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SUSTAINABLE VITICULTURAL MANAGEMENT PRACTICES: MONITORING GRAPEVINE PLANT PERFORMANCE WITH PROXIMAL AND REMOTE TECHNOLOGIES

Settore scientifico-disciplinare
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Abstract

This thesis explores the effects of climate change on viticulture, focusing on how rising temperatures, irregular rainfall, and extreme weather impact vineyard *terroir*. The study evaluates two canopy management techniques – early leaf removal at fruit set (ELR) and foliar application of Basalt Flour® (BF) – compared to control management (C), on their ability to enhance resilience, maintain grape productivity and quality, and promote environmental sustainability.

Over three years (2021–2023), trials were conducted in a Chardonnay vineyard in Umbria, Italy (Orvieto PDO). Mesoclimatic and microclimatic data, about canopy (CH) and near the bunch (BH) temperatures, were collected using a weather station and sensors, while thermal remote sensing assessed the Crop Water Stress Index (CWSI). Physiological measurements, including leaf water potential (Ψpd), chlorophyll content (Chl), and stomatal conductance (gs), were recorded alongside grape production, quality, and carbon storage in annual biomass. Life cycle assessment (LCA) quantified the environmental impact of each practice.

Results showed rising temperatures and water deficits shifted bioclimatic conditions beyond Chardonnay's optimal range. ELR reduced evening BH temperatures, improving heat dissipation, while BF's reflective properties lowered maximum temperatures under arid conditions, also lowering the CWSI values. ELR altered gs during critical stages, improving grape quality but reducing yield, while BF maintained productivity and enhanced chlorophyll accumulation. Carbon storage analysis showed ELR promoted vegetative growth at the expense of reproductive biomass, while BF supported reproductive carbon storage. LCA indicated ELR increased CO_2 emissions by 35% per kg of grapes compared to control, whereas BF raised emissions by only 1%, making it the more sustainable option.

In conclusion, ELR could improve grape quality but has higher environmental costs, while BF is a sustainable, effective method for mitigating climate stress. These findings highlight the importance of balancing productivity with environmental sustainability to address climate challenges in viticulture.

Keywords: *Vitis vinifera* L., climate change, sustainable viticulture, abiotic stresses, canopy management, particle film, carbon sink, carbon footprint.

Riassunto

Questa tesi analizza gli effetti del cambiamento climatico sulla viticoltura, con particolare attenzione a come l'aumento delle temperature, le precipitazioni irregolari e gli eventi meteorologici estremi influenzino il terroir del vigneto. Lo studio valuta due tecniche di gestione della chioma – la defogliazione precoce all'allegagione (ELR) e l'applicazione fogliare di Basalt Flour® (BF) – comparate ad un controllo (C), inerentemente alla loro capacità di migliorare la resilienza, mantenere la produttività e qualità delle uve e promuovere la sostenibilità ambientale.

Nei tre anni di studio (2021-2023), le sperimentazioni sono state condotte in un vigneto di Chardonnay in Umbria, Italia (Orvieto DOP). I dati mesoclimatici e microclimatici, relativi alle temperature in chioma (CH) e vicino al grappolo (BH), sono stati raccolti utilizzando una stazione meteorologica e dei sensori, mentre il telerilevamento termico ha valutato il crop water stress index (CWSI). Sono state effettuate misurazioni fisiologiche, tra cui il potenziale idrico fogliare (Ψpd), il contenuto di clorofilla (Chl) e la conduttanza stomatica (gs), assieme a dati sulla produzione, qualità delle uve e accumulo di carbonio nella biomassa annuale. L'analisi del ciclo di vita (LCA) ha quantificato l'impatto ambientale di ciascuna pratica.

I risultati hanno mostrato che l'aumento delle temperature e il deficit idrico hanno spostato le condizioni bioclimatiche al di fuori del range ottimale per lo Chardonnay. ELR ha ridotto le temperature serali nell'area BH, favorendo la dissipazione del calore, mentre BF ha abbassato le temperature massime grazie alle sue proprietà riflettenti in condizioni aride, abbassando anche i valori del CWSI. ELR ha migliorato la qualità delle uve ma ridotto le rese, mentre BF ha mantenuto la produttività e favorito l'accumulo di clorofilla. L'analisi del carbonio ha mostrato che ELR un risanamento della vegetazione a scapito della biomassa riproduttiva, mentre BF ne migliora lo stoccaggio. L'LCA ha rivelato un aumento delle emissioni di CO_2 in ELR del 35% per kg di uva rispetto al controllo, mentre BF solo dell'1%, risultando più sostenibile.

In conclusione, ELR può migliorare la qualità delle uve ma ha maggiori costi ambientali, mentre BF rappresenta una soluzione efficace e sostenibile per mitigare lo stress climatico. Questi risultati evidenziano l'importanza di bilanciare produttività e sostenibilità per affrontare le sfide climatiche nella viticoltura.

Parole chiave: *Vitis vinifera* L., cambiamento climatico, viticoltura sostenibile, gestione della chioma, film di particelle, sink di carbonio, impronta di carbonio.

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Premise

Over the past few decades, the effects of climate change have become increasingly evident, posing new and unprecedented challenges to viticulture worldwide. Rising global temperatures, shifts in rainfall patterns, and more frequent extreme weather events are significantly altering the *terroirs* that traditionally sustain vineyards. Grapevine development is deeply tied to these external factors, particularly climate, and such changes have profound implications for grape phenology, quality, and overall vineyard productivity, driving a shift in the regions suitable for cultivation. This pressure needs the development of resilient viticultural practices that enable vineyards to withstand and recover from climatic stressors while maintaining constant yield and grape quality. Addressing these challenges requires a combination of long-term strategies, which involve structural changes and investment in strengthening system resilience, and short-term actions focused on immediate effectiveness within a growing season. However, adaptation to climate change alone is insufficient if viticulture contributes to environmental degradation. The need to balance resilience and sustainability highlights the importance of comprehensive impact assessments to evaluate the consequences of viticulture and ensure that adaptive strategies do not cause further harm to ecosystems. Precision viticulture, leveraging technologies like field data and remote sensing, plays a crucial role in optimizing vineyard performance by enabling site-specific management and real-time monitoring of variables such as microclimatic conditions.

This thesis addresses the dual challenge of climate adaptation and sustainable viticulture by developing resilient practices and precision technologies. By integrating advanced monitoring systems and sustainability assessments, it aims to optimize vineyard performance while minimizing impacts. Exploring how climate change affects grape-growing regions, this research offers valuable insights for vineyard managers, policymakers, and the agricultural community

1. INTRODUCTION

1.1 Vineyard management strategies in a climate change scenario

Increasing water scarcity and droughts, wildfires, and risks to food production and safety are only some of the threats due to climate change (Pörtner et al., 2022). Following the unprecedented and record-breaking heat experienced in 2023, the global climate is now edging close to surpassing the 1.5°C threshold established by the Paris Agreement (WMO, 2024), a critical marker aimed at limiting the worst impacts of climate change.

With 7.2 million hectares of planted area in 2023 (OIV, 2024), viticulture is of considerable socio-economic importance worldwide, boasting a deep connection with lands. In viticulture, climate is a central component of *terroir*, as it plays a major role in grapevine phenology, physiology, (Cameron et al., 2022; Kimani, 2024), and grape development and quality (Costa et al., 2020; de Rosas et al., 2022). Its susceptibility to changing environmental conditions (van Leeuwen and Darriet, 2016), has made this plant a bio-indicator of climate change (Brunori et al., 2022; Fernández-González et al., 2013). Temperature is one of the most critical factors in viticulture, directly affecting vine growth and development (Droulia and Charalampopoulos, 2022). Climate change poses significant challenges to viticulture, with rising temperatures, unpredictable rainfall, and extreme weather events disrupting grapevine development and altering the climate of traditional grapevine growing areas (Hannah et al., 2013; van Leeuwen and Darriet, 2016).

To cope with these challenges, vineyard management must be based on both long-term and short-term strategies. Long-term solutions involve forward-thinking approaches designed to strengthen system resilience, although these typically demand significant investment and structural changes within agricultural practices (Fraga et al., 2012; Santos et al., 2021a). On the other hand, short-term strategies can be applied within a single growing season or yearly and can be considered the first protection action to be implemented against adverse climate conditions, often more practical and efficient (Fraga et al., 2012; Santos et al., 2021b). These strategies such as irrigation, green pruning, and protective techniques, help optimize the vineyard's microclimate improving air circulation and sunlight exposure, and change the yield patterns.

Green pruning, or summer pruning, refers to a set of manual or mechanical techniques used in vineyards during the growing season when vines show active vegetative growth (Poni et al., 2023). These managements concur to modify the microclimate of the canopy affecting vine growing, modulating its vigor, the source-sink balance, and allocation of carbon and other nutrients, influencing grape yield and quality (Martínez-Lüscher and Kurtural, 2023; Pulko et al., 2022). In terms of source-sink balance, green pruning influences the relationship between the vine's photosynthetic sources (mature leaves) and its sinks (grapes and developing shoots). The same tissue can be both source and sink, changing roles throughout the season (Garrido et al., 2023; Poni et al., 2023).

Leaf removal is a key short-term practice, that involves the selective removal of leaves to enhance grape quality by improving sunlight penetration and airflow around the fruit. Applied at various stages, leaf removal affects the source-sink relationship with different results. In the early stages (from flowering to fruit set), basal leaf removal can increase air circulation, promoting the healthiness of the bunches, reducing cluster compactness, and promoting higher grape quality influencing grape ripening. However, early defoliation may also reduce yield, highlighting the trade-off between quantity and quality in viticulture. By modifying the microclimate at the cluster level (increased sun exposure and aeration), defoliation is commonly performed in cool and moderate climates, where fruit ripening may be difficult and/or disease pressure high (Gambetta et al., 2020; Mundy et al., 2022; Wurz et al., 2022). In hot, arid climates, while both insufficient and excessive defoliation can increase canopy porosity and expose grape berries to intense sunlight – raising the risk of sunburn (J. M. Gambetta et al., 2020; Gambetta et al., 2021) – leaf removal remains an exceptionally adaptable technique for managing canopy density and optimizing vine microclimate (Poni et al., 2023). Indeed, as heat stress becomes a more significant factor in viticulture, the balance between disease management and sun damage prevention becomes increasingly delicate. Exposition through defoliation enhances berry adaptation to high-light environments, reducing sunburn damage and increasing secondary metabolite concentrations (Gambetta et al., 2021). Additionally, controlled leaf removal boosts resilience to heat damage, highlighting its potential benefits under appropriate conditions (Müller et al., 2023).

In hot and dry climates, another adaptative strategy that could be applied in vineyards is the use of antitranspirants (ATs) distributed on the canopy and production, to reduce biotic and abiotic stresses (Hosseinabad and Khadivi, 2019; Micco et al., 2024). This products could be divided into three main classes of products, depending on the type of action on the plant (Mphande et al., 2023). Metabolic ATs benefit to plant growth under water stress conditions is due to their ability to partially close stomata by influencing guard cells, thereby minimizing water loss (Mphande et al., 2021). In this group, abscisic acid (ABA) is perhaps the most prominent (Mphande et al., 2023). Reflective Ats reflect infrared radiation and ultraviolet rays (Glenn and Puterka, 2010; Petoumenou, 2023). Among these products, extensive use has been made of kaolin, a fine white clay able to lower the temperature of the exposed tissues by reducing the absorption of solar radiation (Cataldo et al., 2022; Frioni et al., 2019; Teker, 2023), and enhances the water status of the vines by increasing leaf water potential, influencing gaseous exchange, and reducing water loss, especially in drought-prone climate (Dinis et al., 2017; Glenn et al., 2010). In addition, the use of kaolin on the canopy showed effects at the level of leaf pigments and an increase in chlorophyll content (Dinis et al., 2017; Rashad et al., 2023), with positive effects on production, with increased yields (Cataldo et al., 2022; Dinis et al., 2017). Also, it has been demonstrated to be good practice to counter the divergence between technological and aromatic maturity in Sauvignon Blanc grapevines (Cataldo et al., 2022), while in Malbec an increase in anthocyanin accumulation was noted (K. Shellie and King, 2013). Dinis et al. (2016) observed an improvement in the antioxidant capacity in berries, correlated with the increased content of secondary metabolites. In addition, foliar sprays with silicates are also effective against pests (Laane, 2018; Rashad et al., 2023; Wang et al., 2022). Finally, film-formings Ats create a physical waterproof barrier over stomata, thereby reducing transpirational water loss (Mphande et al., 2023). Among these products, pinolene and its derivatives have been shown to reduce grapevine's vigour limiting transpiration and photosynthetic activity (Silvestroni et al., 2020). This results in improved water use efficiency (Palliotti et al., 2010), along with delayed ripening, lower soluble solids concentration, and lighter and less compact bunches (Andreotti et al., 2024; Palliotti et al., 2010; Silvestroni et al., 2020). Additionally, chitosan has been shown to enhance titratable acidity at harvest; however, its effects can vary depending on anatomical and physiological differences between cultivars, as well as climatic conditions (Andreotti et al., 2024). Nonetheless, challenges remain with the application of particle films. The timing and frequency of application are crucial, as a consistent layer must be maintained throughout the growing season to preserve their coating properties.

Overall, these short-term strategies aim to limit the impact of abiotic stresses on vine physiologies and production, which, combined with targeted agronomical management, could be promising in the context of mitigating the effects of climate change.

