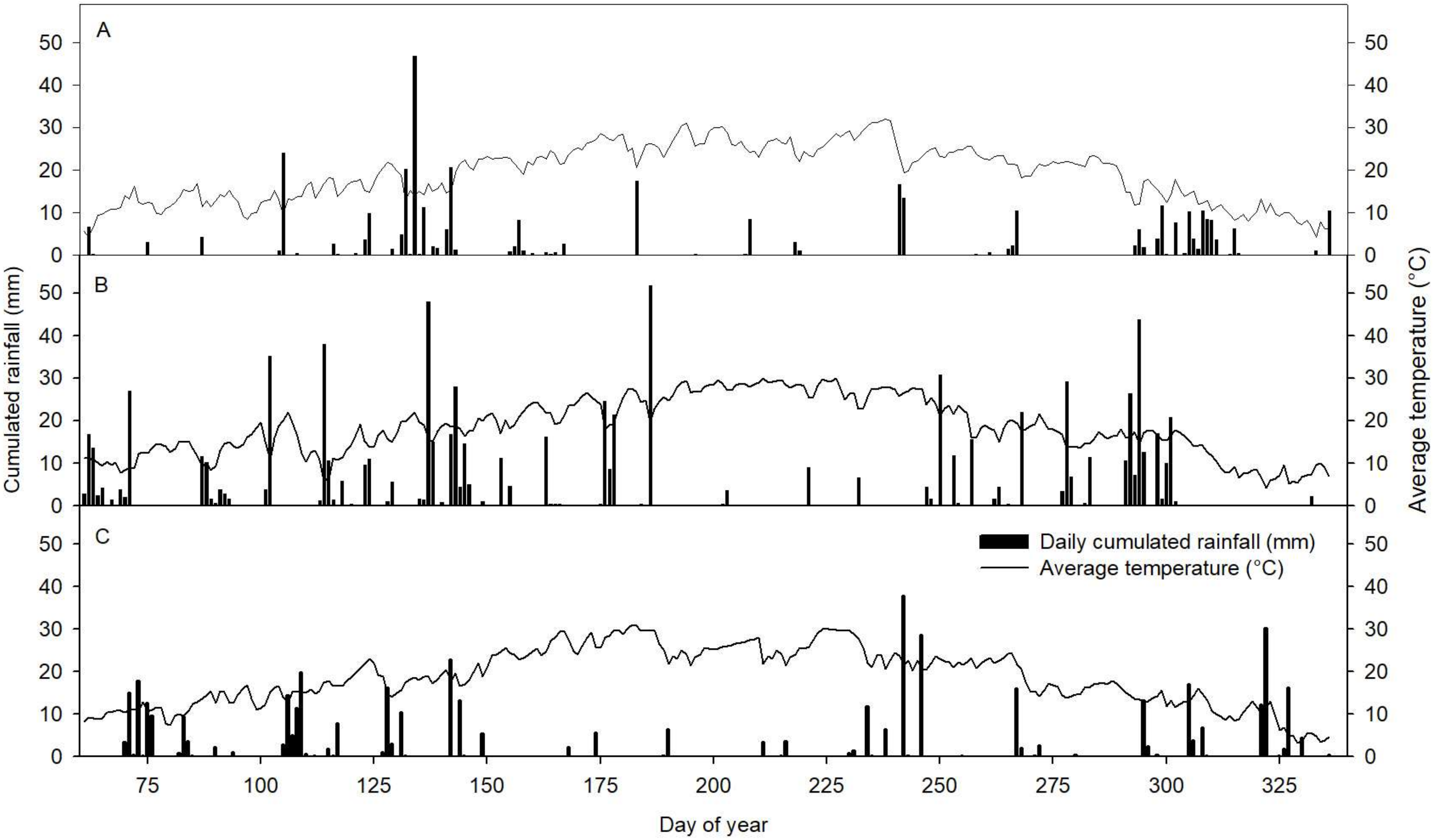


Fig S1 - Daily average air temperature (line) and daily accumulated rainfall (bars) recorded during the vegetative period of the three growing seasons: (A) 2023, (B) 2024, and (C) 2025. Data are reported as day of year (DOY).

Tab. 1S - Monthly crop evapotranspiration (ETc, mm), corresponding irrigation volumes per unit area (Irr, m^3 ha^{-1}), and average daily irrigation supply per plant (L $plant^{-1}$ d^{-1}) from April to September during the 2022–2025 growing seasons. ETc represents crop water consumption expressed as equivalent water depth and was calculated according to the FAO approach ($ETc = ET_0 \times Kc \times Kr$); irrigation volumes were derived assuming 100% ETc restitution and reflect orchard planting density and system configuration adopted in each year.

Years/Months		Apr	May	Jun	Jul	Aug	Sept
2022	Etc (mm)	2.4	3.6	4.4	4.9	4.2	2.5
	Irr (m^3 ha^{-1})	0	22.6	36.8	44.4	33.1	13.4
	L $plant^{-1}$ day^{-1}	0	1	1.5	1.5	1.5	0.5
2023	Etc (mm m^{-2})	7.3	10.7	13.1	14.6	12.5	7.6
	Irr (m^3 ha^{-1})	0	41.8	84.5	107.3	73.2	14.1
	L $plant^{-1}$ d^{-1}	0	1.5	3	4	4	0.5
2024	Etc (mm m^{-2})	14.6	21.3	26.2	29.2	25.0	15.1
	Irr (m^3 ha^{-1})	0	78.7	164.1	209.9	141.7	23.4
	L $plant^{-1}$ d^{-1}	0	2	4	8	8	0.5
2025	Etc (mm m^{-2})	39.0	56.9	69.9	78.0	66.8	40.3
	Irr (m^3 ha^{-1})	0	164.4	392.1	514.0	332.1	16.8
	L $plant^{-1}$ d^{-1}	0	4	16	16	16	0.5

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