To address the growing challenges posed by climate change, precision viticulture (PV) has emerged as an essential tool to mitigate threats to viticulture. By integrating advanced proximal and remote technologies, PV allows for more accurate monitoring and management of vineyards, optimizing resources and reducing environmental impacts. These technologies are designed to provide site-specific data, enabling growers to apply targeted interventions that enhance vine health and productivity while mitigating climate-induced stress (Gebbers and Adamchuk, 2010). One of the critical aspects of precision viticulture (PV) is the ability to monitor temperature variations across the vineyard, as temperature plays a pivotal role in vine physiology and health (Ferro and Catania, 2023).

Among the most used devices to detect variation in the canopy temperature, thermal image has proven its ability to identify water stress (Ammoniaci et al., 2021). Unmanned Aerial Vehicles (UAVs) equipped with thermal cameras, can fly over vineyards, capturing detailed temperature maps that reveal areas where vines may be overheating or experiencing water stress. These thermal variations are often early indicators of physiological stress, allowing for preventative measures to prevent damage. This technology offers high-resolution insights into vine health across large areas, making it possible to assess the vineyard's condition efficiently and with minimal disruption to the vines (Ferro and Catania, 2023). Usability, cost-effectiveness, performance, and relevance to the user are among the most critical factors influencing the adoption of precision viticulture (Rose et al., 2016). Wireless sensor networks (WSNs), which are increasingly used to monitor vineyard vegetation, effectively address these considerations by providing practical and efficient solutions (Kandris et al., 2020). This technology provides real-time data, enabling growers to detect microclimatic variations and support decision-making processes related to irrigation (Xiaoshuan et al., 2015), pest control (Singh et al., 2022), and the study of phenological development (Fuentes-Peñailillo et al., 2021).

By integrating these advanced technologies, precision viticulture enables more informed and timely interventions, promoting sustainable vineyard management while enhancing productivity and resilience to climate variability.

1.2 Enhancing agroecosystem performance and ecosystem services for sustainable viticulture

Sustainable development (SD) is at the heart of the global community's aspirations. In September 2015, more than 150 international leaders met at the United Nations to contribute to global development, promote human well-being and protect the environment, by setting seventeen goals (Sustainable Development Goals - SDG). Special attention should be paid to climate change, considered one of the greatest challenges of our time and whose adverse impacts undermine the ability of all countries to achieve sustainable development (United Nations General Assembly, 2015).

To foster sustainable agricultural development, enhancing agroecosystem services (AES) is essential. This improvement can boost food supply and lessen agriculture's reliance on external inputs, thereby effectively addressing the conflict between agricultural production and environmental issues. In addition to supplying raw materials for human use (provisioning services), agroecosystems offer cultural services, non-material benefits rooted in local practices and knowledge, regulating services that help maintain environmental balance, as well as supporting services that underpin ecosystem functionality (Liu et al., 2022). However, modern agricultural industrialization has led to a decline in some AES, impeding SDGs related to environmental quality and resource conservation (Padhiary and Kumar, 2024; Vila-Traver et al., 2021). Evaluating AES requires specific indicators and assessment methods, currently divided into public participation, sample plot observation, empirical and mechanism models, and valuation approaches (Liu et al., 2022). By strengthening AES research, agroecosystems can be managed to support sustainable agricultural goals, aligning productivity with environmental conservation.

It is crucial to establish clear guidelines based on robust studies that provide a concrete understanding of the most effective actions to take to enhance the ecosystem services and at the same time to repay the efforts by producers (White and Hanley, 2016). The Common Agricultural Policy (CAP) (EU, 2024) supports these efforts with greening measures, agri-environment-climate measures (AECMs), and eco-schemes that promote sustainable farming practices and carbon farming. A growing emphasis is being placed on the carbon sink function of agroecosystems and carbon farming actions (Brunori et al., 2016; Demestihas et al., 2017; Montanaro et al., 2017), which are measures implemented at a farm level by managing carbon pools, fluxes, and greenhouse gas emissions to mitigate climate change (COWI et al., 2021).

To study the carbon sink function of vineyards, various techniques have been used. Net Ecosystem Exchange (NEE) measurements, quantify the net carbon exchange between the atmosphere and ecosystem on a vast scale using the application of micrometeorological techniques, such as eddy covariance (EC). This approach is particularly useful for observing CO_2 fluxes and their seasonal variability in real-time and is widely used within the European Integrated Carbon Observation System (ICOS) network to monitor greenhouse gases (GHGs) balances in different agricultural and natural ecosystems (Rebmann et al., 2018; Storm et al., 2023). In particular, through EC, it has been shown how vineyards can sequester CO_2 during critical phenological stages (Gianelle et al., 2015; Guo et al., 2014; Vendrame et al., 2019). However, this technique does not allow for a precise and site-specific assessment, as flux measurements typically cover an area ranging from a few hectares to square kilometers (Rebmann et al., 2018). Furthermore, the accuracy of this technique is dependent on stationary atmospheric conditions, the homogeneity of the study terrain, and the surface energy balance (Shi et al., 2022). To reduce the scale of the study, respiration chambers can be used. These chambers are widely employed to measure the respiration of terrestrial ecosystems due to their low cost, energy efficiency, and easy transport (Baneschi et al., 2023). They are primarily used to assess the exchange of CO_2 between the soil and atmosphere (Callesen et al., 2023; Cirigliano et al., 2023). More specific techniques involve direct measurements to assess net primary production (NPP) by estimating carbon accumulation in plant organs and soil through carbon concentration assessments (Brunori et al., 2016; Scandellari et al., 2016) and allometric models (Song et al., 2023; Zhang et al., 2021). New technologies, such as LiDAR (Light Detection and Ranging), enable the analysis of biomass distribution and plant architecture using 3D imaging, allowing for precise biomass production quantification (Li et al., 2024; Tagarakis et al., 2018). Moreover, predictive models like STELLA, a dynamic tool that simulates vine dry mass production, have been developed, offering valuable insights into vineyard carbon dynamics (Poni et al., 2006b; Salvi et al., 2021).

These various approaches, each with its unique advantages, provide complementary insights into vineyard carbon fluxes, laying the groundwork for a more detailed analysis of the potential of vineyards to sequester CO_2.

Potential of vineyards on carbon sequestration

In recent years, there has been growing attention toward perennial crops due to their potential to sequester moderate levels of carbon, contributing to emissions reduction and carbon storage within agroecosystems (Nardino et al., 2013; Plénet et al., 2022; Zanotelli, 2018; Zanotelli et al., 2013), also playing a key role in sustaining food production. Among these, viticulture stands out as a globally significant socio-economic sector, with 7.3 million hectares under cultivation worldwide, including 3.3 million hectares in Europe (OIV, 2023), forming a potential carbon sink.

The process by which vine plants (*Vitis vinifera* L.) capture atmospheric carbon dioxide (CO_2) begins in their green organs (source), where CO_2 is absorbed and converted into photosynthates through photosynthesis. These photosynthates are then transported to different storage structures (sinks) within the plant, contributing to biomass growth and the plant's net primary production (NPP) (Lovett et al., 2006; Scandellari et al., 2016).

Two carbon pools can be identified: the below-ground biomass (Below-ground Net Primary Production - BNPP), consisting of the roots that account for approximately 40% of net primary production (NPP) (Lovett et al., 2006; Scandellari et al., 2016), and the above-ground biomass (Above-ground Net Primary Production - ANPP), which include wood, shoots (counting leaves and pruning shoots) and reproductive organs (Brunori et al., 2016; Pitacco and Meggio, 2015). A portion of the fixed carbon supports the growth of vegetative and reproductive structures, while another one is stored as non-structural carbohydrates (NSC), essential for sustaining the plant at the start of the vegetative cycle supplying energy before it resumes active photosynthesis (Tixier et al., 2019). Also, within the vineyard ecosystem, a significant portion of the carbon is stored in the soil as soil organic carbon (SOC) (Callesen et al., 2023) (Figure 1).

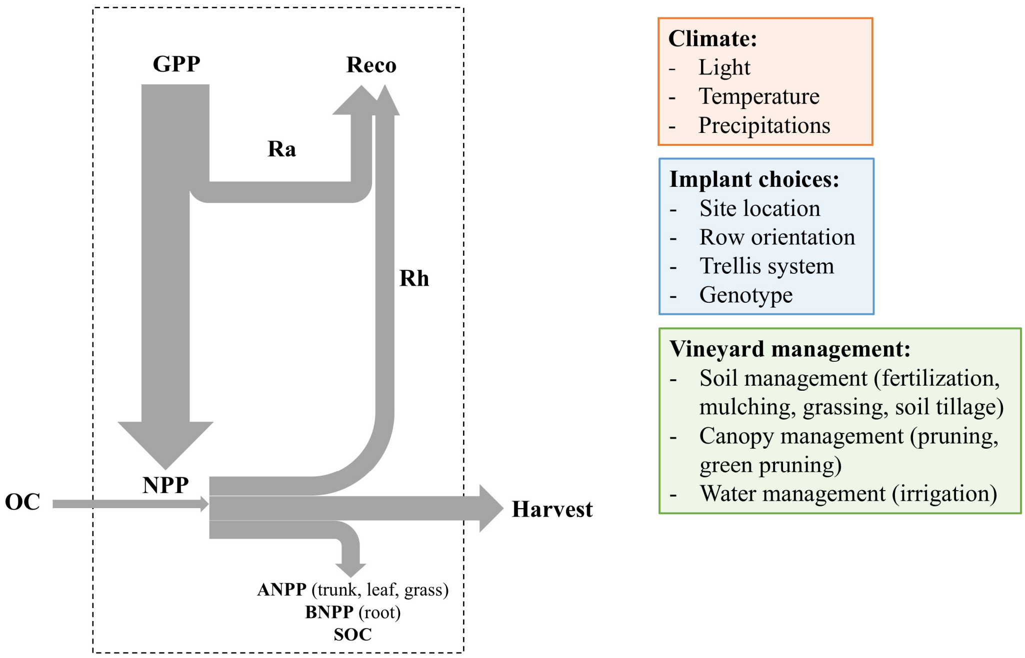

Figure 1. *Carbon cycle scheme within a vineyard ecosystem (dashed line) and the main factors influencing it (GPP – gross primary production; NPP -net primary production; ANPP – above-ground net primary production; BNPP – below-ground net primary production; SOC – soil organic carbon; Ra – autotrophic respiration; Rh – heterotrophic respiration; Reco – ecosystem respiration; OC – organic carbon fertilization) (modified from Zanotelli et al., 2013).*

A principal factor regulating net photosynthetic rate (Pn), photosynthetic photon flux density (PPFD), and overall dry matter accumulation and contents of major carbohydrates in above- and below-ground organs, is light quality, with blue and red wavelengths proving especially favorable to plant growth (Liu et al., 2023). Also, leaf expansion and leaf positioning are essential for optimizing light capture, and hence photosynthesis and dry matter accumulation (González et al., 2021). Photosintesys, together with shoot and leaf growth (Greer, 2017) is hardly dependent on meteorological parameters, being strongly influenced by temperatures (Ferro and Catania, 2023) with an optimum between 20 to 30°C (Greer and Weedon, 2012). Above this range, photosynthetic rates decline sharply, reaching minimal levels at 45 °C, likely due to limitations in ribulose-1,5-bisphosphate (RuBP) carboxylation, indicating that elevated temperatures impair carbon fixation (Greer and Weedon, 2012). In conditions of both radiative excess and thermal stress, stomatal conductance may be reduced to varying degrees, depending also on water stress and genotype (Serrano et al., 2024), first reducing the efficiency of photosystem II (ΦPSII), and then triggering the breakdown of PSII reaction centers, leading to irreversible damage (Palliotti and Poni, 2015). Finally, sink strength determines photoassimilates importation and accumulation, thus controlling crop yield (Li et al., 2021). Thus, the choice of the planting site, with optimal climatic conditions, row orientation, trellis system, and slope (Novara et al., 2019), is crucial in determining the strengthening of the carbon sink function of the vineyard.

The fluctuation of the NEE during the year depends primarily on the phenological stage. During the early stages of vegetative growth in early spring, plant shoots use NSC stored in perennial organs (mainly roots and trunk) until they acquire sufficient leaf mass to satisfy their respiratory needs, approximately until anthesis (Lebon et al., 2008), a period in which the plant begins to effectively increase carbon sequestration from the atmosphere (Hernández-Montes et al., 2017) with its climax during the veraison period (Guo et al., 2014; Pitacco and Meggio, 2015). This reduces the utilization of reserve carbohydrates and initiates the carbon storage process (Tixier et al., 2019). Also, the phenological phases affect soil respiration, with an increase of root respiration from budburst to pea-size berry stage and then a decrease until the ripening stage (Hernández-Montes et al., 2017).

The coordinated implementation of vineyard management practices can substantially alter the sink function of the vineyard ecosystem. As the soil represents one of the main CO_2 emissions (Brunori et al., 2016), soil management plays a fundamental role. Organic managed vineyards can enhance the carbon fixation in the soil (Brunori et al., 2016), while in conventional vineyards, fertilization can make the difference, with a reduction of soil respiration (Rs) with the use of organo-mineral fertilizers (Cirigliano et al., 2023). Additionally, inter-row grass cover contributes to carbon storage, with the choice of plant species being critical, with leguminous species, in particular, offering higher carbon and nitrogen assimilation (Callesen et al., 2023; Pitacco and Meggio, 2015; Sharifi et al., 2024), while mulching can improve soil quality and fertility, enhancing the carbon soil content (DeVetter et al., 2015). Soil water availability further influences carbon storage, with higher carbon retention observed in years of heavy summer rainfall (Vendrame et al., 2019), while irrigated vines sequester 30-40% more carbon than non-irrigated vines across cultivars (Hernández-Montes et al., 2022). Carbon storage in grapevines is additionally impacted by vine age, with younger vines demonstrating a higher annual CO_2 sequestration capacity (Song et al., 2023; Williams et al., 2020), as well as by genotype (Hernández-Montes et al., 2022) and pruning practices that modulate biomass accumulation and the source-sink balance (Xue et al., 2024).

1.3 Life cycle methods for environmental sustainability assessment of vineyard.

In order to support policy addressed to reduce the environmental impact of viticulture through sustainable practices, accurate assessment methods of greenhouse gas (GHG) emissions are required. Agriculture and land use notably contribute to global emissions (Nabuurs et al., 2022). Within viticulture, transparent, standardized methods can provide valuable insights into its environmental footprint. As recommended by the International Organisation of Vine and Wine (OIV, 2020), Life Cycle Thinking represents a comprehensive and valuable approach for assessing emissions and other environmental impacts of products and services, supporting efforts to reduce the sector's carbon footprint and align with broader sustainability goals.

Life Cycle Assessment (LCA) has emerged as an effective method for impact assessment not only for science but also for policy, allowing for an inclusive evaluation of farming systems' environmental performance (Notarnicola et al., 2017), from both ecological and socio-economic perspectives. Its holistic attitude is therefore crucial in light of the three dimensions of sustainability (Baiano, 2021). By adopting a systematic approach that quantifies the environmental impacts of products and services throughout their life cycle (ISO, 2006a), LCA can highlight key areas of environmental strength and weakness within the sustainability framework, assisting in the optimization of farming systems. The ability to define system boundaries also enables LCA to focus on specific stages or the entire life cycle, allowing a comparative evaluation between different farming systems (e.g. di Cristofaro et al., 2024; Litskas et al., 2020), use of products (Oppon et al., 2023), and predicting the potential impacts of new techniques and practices (e.g. Balafoutis et al., 2017; Frota de Albuquerque Landi et al., 2021).

As regards its application to the viticulture sector and systems, the LCA method can be applied across different stages of grape and wine production, focusing the analysis on specific production chain segments (Ferrara and De Feo, 2018). Accordingly, setting precise system boundaries and functional units is crucial for accurately evaluating impacts, allowing a deep understanding of the production system and enabling meaningful comparisons across various farming practices. These boundaries can encompass all stages, from vineyard establishment (*cradle*) to grape cultivation and wine production (*gate*) and product end-of-life (*grave*). This flexibility supports either a full *cradle-to-grave* LCA or more focused approaches like *cradle-to-gate*, *gate-to-gate* or *gate-to-grave* (Casolani et al., 2022). The adoption of precise system boundaries depends on the goal and scope of the LCA analysis. In Figure 2 the overview boundaries of a conventional viticultural system are reported.

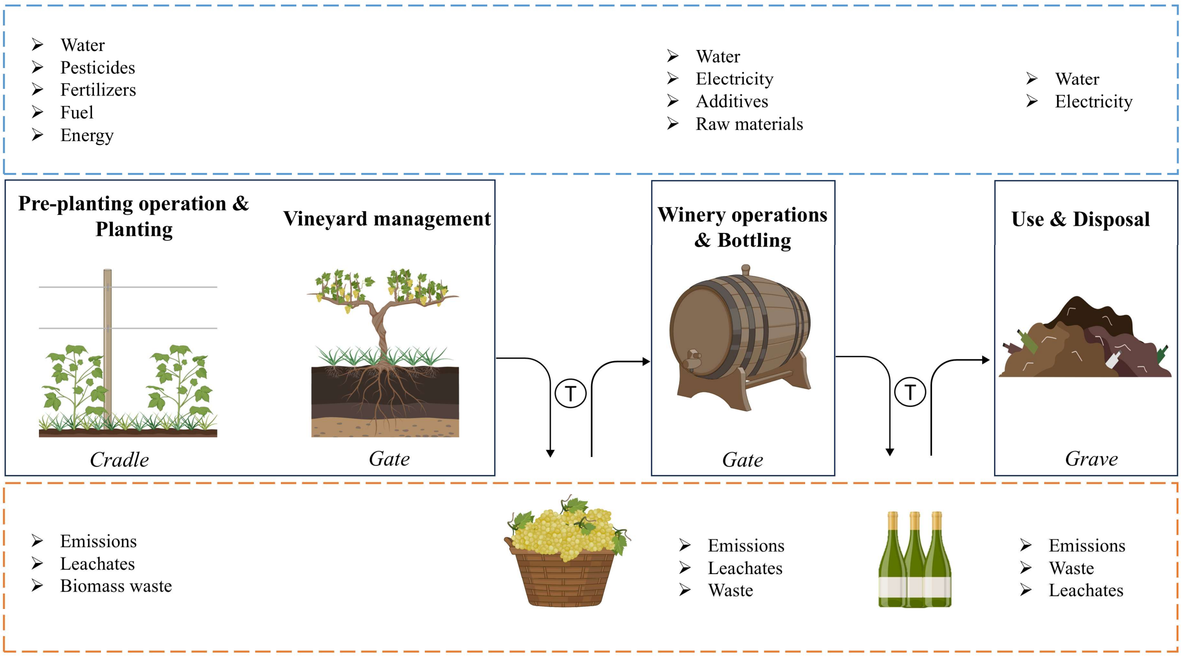

Figure 2. *Boundaries of a wine production system showing the main stages, from cradle to grave (T – transport) and their respective inputs (blue dashed box) and outputs (orange dashed box).*

The starting point of a wine production system is the vineyard planting, covering several practices, such as soil preparation, irrigation setup, vines' planting, and inputs, above all fertilizers and pesticides. Next, the on-farm production phase spans the vineyard's productive cycle, encompassing irrigation, pest management, fertilization, pruning, harvesting, and within-farm transport (Ferrara and De Feo, 2018). After on-farm activities, the grapes are sent to the winery for the transformation process, including fermentation, bottling and packaging, and waste disposal (Vinci et al., 2022). Next, the distribution stage accounts for emissions and resources used to transport wine to retailers and consumers (i.e., product distribution and consumption). Finally, the end-of-life phase involves waste management of packaging materials in relation to their disposal, recycling, or reuse with potential benefits from circular practices (e.g. bottle reuse and recycling infrastructure; Point et al., 2012). According to the main literature, the agricultural phase in the vineyard (i.e., planting, grape production, and harvest) is one of the most impactful steps of the whole wine production system. Therefore, most of the articles refer to this stage (including 46% for the grape growth and production stage only; Ferrara and De Feo, 2018).

As viticulture faces the challenges posed by climate change, innovative and sustainable wine-growing systems based on mitigation and adaptive management strategies are required. However, environmental efforts should be balanced with productive aspects, to maintain both the quantitative and qualitative standards of grape production. Despite the abundance of studies on the viticulture sector, a deep understanding of "when, where, and how" innovative strategies respond to climate change (Naulleau et al., 2021) is still lacking. For this purpose, multi-lever approaches are essential to evaluate the ecological, economic, and social aspects of sustainability in the winegrowing sector (D'Ammaro et al., 2021).

2. MATERIALS AND METHODS

2.1 Experimental area

The present study was conducted in a non-irrigated Chardonnay B. (Italian Catalogue code 298) (*Vitis vinifera* L.) vineyard grafted on *V. berlandieri* x *V. rupestris* rootstock (1103 P) established in 2000 in central Italy in the Orvieto Protected Denomination of Origin – Umbria (42°38’55’’N 12°15’01’’ E – 143 m a.s.l.).

The vineyard is located on a plateau with east-west (EW) oriented rows and vines trained in a cordon vine-training system at a spacing of 1.0 m x 2.20 m (inter- and intra-row) for a 4500 vines/ha density. Each vine had a bud-load of about 10 nodes; the cane raised 0.80 cm from the ground with two pairs of top catch wires for a canopy wall extending about 1.80 m above the main wire.

Inter-row management was performed by multiple soil tillages (three to four per year) to limit native grass development. Winter pruning is done by hand, while the harvest is mechanized. The canopy is mechanically trimmed once shoots outgrew the top foliage wire.

2.2 Experimental design

The study was carried out during three consecutive seasons (2021-2023) and involved the application of three canopy management practices (Figure 3): (i) an early leaf removal (ELR) carried out by manually removing six basal mature leaves in BBCH-071 phase (Lorenz et al., 1995); (ii) foliar application of corroborant based on Basalt Flour® type XF (BF) (Table 1S), a non-systemic coating agent that can be used in organic farming following Regulation (EU) 2018/848 and Presidential Decree 28/02/2012 No.55. BF was used with a concentration of 3% per liter of water, applied on the canopy from the inflorescence visible (BBCH-053) to harvest (BBCH-089), for 4-5 times during the growing season, depending on the canopy development and climatic conditions; (iii) ordinary canopy management without leaves removal and BF application (C).

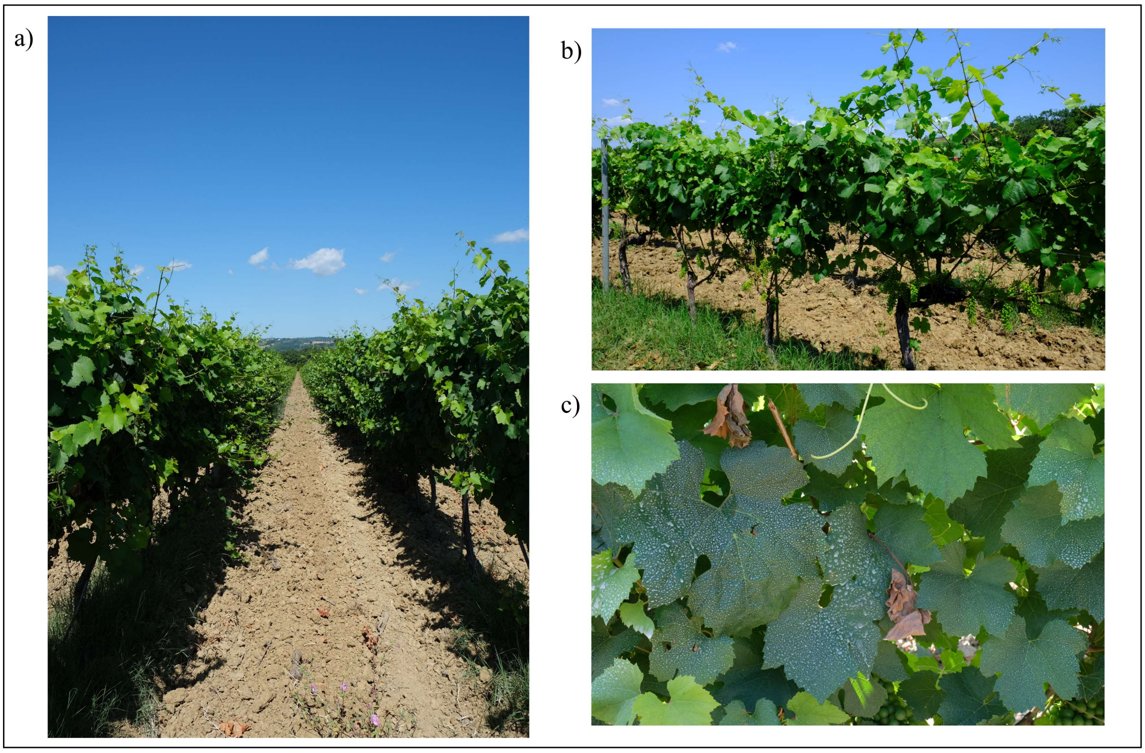

Figure 3. *Study vineyard (a), details of vines with leaf removal (b), and leaves with application of basalt flour (c).*

Each strategy was applied on three consecutive rows of 70 vines. To avoid the border effect, three blocks in the central rows have been selected for repeated measures (Figure 4).

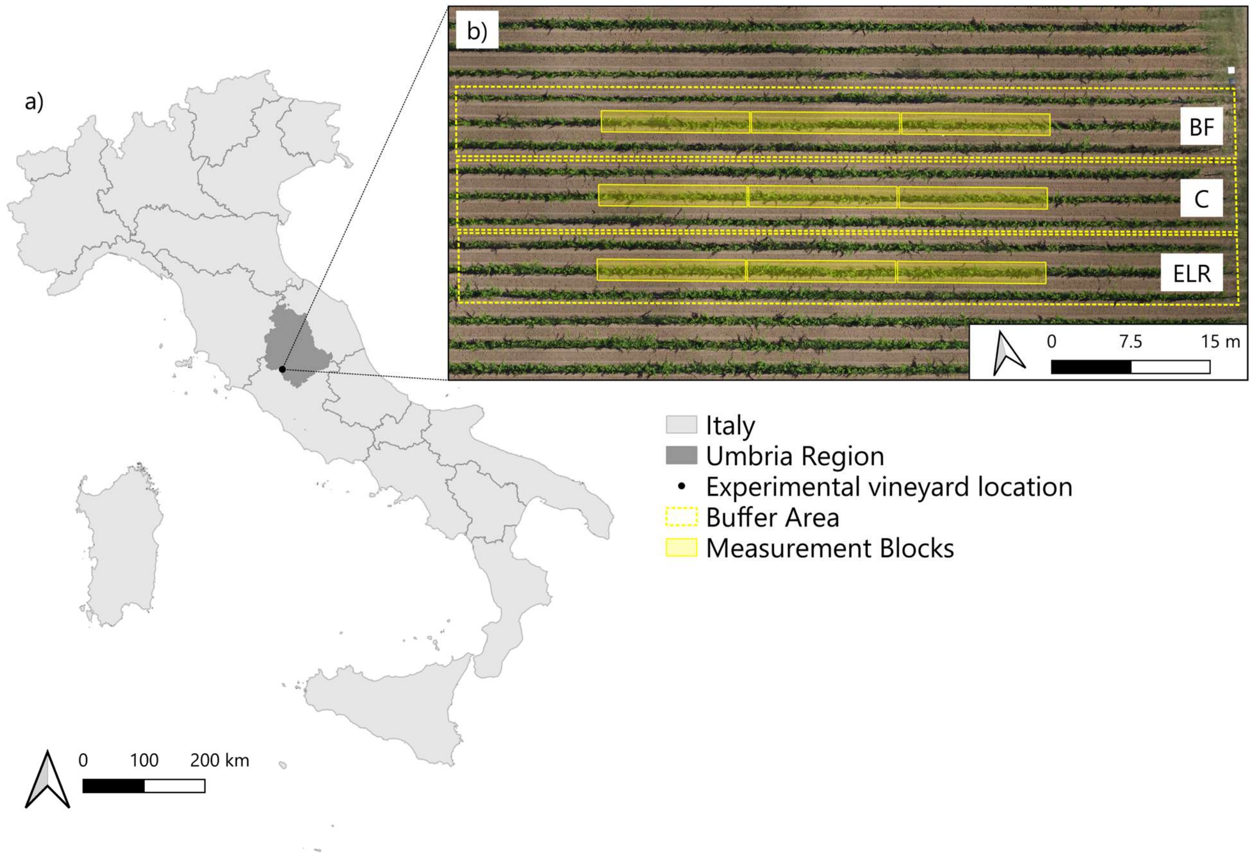

Figure 4. *Location of the experimental area (a) and experimental vineyard (b) of each strategy (control – C; foliar application of basalt flour – BF; early leaf removal – ELR). The yellow dashed lines represent the whole study area, including the buffer zone, while the shaded rectangle displays the blocks.*

2.3 Characterization of the study area

Soil properties

Within the study area, three soil profiles (basalt flour treatment – P1, control – P2, early leaf removal – P3; Figure 5) were surveyed and characterized for physical, chemical, and hydrological soil properties. Each soil profile with dimensions of 50 x 1.50 x 1 m in size has been described, photographed, and classified according to the international soil classification system of the Soil Survey Staff (1999). The profiles identified in the transect are characterized by deep horizons, following an Ap-Bw(k)-BC sequence, and show moderate pedological development. A horizon of secondary calcium carbonate accumulation, evidenced by the presence of nodules and concretions, is observed in all three profiles. This horizon appears at progressively greater depths from profile P1 to P3, with upper boundaries at depths of 25 cm, 35 cm, and 55 cm, respectively.

From each horizon, soil samples were taken to assess the principal physical and chemical characteristics (Table 2S and

Table 3S): texture, pH, electric conductivity, total and active limestone, soil organic matter, assimilable phosphorus, and cation exchange capacity and exchangeable bases (Ca, Mg, K, Na).

Figure 5. *Photographs of the three soil profiles: (a) P1 – basalt flour treatment, (b) P2 – control, and (c) P3 – early leaf removal.*

In general, the soil profiles (P1, P2, and P3) show substantial similarities in key physical and chemical properties. The soils have similar textural properties, predominantly clay-loam. All soils are classified as strongly calcareous (Warren and Saurette, 2022) and exhibit moderately to strongly alkaline conditions, with pH values ranging from 8.2 to 8.5 (Bichi and Bello, 2013), typical for calcareous soil. Cation exchange capacity (CEC) values range from 20.29 to 28.64 meq/100g, indicating a moderate ability of the soils to retain and supply essential cations. The soil organic matter (SOM) content is low (< 1 %), indicating soil degradation (Obalum et al., 2017). The low SOM levels can be attributed to several factors linked to conventional farming practices and soil tillage. Conventional tillage disturbs the soil structure, increasing SOM decomposition through enhanced microbial activity and exposure to air, leading to faster organic matter breakdown (Bonifacio et al., 2024; Francaviglia et al., 2023). Additionally, conventional farming involves minimal organic inputs, further limiting SOM accumulation in the soil (Voltr et al., 2021).

Undisturbed samples at two different depths for each pit, dependent on the presence of vine roots, were used to determine the pF curves over the full range of 0–4.2 pF (Figure 1S). Hydrological constants and bulk density were analysed on undisturbed samples taken using stainless steel cylinders (0.6 x 0.27 cm), at two depths (0-50 cm and 50-80 cm). The matrix potential points, expressed in pF, were determined from 0 to 2 in a Stackman's tank (Stakman et al., 1969), while from 2.5 to 4.2 in a Richards' pressure apparatus (Richards, 1948). The available water capacity (AWC) was then calculated from the difference between the soil's water content at field capacity (FC) and permanent wilting point (PWP) (White, 2003). The samples were then dried in an oven at 105°C to determine the bulk density (Table 4S). The soils across the three profiles display similar characteristics in terms of available water content (AWC), air capacity (AC), and bulk density, though variations are noticeable with depth. Bulk density tends to decrease with increasing depth in all profiles, ranging from 1.59 g/cm^3 at the shallowest layer in P1 to 1.46 g/cm^3 at the deeper layer. This trend corresponds to improved water retention, as indicated by the AWC values, which range from 18.51% to 14.22% across the profiles. The available water content, particularly in the deeper layers of profiles P2 and P3, suggests favorable conditions for deep-rooted vines, ensuring adequate moisture availability even in drier periods. Air capacity (AC) tends to diminish with increasing depth, indicating that aeration may become a limiting factor in deeper soil horizons. Particularly, AC values ranged from 9.10 to 5.30% in the surface and deep layer of P1, respectively. This denotes a scarcity of air within all soils analyzed. With values falling below 9%, fine-textured soils become susceptible to periodic anaerobiosis phenomena (Reynolds et al., 2015).

Mesoclimatic data

Mesoclimatic data for each year (2021-2023) were made available thanks to an iMETOS® 3.3 (Pessl Instruments GmbH, Weiz, Austria) weather station located near the experimental vineyard (42°38'55" N 12°15'01" E – 142 m a.s.l.).

Annual average temperature (Tavg – °C), amount of precipitation (P – mm), and dry days (DD – n) with precipitation < 1 mm (Polade et al., 2014) were determined on a yearly basis. In addition, during the growing season, the bioclimatic indices (Winkler index (°C) – WI; heliotermal index of Huglin (°C) – HI; cool night index (°C) – CI; average growing season temperature (°C) – AvGST; growing season precipitation (mm) – GSP; number of rainy days (n) – RD; number of dry days (n) – DD; number of consecutive dry days (n) – CDD; number of days that reaches and surpass 30°C (n) – T30; number of days that reaches and surpass 35°C (n) – T35) shown in Table 1 were calculated.

Table 1. *Bioclimatic indices (Winkler index – WI; heliotermal index of Huglin – HI; cool night index– CI; average growing season temperature – AvGST; growing season precipitation – GSP; number of rainy days – RD; number of dry days – DD; number of consecutive dry days – CDD; number of days that reaches and surpass 30°C– T30; number of days that reaches and surpass 35°C – T35) for the vegetative period (April – September/October) were calculated for the three seasons 2021-2023.*

Bioclimatic index	Equation	Reference
Winkler index (WI – °C)	$\sum_{01/04}^{31/10} \frac{(Tmin + Tmax)}{2} - 10$	(Winkler et al., 1974)
Heliothermal Index of Huglin (HI – °C)	$\sum_{01/04}^{30/09} \frac{(Tmean - 10) + (Tmax - 10)}{2} \times d^*$	(Huglin, 1978)
Cool night index (CI – °C)	$\frac{\sum_{i=1}^{30} Tmin}{30}$	(Tonietto, 1999)
Average growing season temperature (AvGST – °C)	$\frac{\sum_{01/04}^{31/10} [\frac{Tmin + Tmax}{2}]}{n}$	(Jones et al., 2010)
Growing season temperature (GSP – mm)	$\sum_{01/04}^{31/10} P$	(Vršič et al., 2024)
Number of rainy days (RD – n)	$\sum_{01/04}^{31/10} n° \ RD \ (P \geq 1 \ mm)$	(Felix and Jung, 2022)
Number of dry days (DD – n)	$\sum_{01/04}^{31/10} n° \ DD \ (P \geq 1 \ mm)$	(Felix and Jung, 2022)
Number of consecutive dry days (CDD – n)	$\sum_{01/04}^{31/10} consecutive \ DD \ (P < 1 \ mm)$	(Kostopoulou and Jones, 2005)
Number of days exceeding 30°C (T30 – n) and 35°C (T35 – n)	$\sum_{01/04}^{31/10} n°days \ with \ T \geq 30°C$ $\sum_{01/04}^{31/10} n°days \ with \ T \geq 35°C$	(OIV, 2012)

T_{mean}, T_{max}, and T_{min}: mean, minimum and maximum temperature (°C); P; precipitation (mm)

* *d* is a latitude coefficient that takes into consideration the length of the day;

2.4 Microclimatic data

To monitor the microclimate data, a custom system based on a Wireless Sensor Network (WSN) was developed to detect microclimatic data in the vineyard in real-time. Three ground sensor platforms (GSPs) per strategy were installed and the data were sent to the gateway via Long Range (LoRa) radio-frequency. The internal hardware is composed primarily of a Raspberry Pi 4 Model B (https://www.raspberrypi.com/products/raspberry-pi-4-model-b/), a DFROBOT Solar Power Manager V1.0 (https://www.dfrobot.com/product-1714.html) connected to solar panel able to recharge a 6000mAh battery. The WSPs are equipped with two Adafruit SHT-10 temperature and humidity probes (https://www.adafruit.com/product/1298), to detect the air temperature in the canopy at two different heights from the soil, at 80-100 cm (on the fruit head of the vines in the bunch area – BH) and 150 cm (upper part of the canopy – CH).

The WSN was installed in 2021, from the 15th of June to the 31st of October, and in 2022, from the 1st of April to the 31st of October. Daily average, maximum, and minimum were calculated in each strategy from fruit set to harvest. For the same period in each strategy and at each sensor height, the average (AvGST), maximum (MaxGST), and minimum (MinGST) of the period were calculated on the temperatures (Ramos et al., 2008). Also, the cool night index (CI), and thermal excursion (TE) were calculated. Dynamic indices were also identified, and calculated based on the solar height range on the horizon using 30° as the threshold (Matese et al., 2013). Four ranges of solar height were therefore considered: <30° (in the morning – dMi), >30° (broad daylight – dBDi), <30° (evening – dEi), and 0° (night – dNi). Solar height was calculated using the NOAA solar position calculator tool (NOAA, 2024).

2.5 Thermal imagery

An unmanned aerial vehicle (UAV) equipped with a Zenmuse XT thermal camera (DJI, company, Shenzhen, China) was used, allowing for the identification of thermal alterations of the leaf surface measuring the temperature of plant tissues. The collected images were used to build an orthomosaic of the study area with the Agisoft Metashape Professional software. The resulting orthophoto has been imported into the software-QGIS (version 3.28.11) for analysis. To verify the accuracy of the temperatures measured by the camera on the UAV and the real temperature on the soil, the ground reference panels (GRPs) of size 60x60 cm were positioned with the values of emissivity noted, two of white Teflon (Emissivity 0.94) and two of black color (Emissivity 0.96). For each GRP, 3 temperature measurements were carried out with the PRO RS-9862S (RS, components, UK) infrared thermometer (± 0,5°C, emissivity 0.10-1.00). Image calibration was performed by generating a linear correlation between the temperature data collected on the ground on the GRPs and corresponding temperatures on the thermal images from the drone.

To analyze the water stress of the canopy, the Crop Water Stress Index (CWSI) was used as one of the most popular indices. The CWSI was calculated using the following equation (Jones et al., 2002):

$$CWSI = \frac{(Tc - Twet)}{(Tdry - Twet)}$$

Where:

- Tc (°C) is the measured canopy temperature with the thermal camera;

- Twet (°C) is the canopy temperature of well transpiring or non-stressed crop;

- Tdry (°C) is the canopy temperature of a non-transpiring or severely stressed crop.

The reference temperature for Twet and Tdry was obtained by measuring the surface temperature, of the reference canopy leaves (on plants outside of the experimental perimeters) sprayed on both sides respectively with water and petroleum jelly (vaseline). The temperatures were taken again using the PRO RS-9862S.

2.6 Physiological measurement

Physiological measurements were taken during the three seasons (2021-2023) to understand the response of the vines to the different management practices.

Leaf water potential (Ψ), expressed in MPa, was determined using a Scholander pressure bomb (Model 3115 Soil moisture Equipment Corporation, CA, USA) from pre-veraison (BBCH-079) to harvest (BBCH-089), on three fully expanded leaves on the light-exposed part of the canopy (south). The measurements were carried out at predawn (~5:00 h, Ψpd) twice a week in 2021, and once a week in 2022 and 2023. The pre-dawn leaf water potential thresh-olds were evaluated according to Carbonneau (1998) (Table 2).

Table 2. *Predawn leaf water potential (Ψpd) and the respective grapevine water status (Carbonneau, 1998).*

Ψ_{pd} (MPa)	Water status of vine
$0 > \Psi_{pd} \geq -0.2$	Mild or absent water stress
$-0.2 > \Psi_{pd} \geq -0.4$	Mild to moderate water stress
$-0.4 > \Psi_{pd} \geq -0.6$	Moderate severe water stress
$\Psi_{pd} < -0.6$	Severe stress

The chlorophyll content and the stomatal conductance measurements were carried out in three phenological phases fruit set (BBCH-071), berry touch complete (BBCH-079), and berries ripe for harvest (BBCH-089). The total chlorophyll content (Chl) measurements were carried out with the MC-100 Chlorophyll Concentration Meter (Apogee Instruments Inc., UT, USA). The measures were taken on fifteen mature leaves for each practice. Stomatal conductance (gs), was measured using an SC-1 steady-state leaf porometer (Decagon Devices, WA, USA). Measurements were made on five random mature leaves per practice, during the hottest hours of the day (12:00-13:00 h). According to Cifre et al. (2005), based on gs three levels of water stress could be classified as reported in Table 3.

Table 3. *Stress level range for the stomatal conductance (gs) (Cifre et al., 2005).*

g_s (mmol H_2O $m^{-2}s^{-1}$)	Stress level
$500 > g_s > 150$	Mild stress
$150 > g_s > 50$	Medium stress
$g_s < 50$	Severe stress

2.7 Vine vigor, grape yield, and quality data

For each treatment implemented in the vineyard over the three consecutive seasons (2021-2023), one vine from the central row was selected from each of the three blocks. At harvest (BBCH-089), the number of shoots per vine was recorded, and three bunches per vine were randomly taken to measure the fresh weight of the bunch (W_{bu} – g), the berries weight (W_{be} – g), and the number of berries per bunch. Fresh grape samples were crushed to extract juice to determine total soluble solids (TSS – °Brix). Samples were centrifugated with a NEYA 16R (REMI, Mumbai, India) at a temperature of 4°C and with 8500 rpm for 15', to analyze pH, and total acidity (TA – grams of tartaric acid per litre). These were detected using an automatic titrator (FLASH Automatic Titrator, Steroglass, Perugia, Italy). The samples were titrated with 0.1 M NaOH to reach a pH of 7. The TSS content was determined using a HI 96814 wine refractometer (Hanna Instruments, RI, USA).

At wood maturation (BBCH 091), shoot samples on each vine were collected to measure the fresh weight of stems and leaves.

The real fertility was calculated with the following formula:

$$Real\ fertility = \frac{Number\ of\ bunches\ per\ plant}{Number\ of\ shoots\ per\ plant}$$

In addition, the average yield per vine was estimated by taking the average bunch weight and multiplying it by the number of bunches per plant. The same was similarly done with the stems and leaves to estimate the vegetative biomass.

2.8 Carbon storage on annual above-ground biomass

The fresh weight of leaves and stems was taken separately on each shoot sample collected. The same thing was done on the total berries for each bunch. The dry weight (DW) was obtained on three samples per organ by putting samples in an oven at 70°C until complete moisture loss (according to Petrie et al., 2000). The samples were then minced and three subsamples were analyzed with a Vario MACRO cube analyzer (Elementar Analysensysteme Vario MACRO cube, Germany) to derive the total organic carbon (TOC).

The carbon storage was evaluated for both the above-ground vegetative biomass (comprising stems and leaves) and the reproductive biomass (berries). Finally, the quantity of fixated carbon dioxide (tCO_2 eq. $ha^{-1}year^{-1}$) was calculated following the formula of Brunori et. al (2016):

$$tCO2\ eq.ha^{-1}\ year^{-1} = N°_{gv} \times TOC \times DW \times 10^{-6} \times 3.666$$

where $N°_{gv}$ is the number of grapevines per hectare (4500 plants per ha), TOC is the total organic carbon ($g \cdot g^{-1}$ of dry weight) of the considered organ, and DW is the dry weight of the organ under study expressed in grams. To convert the grams into tons, the conversion factor of 10^{-6} is added to the formula. To calculate the corresponding CO_2 equivalent, the conversion factor of 3.666 was used (Coto-Millán et al., 2008).

2.9 Sustainability assessment (Life Cycle Assessment – LCA)

In accordance with the guidelines provided by the international standards of the ISO 14040-14044 series, the Life Cycle Assessment (LCA) conducted in this research is structured into four mandatory phases (ISO, 2006a, 2006b). LCA analysis is structured as follows: after the definition of objectives, system boundaries, and functional units (here acting for the goal and scope definition, the first phase of ISO standard framework) data about inputs and outputs of the system are collected in the Life Cycle Inventory (LCI; i.e., the second phase provided by the ISO standard framework), accurately describing all the material and energy flows of the investigated systems. LCI is followed by the impact assessment phase (third phase), which evaluates the potential environmental impacts based on the inventory data. Finally, the results interpretation (the last ISO standard framework phase) is postponed to the results and discussion section, in order to examine the main findings, identify areas for potential improvement, and argue related recommendations.

Goal and scope definition

This study assessed three management practices (ELR, BF, and C) for an innovative and more sustainable wine-growing system over three years (2021, 2022, and 2023) using the LCA method. In detail, the environmental performances of the three different strategy systems were compared, focusing also on productive and qualitative aspects of grape production. The environmental performances of the investigated systems were assessed and compared based on their carbon footprints.

System boundaries and functional unit

A "gate to gate" approach was adopted to evaluate the impacts on climate change on annual cycles of investigated farming systems, setting our system boundaries in the vineyard (Figure 6). The considered in-field practices relate to (i) soil management (tillage, weeds control, fertilization) (ii) crop management (pruning, green pruning, harvest), and (iii) plant protection (treatments). The system boundaries considered for the comparative LCA study include material and energy inputs involved in the farming processes. Extraction/transformation of raw materials and production/maintenance of infrastructures were not included. On the other hand, production processes for chemical and organic preparations (e.g. herbicides, biocides, and fertilizers) are considered in the LCA study.

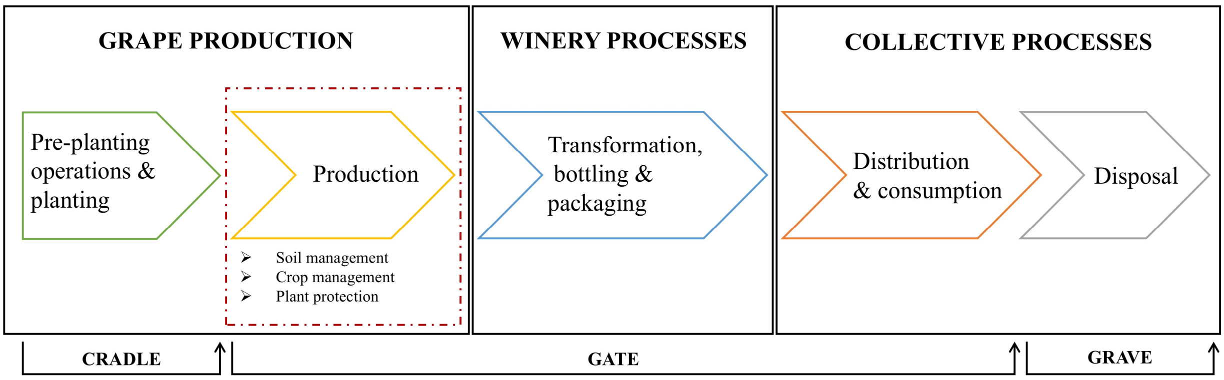

Figure 6. *System boundaries (dashed red line) of the investigated wine-growing systems.*

The Functional Unit (FU) represents the selected reference unit in a LCA analysis, enabling the comparison of different systems with the same function (ISO, 2006a, 2006b). For the assessment of the environmental performance of farming systems, in the present LCA study, we choose two functional units (FU). Emissions per hectare was adopted as the first FU of the LCA analysis. The surface unit mainly focuses on the direct environmental impacts of farming activities rather than the ratio of impact to product (van der Werf et al., 2007). In this sense, production is often used as a measure of environmental efficiency in agricultural systems. In accordance with the Product Category

Rules (EPD International, 2020), which indicates biomass or volume as a default unit for assessment of the environmental performance of agro-food products and farming systems, the present LCA analysis was carried out by adopting the emissions per kg of harvested grapes as second FU.

Life Cycle Inventory and impact assessment

LCA inventories of the three investigated systems were mostly based on primary data acquired through questionnaires carried out on the farm. Table 4 summarizes input and output of the farming practices and related frequency implemented for each investigated system in the three reference years. Detailed information about mechanization, agronomic aids, and residues of the four production systems are reported in supplementary material in the Supplementary section (Table 5S and Table 6S). Inventories were finally achieved with secondary data from a global database. The LCA analysis is carried out using SimaPro software - version 9.4.0.2, a standardized software developed by Pré consultants in accordance with the ISO standards. The reference database adopted for our analysis is Ecoinvent 3.3. The carbon footprints of the three different systems in the three years were estimated through the IPCC 2021 GWP_{20} (including CO_2-uptake) method. This method covers GWP_{20} fossil, GWP_{20} biogenic, GWP_{20} land transformation, and GWP_{20} CO_2-uptake (Masson-Delmotte et al., 2021). IPCC 2021 GWP method provides for the most complete assessment of effects on climate change due to emissions of different GHG, making it mostly suitable (and chosen) for climate-related LCA analyses of agro-food products (McAuliffe et al., 2023).

Table 4. *Inventory of the practices implemented in the three wine production systems and related frequency for each year. In the grey background are reported the practices added for the systems: leaf removal for ELR and basalt flour treatment for BF.*

PRACTICE	PROCESSING	INPUT	OUTPUT	NUMBER OF PASSAGES		
				2021	2022	2023
Soil management						
Subsoiling	Service of tillage, and subsoiling, by subsoiler plow on an area of one hectare	Process includes the use of diesel-powered agricultural machinery (1.2 h with a 90 hp tractor)	Emission linked to 21.6 L/ha diesel combustion in tractor	1	1	1
Weed control	Service of currying by weeder on an area of one hectare	Process includes the use of diesel-powered agricultural machinery (0.75 h with a 105 hp tractor)	Emission linked to 18.5 L/ha diesel combustion in tractor	3	2	3
Fertilization	Service of fertilising, by broadcaster on an area of one hectare	Process includes the use of diesel-powered agricultural machinery (0.5 h with a 105 hp tractor)	Emission linked to 12.5 L/ha diesel combustion in tractor	1	1	1
Crop management						
Topping	Service of mowing by motor mower on an area of one hectare	Process includes the use of diesel-powered agricultural machinery (1 h with a 105 hp tractor)	Emission linked to 25 L/ha diesel combustion in tractor. Organic carbon returned to the soil	2	1	3
Suckering	Service of application of plant protection product by field sprayer on an area of one hectare	Process includes the use of diesel-powered agricultural machinery (1 h with a 105 hp tractor)	Emission linked to 25 L/ha diesel combustion in tractor. Organic carbon returned to the soil	2	1	3
Winter pruning	Manual pruning	None	Organic carbon returned to the soil	1	1	1
Harvesting	Service of harvesting on an area of one hectare	Process includes the use of diesel-powered agricultural machinery (2.5 h with a 105 hp tractor)	Emission linked to 62.5 L/ha diesel combustion in tractor	1	1	1
Leaf removal	Service of mowing by motor mower on an area of one hectare	Process includes the use of diesel-powered agricultural machinery (1.2 h with a 105 hp tractor)	Emission linked to 30 L/ha diesel combustion in tractor. Organic carbon returned to the soil	1	1	1
Plant protection						
Treatments	Service of application of plant protection product by field sprayer on an area of one hectare	Process includes the use of diesel-powered agricultural machinery (0.6 h with a 105 hp tractor)	Emission linked to 15 L/ha diesel combustion in tractor	9	7	11
Basalt flour treatments	Service of application of plant protection product by field sprayer on an area of one hectare	Process includes the use of diesel-powered agricultural machinery (0.6 h with a 105 hp tractor)	Emission linked to 15 L/ha diesel combustion in tractor	3	5	5

2.10 Statistical analysis

The statistical analysis was carried out on previously screened data, appropriately selected to exclude any outliers. All data related to carbon storage were analyzed to establish the normality of the distribution and homoscedasticity, respectively with Shapiro-Wilk's test and Levene's test. Then the analysis of variance (ANOVA) was performed, followed by Tukey's Honestly Significant Difference (HSD) test to identify specific group differences. All data were analyzed for a fully randomized design and the statistical significance was set at $p < 0.05$.

Multiple linear regression analyses were conducted to determine whether the weather station data correlated with the data from ground sensor platforms for each year, management practice, and sensor height, considering the average, minimum, and maximum daily temperatures. Additionally, regression analyses were performed to better understand the relationship between the carbon stored in the annual above-ground vegetative biomass and the carbon stored in the reproductive biomass per year per hectare, conducted for each year and management strategy across the three years of study.

All statistical analyses were conducted using R version 4.3.2 (https://posit.co/download/rstudio-desktop/).

3. RESULTS AND DISCUSSIONS

Viticulture is highly sensitive to climate change and is considered a bioindicator of climate change (Biasi et al., 2019; Brunori et al., 2022; Fernández-González et al., 2013). Consequently, the study of the vineyard microclimate and, more specifically, of vines (canopy) can be a useful tool for analysing the physiological response of plants to climate changes and for improving their productive performance and ecosystem functions through specific canopy management techniques. Ecological and digital transitions, promoted by the European Green Deal and the Common Agricultural Policy (CAP) 2023-2027, offer an integrated approach to address viticultural challenges by understanding how to manage vineyard microclimates, enhance the healthy status of agro-ecosystems, improve sustainability by preserving quality and yield, reduce environmental impacts, and increase the resilience of vines under limited environmental conditions.

The study area is considered a climate-vulnerable grape-growing area (Biasi et al., 2019), due to adverse climate conditions characterized by increasing air temperature and the alteration of precipitation patterns that are compromising the suitability of this traditional grape-growing area.

The study aims to identify adaptive viticultural practices on an agricultural scale to mitigate the effects of these climatic trends while preserving ecological functions (carbon absorption), yield, and berry quality. During the three seasons (2021-2023) under investigation, the induced effects of management techniques were analysed: early leaf removal (ELR), application of a foliar biostimulant (basalt flour - BF), and standard canopy management (canopy trimming, shoot thinning – C) on the plant's microclimate and consequently on physiological responses in terms of water stress, leaf senescence, and carbon allocation. The data were collectively utilized to evaluate the Life Cycle Assessment (LCA), a methodology aimed at assessing the environmental impacts linked to vineyard practices.

Mesoclimatic characterization

In the study area, for the three consecutive seasons 2021, 2022, and 2023, the Tavg were 13.78 °C, 15.13 °C, and 14.76 °C, respectively, while the P was 628 mm in 2021, 296 mm in 2022, and 436 mm in 2023. In 2021, the thermo-pluviometric diagram (Figure 7) showed an arid period between June and September (Figure 7a) with 280 DD. In 2022, the arid period lasted from May until October (Figure 7b), with a total number of 324 DD; the season 2023 was characterized by a humid period with abundant rainfall in spring (Figure 7c), with a total P of 124 mm falling in May, but with a similar number of total DD as in 2022 (317 days).

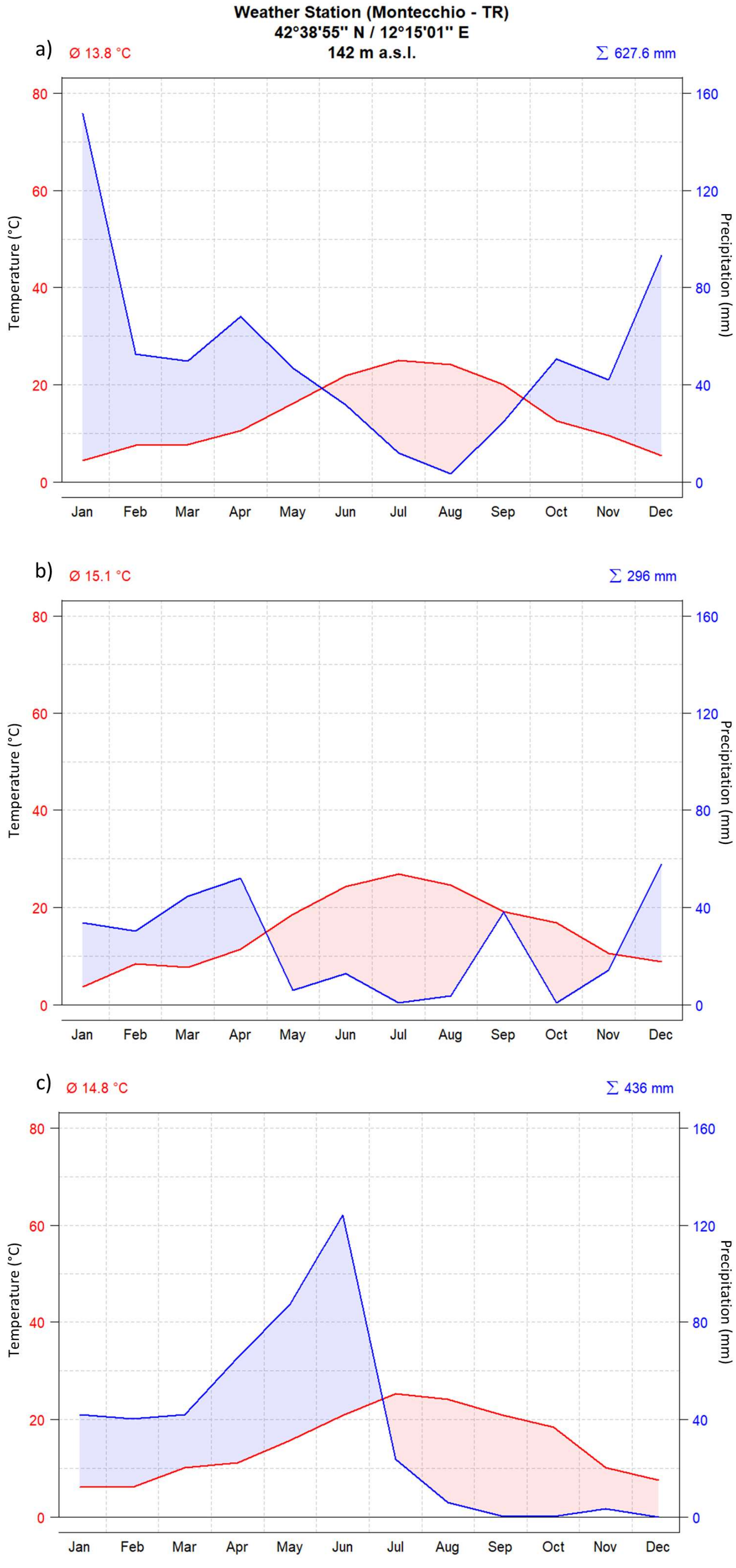

Figure 7. *Thermo-pluviometric diagram of 2021 (a), 2022 (b), and 2023 (c). The graph shows the mean monthly temperature (red line – °C) and total monthly precipitation (blue line – mm). Shaded blue areas indicate humid periods (precipitation ≥ 2 times the mean temperature), while shaded red areas represent arid periods (precipitation < 2 times the mean temperature).*

Table 5 reports the principal bioclimatic indices and meteorological parameters of the growing season (1st April- 30th September/31st October).

Table 5. *Principal meteorological parameters for the three growing seasons: 2021, 2022, and 2023 (WI – Winkler index; HI – heliotermal index of Hulglin; AvGST – growing season temperature; GSP – growing season precipitation; RD – rainy days; DD – dry days; CDD – consecutive dry days; CI – cool night index).*

	2021	**2022**	**2023**
WI (°C)	1928	2262	2128
HI (°C)	2674	2689	2453
AvGST (°C)	19.34	20.80	20.51
GSP (mm)	238	115	308
RD (n)	40	14	33
DD (n)	174	199	181
CDD (n)	29	57	88
T30 (n)	94	85	61
T35 (n)	37	24	12
CI (°C)	15.16	19.39	17.34

The two years 2021 and 2023 (with an accumulation respectively of 1929°C and 2128°C) fall within *Region IV* for the WI, while 2022 (by accumulating 2262°C) in *Region V*, the warmest possible region for viticulture, for higher mean temperatures during the year (Amerine and Winkler, 1944). *Region IV* is generally suitable for high-yield production and acceptable table wines, while Region V is typically only associated with high-production wine. Traditionally, Chardonnay is recommended for cooler regions (*I-III*), where it achieves optimal balance and complexity (Amerine and Winkler, 1944). All three years are classified as *warm* according to the Huglin index (Jones et al., 2010), accumulating 2674°C in 2021, 2689°C in 2022, and 2453°C in 2023. Studies have shown that the increasing trend in mean temperatures is raising bioclimatic indices values, reshaping traditional cultivation areas across the Mediterranean basin, and driving a shift toward warmer viticultural zones (Bucur et al., 2019; Charalampopoulos et al., 2024; Faralli et al., 2024).

The 2021 growing season was characterized by *warm* temperatures (Jones et al., 2010) (with an AvGST of 19.34°C) and distributed precipitation, with a total of 40 RD, 174 DD, and 29 CDD. The 2022 and 2023 seasons were characterized by low precipitation, with 2022 experiencing lower levels recording a total accumulation of 115 mm, mostly concentrated in April and September, and 199 DD, while 2023 was characterized by 308 mm of rain, most of it in May and June, 181 DD and a prolonged period of drought represented by 88 CDD. The T30 and T35 were higher in 2021, however, the years

2022 and 2023 were found to have higher AvGST, with 20.80°C for 2022 and 20.51°C for 2023, characterizing these two years as *hot* (Jones et al., 2010). Again, as already seen for the Winkler and Huglin bioclimatic indices, these temperatures, above the average of the area (Biasi et al., 2019), are not considered optimal for growing Chardonnay, which favors cooler average temperature (Liles and Verdon-Kidd, 2020). Values of the CI before the harvest, which occurred the last week of August in 2021 and 2023, and in mid-August in 2022, were 15.16 in 2021 and 17.34°C in 2023, making both years fall on temperate nights (Tonietto and Carbonneau, 2004), while 2022 fell within the class of warm nights with 19.39°C, which can affect berry colour and aromatic potential (Tonietto and Carbonneau, 2004).

Data indicate that the area in question is becoming less favorable for growing Chardonnay, traditionally used to produce Orvieto wines, as rising temperatures push for higher bioclimatic index values. To sustain wine production in existing vineyards, it is essential to implement adaptive management practices to maintain quality levels.

Microclimatic characterization

During the 2021 and 2022 seasons, microclimatic vineyard evaluation through wireless ground sensor platforms (GSPs) allowed the monitoring of canopy climate conditions: canopy (CH) and bunch area (BH). The daily maximum temperature and precipitation for 2021 and 2022 are shown in Figure 8.

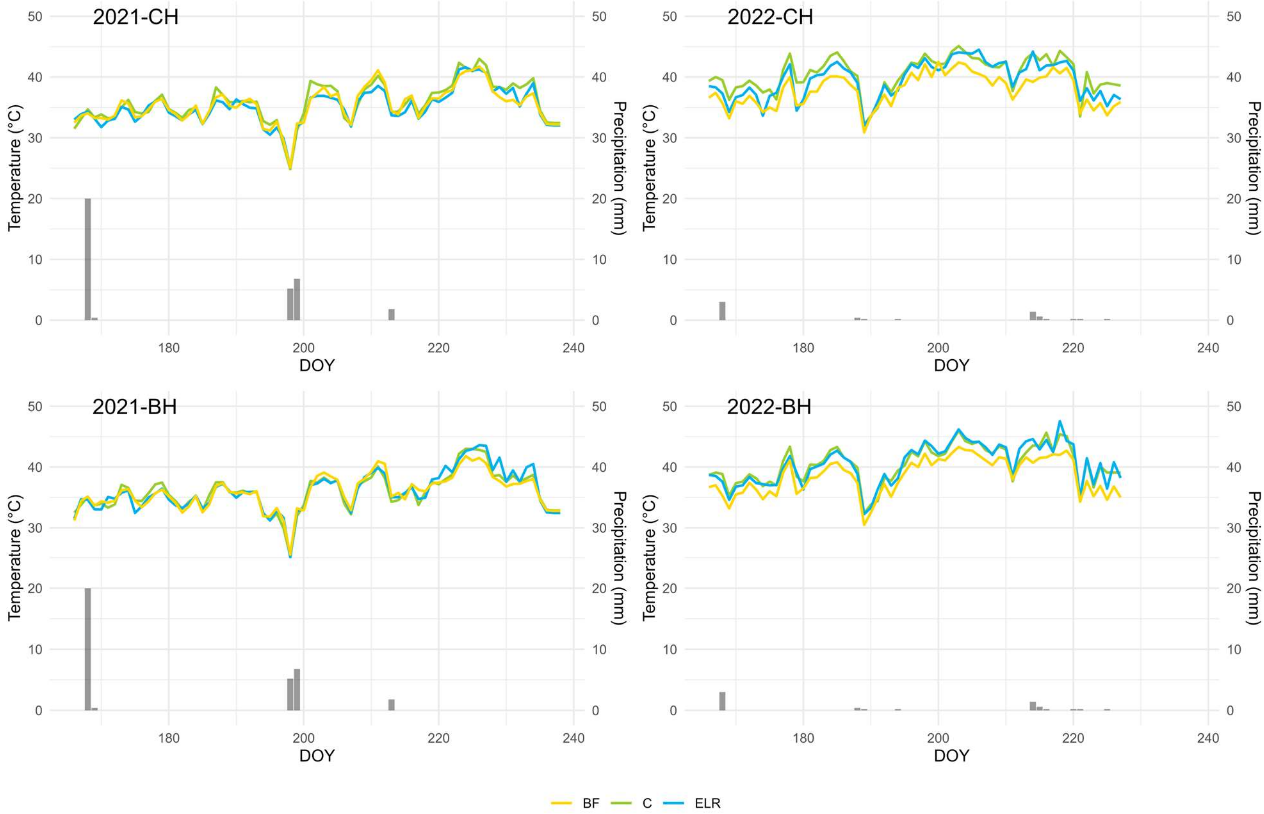

Figure 8. *Maximum temperature in the canopy (CH) and bunch area (BH) treated by different management practices: (control – C; foliar application of basalt flour – BF; early leaf removal – ELR). The graphs also show the precipitations that occurred during the berry development in the seasons 2021 and 2022 (DOY – day of year).*

During the berry development stages, from fruit set to harvest (DOY 238 in 2021 and DOY 228 in 2022), grapevines have experienced limiting conditions in terms of water stress, with extreme thermal conditions – maximum daily temperature frequently exceeded 35°C. In 2021, absolute maximums occur between August 12th and 14th (DOY 224-226), with peaks of 41.6°C and 43.6°C reached by ELR in CH and BH, respectively. In 2022, maximum temperatures occur between late July and early August, varying between 42.5°C (BF in CH) and 47.55°C (ELR in BH). The absolute minimum values (Figure 2S) in 2021 were observed in DOY 218, with temperatures of 13.4°C (BF in CH) and 13.98°C (C in BH), while in 2022 in DOY 171, with 12.7°C in CH, both for ELR and BF, and 12.85°C in BH in control vines. Minimum daily temperatures tended to show more seasonal stability, while maximum temperatures were subject to more pronounced fluctuations.

In addition, daily average temperatures (Figure 3S) reached the maximum peaks in 2021 around mid-August, with the highest recorded on the 12th of August (DOY 224) for C and BF in CH (30.33°C and 29.95°C, respectively) and in BH (31.11°C and 30.32°C, respectively), while for ELR the peak is reached on the following day (DOY 225), with 31.33°C in CH and 32.04°C in BH. In 2022, maximum peaks were observed between late July and mid-August, with temperatures between 30.44°C and 31.88°C in CH and between 30.88°C and 32.25°C in BH.

Average temperature data from ground-based sensor platforms in the canopy and bunch area (CH and BH) demonstrated a strong correlation (Figure 4S and Figure 5S) with nearby weather station data, with daily average temperatures achieving R^2 values of 0.78 overall and 0.83 for specific treatments in 2022. While maximum temperatures correlated well, daily minimum temperatures showed a weaker correlation, possibly due to the nearby forest's cooling effect at night (Peña Quiñones et al. 2020). The findings indicate that GSPs effectively capture daily temperature trends, though variations exist, particularly for minimum temperatures.

In Table 6 the results for the microclimatic indices are reported. Considering the whole season, differences could be found between the two years, with similar gaps for both CH and BH. AvGST in 2022 was higher than in 2021, with an average temperature from fruit set to harvest that was 1.5°C higher. Meanwhile, MaxGSD was 3.7°C higher in 2022, with 77% more days exceeding 30°C than in 2021, a value that is doubled if we take in consideration the days on which temperatures exceeded 35°C. The MinGSD remained stable between the two years, which led to a rise in the thermal excursion (TE) of about 3°C in 2022. The cool night index (CI) has lower average values in CH than in BH, which may be most affected by the soil storing heat during the day and allowing it to be gradually released at night (Costa et al., 2023; de Rességuier et al., 2023). However, only in C and ELR in 2021 significant differences were noted ($p < 0.05$) between the two areas.

In 2021, a difference between the two management practices C and ELR was observed in the MinGSD temperatures. In the bunch area (BH) ELR exhibited significantly lower temperatures ($p < 0.05$) than C. For C, a highly significant temperature difference ($p < 0.05$) was noted between CH and BH, with air temperatures being higher in the latter.

Table 6. *Microclimate indices evaluated using the ground sensor platforms for the two different sensors placed in the canopy (CH) and bunch (BH) area on the different management practices used (control – C; foliar application of basalt flour – BF; early leaf removal – ELR) in the two study years, 2021 and 2022.*

		2021			2022		
		C	ELR	BF	C	ELR	BF
AvGST (°C)	CH	26.41 ± 0.04 ns	26.3 ± 0.14 ns	26.4 ± 0.12 ns	28.1 ± 0.13 a	28.19 ± 0.13 a	27.38 ± 0.12 b
	BH	26.62 ± 0.26 ns	26.5 ± 0.43 ns	26.6 ± 0.31 ns	28.25 ± 0.29 ns	28.23 ± 0.16 ns	27.50 ± 0.20 ns
MaxGST (°C)	CH	36.0 ± 0.61 ns	35.26 ± 0.36 ns	35.50 ± 0.44 ns	40.42 ± 0.38 a	39.61 ± 0.25 a	37.93 ± 0.29 b
	BH	36.1 ± 0.88 ns	36.09 ± 0.97 ns	36.02 ± 1.19 ns	40.39 ± 0.83 ns	40.19 ± 0.29 ns	38.55 ± 0.52 ns
MinGST (°C)	CH	17.66 ± 0.05 ns	17.84 ± 0.03 ns	17.79 ± 0.05 ns	17.75 ± 0.06 ns	17.91 ± 0.29 ns	17.67 ± 0.24 ns
	BH	18.08 ± 0.01 a	17.74 ± 0.06 b	17.93 ± 0.11 ab	17.91 ± 0.11 ns	18.05 ± 0.21 ns	17.73 ± 0.14 ns
		*					
CI (°C)	CH	18.04 ± 0.04 ns	18.2 ± 0 ns	18.25 ± 0.03 ns	18.49 ± 0.09 ns	18.60 ± 0.05 ns	18.52 ± 0.08 ns
	BH	18.55 ± 0.03 ns	18.35 ± 0.03 ns	18.4 ± 0.29 ns	18.79 ± 0.09 ns	18.66 ± 0.03 ns	18.81 ± 0.08 ns
		**	**				
TE (°C)	CH	19.70 ± 0.41 ns	18.14 ± 0.33 ns	18.70 ± 0.48 ns	23.24 ± 0.48 a	22.35 ± 0.23 a	20.52 ± 0.46 b
	BH	19.14 ± 0.77 ns	19.89 ± 1.07 ns	19.13 ± 1.37 ns	23.39 ± 1.20 ns	23.62 ± 0.87 ns	21.34 ± 0.98 ns
T30 (n)	CH	67 ± 0.0 ns	67 ± 0.6 ns	67 ± 0.3 ns	116 ± 5.69 ns	118 ± 0.00 ns	121 ± 0.58 ns
	BH	67 ± 0.0 ns	67 ± 0.7 ns	68 ± 0.3 ns	124 ± 1.76 a	118 ± 0.00 ab	117 ± 0.00 b
							**
T35 (n)	CH	41.0 ± 4.93 ns	37 ± 3.53 ns	41.00 ± 2.65 ns	91 ± 7.57 ns	93.00 ± 3.21 ns	76.00 ± 5.77 ns
	BH	37.0 ± 4.10 ns	40 ± 6.64 ns	44 ± 9.29 ns	93 ± 2.33 a	94.00 ± 1.00 a	73.00 ± 1.73 b
dNi (°C)	CH	20.86 ± 0.10 ns	21.12 ± 0.14 ns	21.09 ± 0.11 ns	21.36 ± 0.04 ns	21.04 ± 0.20 ns	21.45 ± 0.12 ns
	BH	21.23 ± 0.07 ns	20.83 ± 0.07 ns	21.16 ± 0.25 ns	21.54 ± 0.09 ns	21.04 ± 0.20 ns	21.44 ± 0.07 ns
		*					
dMi (°C)	CH	20.03 ± 0.21 ns	20.14 ± 0.10 ns	20.34 ± 0.05 ns	20.74 ± 0.05 a	20.91 ± 0.08 a	20.41 ± 0.06 b
	BH	19.88 ± 0.34 ns	19.28 ± 0.21 ns	19.87 ± 0.30 ns	21.16 ± 0.54 ns	20.71 ± 0.24 ns	20.04 ± 0.04 ns
			*				**
dEi (°C)	CH	28.28 ± 0.13 b	28.84 ± 0.02 a	28.64 ± 0.09 ab	29.69 ± 0.08 ns	29.46 ± 0.21 ns	29.55 ± 0.14 ns
	BH	28.88 ± 0.12 a	28.39 ± 0.04 b	28.78 ± 0.08 a	29.87 ± 0.07 ns	29.39 ± 0.19 ns	29.56 ± 0.08 ns
		*	**				
dBDi (°C)	CH	31.70 ± 0.23 ns	31.95 ± 0.77 ns	31.37 ± 0.35 ns	34.96 ± 0.30 a	34.10 ± 0.22 ab	33.12 ± 0.26 b
	BH	32.75 ± 1.09 ns	31.16 ± 0.40 ns	31.79 ± 0.81 ns	34.31 ± 0.91 ns	34.40 ± 0.25 ns	33.43 ± 0.15 ns

Note: Data are expressed as mean ± standard error (n=3). Lowercase letters indicate significant differences ($p < 0.05$) between strategies within the same year (ns = absence of significance - $p > 0.05$). The asterisks denote differences between CH and BH in the same management practices (*: $p < 0.05$; **: $p < 0.01$). The analysis was conducted using ANOVA with Tukey HSD post-hoc test.

Av-Max-Min-GST – average-minimum-maximum-growing season temperature; CI - cool night index; TE - thermal excursion; T30/T35 – number of days with temperature ≥ to 30/35°C; dNi – dynamic night index; dMi – dynamic Morning index; dEi – dynamic evening index; dBDi – dynamic broad daylight index

Looking at the dynamic indices (Table 6), it can be seen that in 2021 the differences between the management practices, are greater during the evening hours (dEi), with significantly lower temperatures in the bunch area of the ELR strategy, in comparison to both C and BF. This may be attributed to reduced foliage in the defoliated vines in the bunch zone, which facilitates faster heat dissipation, while the control vines exhibit higher temperatures due to increased resistance to heat exchange, trapping heat absorbed during the day (Peña Quiñones et al., 2020; Risco et al., 2014). In 2022 no differences in the dEi were detected. Air temperature is highly influenced by light exposure, making row orientation a key factor in shaping the vineyard microclimate. Vineyards characterized by an east-west (EW) exposure, as in this case, have constant light radiation during the day on the canopy (Hunter et al., 2016), while in the bunch area, the upper leaves tend to shade the bunches (Anić et al., 2021; J. M. Gambetta et al., 2020), which explains the lack of significant differences in maximum temperatures between defoliated and non-defoliated management. Furthermore, even though defoliation exposes the bunches to more light radiation, the sunburns identified in the field were of low intensity and mostly found in the headland area (in the east of the vineyard), where light exposure was more concentrated during the early morning hours. (Figure 9).

Figure 9. *Sunburn detected on the headland under ELR management.*

In 2022, basalt flour was found to have lower temperatures than the other strategies, with significant differences ($p < 0.01$) in CH compared to the other two management practices. This is particularly due to lower maximum temperatures, reached during the morning hour and during the day when the sun is at its peak (as shown by dMi and dBDi). Therefore, like other particle films, basalt flour (BF) can create a protection layer on the canopy effectively reducing temperatures, particularly in dry, arid conditions (Cataldo et al., 2022; Teker, 2023). On the contrary, the lower number of treatments carried out in 2021 and the higher amount of repeated rainfall may have lowered the coating effect of basalt flour through washout.

Thermal image to site-specific abiotic stress detection

The Crop Water Stress Index (CWSI) (Figure 10) revealed distinct impacts of canopy management treatments on vine water stress levels in June and July. In June (Figure 10a), ELR had the lowest CWSI value (0.36±0.02), significantly lower than both C (0.43±0.01) and BF (0.48±0.01). Thus, CWSI shows slight-to-moderate stress values (CWSI<0.5) for all three management practices during this period (Yang et al., 2022). In July (Figure 10b), ELR exhibited the highest CWSI (0.62 ± 0.03), while C showed a CWSI of 0.56 ± 0.03, both falling within the severe-to-extreme stress range (CWSI>0.5). In contrast, the BF treatment showed the lowest CWSI values (0.50±0.03), again suggesting a potential buffering effect that may moderate water stress through improved reflective properties that lower canopy temperature and so affect the CWSI (Pou et al., 2014).

Finally, it can be seen that, particularly in July, CWSI values can be strongly influenced by the edge effect. Indeed, pronounced stress (dark red area pixels to the east in the Figure 10b) can be seen in the vineyard near the service areas of the vineyards (headland service road), while CWSI decreases (area identified by green-to-blue pixels) near the ecological functional area (forest – not shown in the figure). Thus, it can be highlighted that remote maps have great potential for the identification of site-specific stresses.

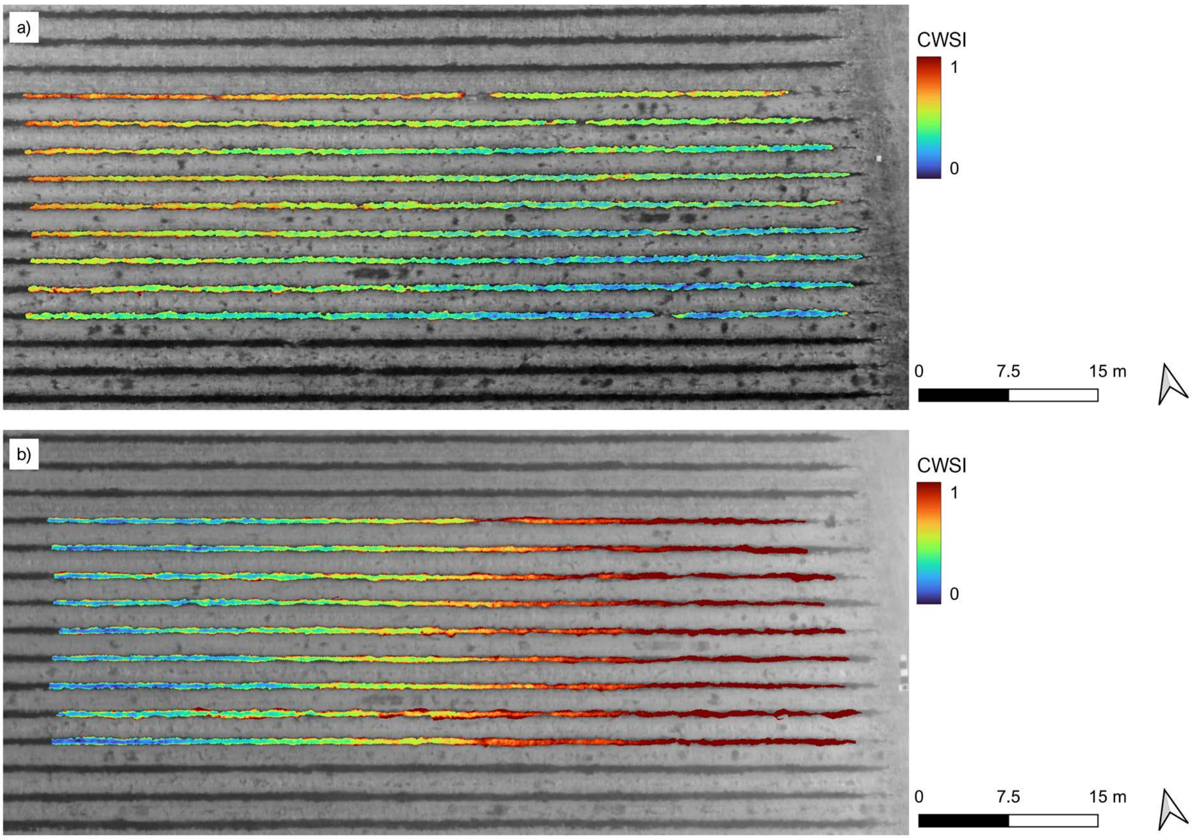

Figure 10. *Crop Water Stress Index (CWSI) for the tested area of the vineyard in June (a) and July (b).*

Physiological response

Changes in microclimate, shaped by different canopy management practices, are tightly interlinked with grapevine physiological processes in a bidirectional relationship, both of which are strongly influenced by overarching climatic conditions. These interactions influence factors such as leaf water potential, gas exchange, chlorophyll content, photosynthesis, and carbon dioxide uptake (de Rességuier et al., 2023; Rafique et al., 2023). In this study, the physiological performances of grapevines were monitored across three consecutive seasons to evaluate how different canopy management strategies modulate these processes through their impact on microclimatic conditions.

The predawn leaf water potential (Ψpd) (Figure 11) values were recorded across the three seasons (2021, 2022, and 2023). In 2021, Ψpd ranged from approximately -0.27 MPa (day of year [DOY] 183 and 189 – BBCH-079) to -0.62 MPa (DOY 246 – BBCH-089/091). In 2022, values varied from -0.38 MPa (DOY 197 – BBCH-079) to -0.72 MPa (DOY 231 – BBCH-089/091), in 2023, Ψpd ranged from -0.17 MPa (DOY 183 – BBCH-079) to -0.48 MPa (DOY 238 – BBCH-089). Maximum Ψpd values were generally observed around the onset of ripening (BBCH-079), with the lowest values occurring at the harvest time (BBCH-089). According to the stress classification scale proposed by Carbonneau (1998), these values correspond to different stress levels each year. In 2021, the vines shifted from mild-moderate stress (BBCH-079 – BBCH-081) to moderate-severe stress (BBCH-089) levels. In 2022, stress levels varied from mild-moderate (BBCH-079/BBCH-081) to severe (BBCH-089), while in 2023, the vines showed mild stress from BBCH-079 to BBCH-081, which progressed to moderate stress during the ripening period (BBCH-089). The findings from the water potential study align with the meteorological data gathered from the weather station. No statistically significant differences were observed between the vineyard management practices on any given day across all three ripening seasons ($p > 0.05$). Although recent research is casting doubt on the actual factors regulating predawn leaf water potential values (García-Tejera et al., 2021; Groenveld et al., 2023), this parameter remains a factor related to soil water availability (Ratzmann et al., 2019). García-Tejera et al. (2021) emphasized that Ψpd is influenced not only by water availability but also by a range of factors including cultivar, environmental conditions, soil type, and the relationships between the canopy and root system. In this study, since these factors are homogeneous across management practices, and there are no differences between them, it can be confirmed that the primary driver of variation in Ψpd across the three seasons, is climate.

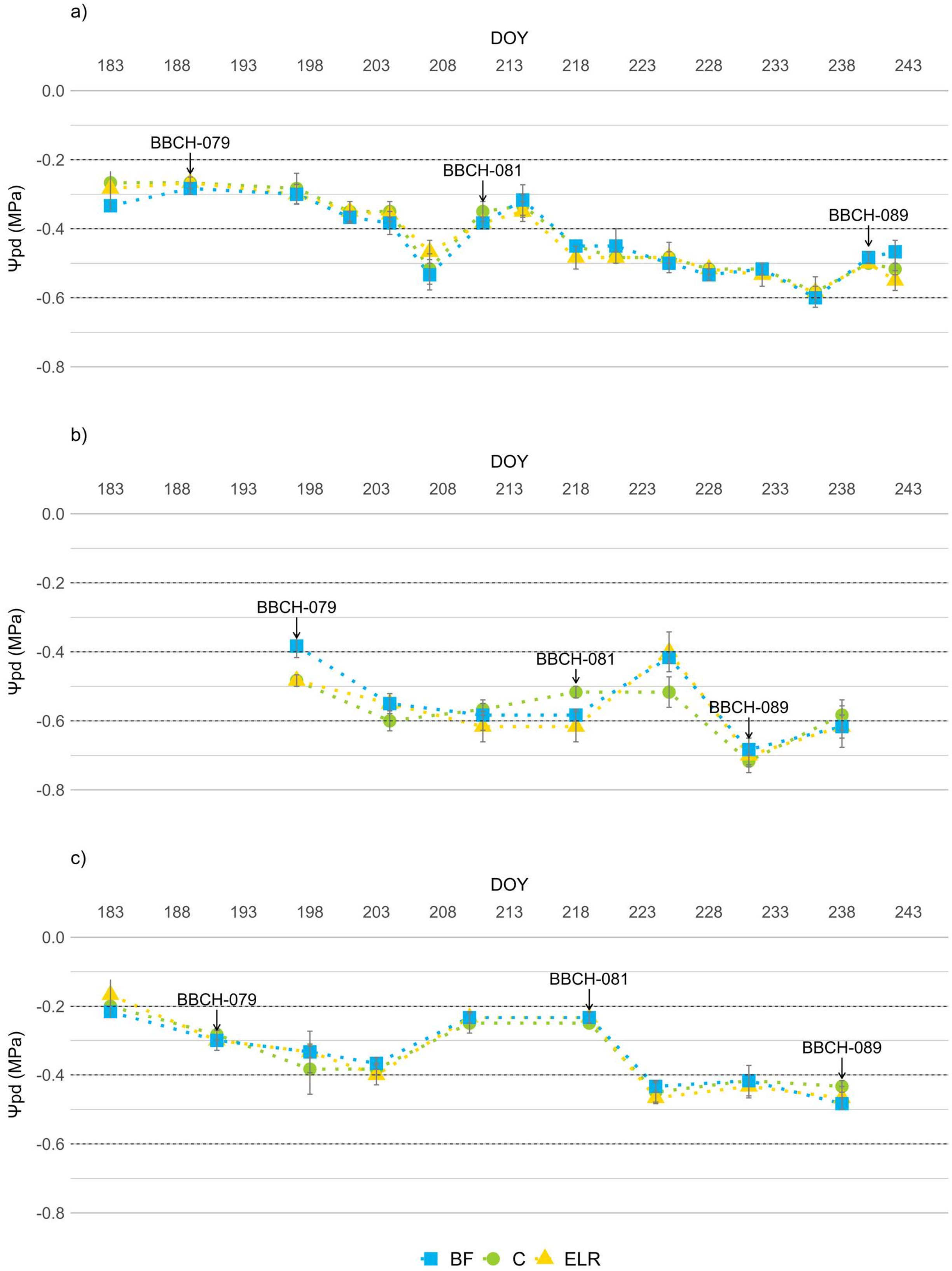

Figure 11. *Seasonal pattern of predawn leaf water potential (Ψpd) for the three management practices (control– C; foliar application of basalt flour – BF; early leaf removal – ELR) from data collected on different days of the year (DOY) in the three ripening seasons: (a) 2021, (b) 2022, and (c) 2023 (mean and standard error; n=3). The approximate periods of the berry ripening phase are shown by the BBCH scales (BBCH-079 – berry touch complete; BBCH-081 – beginning of ripening; BBCH-089 – berries ripe for harvest). Stress limits are highlighted (black dashed lines) according to the scale proposed by Carbonneau (1998).*

Among physiological processes, stomatal conductance (gs) was monitored over the three seasons to measure gas exchange, along with leaf senescence using chlorophyll content as a parameter (Table 7).

Table 7. *Stomatal conductance (gs) and leaf chlorophyll content (Chl) for the three management practices (control – C; foliar application of basalt flour – BF; early leaf removal – ELR) in three BBCH phenological stages (BBCH-071 – fruit-set, BBCH-079 – complete bunch closure, BBCH-089 – harvest) for three years of study (2021, 2022, and 2023).*

		gs			Chl		
		BBCH-071	BBCH-079	BBCH-089	BBCH-071	BBCH-079	BBCH-089
2021	C	524.7 ± 42.2 ns	686.5 ± 30.0 a	428.0 ± 38.1 ns	359.6 ± 7.1 ns	344.2 ± 7.5 ns	330.1 ± 14.6 ns
	ELR	569.1 ± 84.0 ns	501.6 ± 0.5 b	329.0 ± 16.1 ns	365.1 ± 8.5 ns	326.9 ± 8.8 ns	378.9 ± 12.1 ns
	BF	673.4 ± 19.9 ns	576.9 ± 7.0 b	333.9 ± 22.8 ns	339.6 ± 7.5 ns	340.1 ± 10.7 ns	341.1 ± 8.7 ns
2022	C	415.7 ± 17.2 ns	316.7 ± 25.6 a	160.4 ± 24.1 ns	352.3 ± 7.2 b	331.5 ± 10.2 ab	300.3 ± 10.7 b
	ELR	405.0 ± 21.4 ns	202.4 ± 18.0 b	116.5 ± 28.5 ns	361.2 ± 7.7 ab	304.0 ± 12.8 b	348.1 ± 5.4 a
	BF	538.2 ± 70.2 ns	287.5 ± 28.8 ab	146.3 ± 15.5 ns	389.0 ± 7.1 a	362.1 ± 6.3 a	338.1 ± 13.5 a
2023	C	388.8 ± 51.4 ns	315.5 ± 79.2 ns	347.5 ± 31.8 ns	374.7 ± 14.8 ns	369.4 ± 10.4 a	401.3 ± 15.1 a
	ELR	342.9 ± 37.2 ns	286.0 ± 37.9 ns	336.4 ± 50.7 ns	381.0 ± 14.4 ns	399.1 ± 10.0 a	386.8 ± 16.0 a
	BF	447.3 ± 34.9 ns	354.2 ± 34.8 ns	308.7 ± 46.0 ns	351.3 ± 7.3 ns	367.8 ± 7.7 a	336.5 ± 10.5 b

Note: Data are expressed as mean ± standard error. Lowercase letters indicate significant differences ($p < 0.05$) between strategies within the same year. Non-significant differences ($p > 0.05$) are indicated by ns. The analysis was conducted using ANOVA with Tukey HSD post-hoc test.

In 2021 gs values remained relatively high, with water stress classified, according to Cifre et al. (2005), as mild (500 mmol H2O $m^{-2}s^{-1}$ > gs > 150 mmol H2O $m^{-2}s^{-1}$), showing a slight decrease only at harvest. In 2022, vines were under mild water stress at BBCH-071 that progressively increased to medium (150 mmol H2O $m^{-2}s^{-1}$ > gs > 50 mmol H2O $m^{-2}s^{-1}$) up to harvest (BBCH-089). The lower gs values observed at harvest in 2022 correspond to unfavorable environmental conditions (as indicated by season-warm temperature with an AvGST of 20.8°C and low precipitation, only 115 mm during the vegetative season), which caused a significant reduction in stomatal conductance. The values reached at BBCH-089, so when gs reaches and falls below 150 mmol $m^{-2}s^{-1}$, denote that the stress induced by stomatal limitations remains dominant (Cifre et al., 2005). In 2023, gs remained constant at all phenological stages, and under all management practices.

Stomatal regulation represents the first mechanism that the vine adopted to avoid water loss and to leaf cavitation. In *Vitis vinifera* L. this response varies by genotype, with isohydric varieties (which maintain a constant water potential) and anisohydric varieties (which undergo a reduction in water potential). Chardonnay, the varieties objected of this study, is generally classified as an anisohydric variety (Pou et al., 2012), can, however, adopt isohydric behavior under moderate water deficit conditions (Hugalde and Vila, 2014). Although the seasons under investigation are characterized by significantly different temperature and rainfall regimes, grapevine is very tolerant to mild and medium water deficit (G. A. Gambetta et al., 2020), however, if subjected to high water stress, it may respond by activating protective systems by closing stomata affecting leaf senescence, the cumulative rate of photosynthesis and water-use efficiency during the growing season, crucial factors for crop yield and productivity (Faralli et al., 2019).

Significant differences between management practices were observed during cluster closure (BBCH-079) in the vintages of 2021 and 2022, particularly in the strategy involving ELR, with significantly lower gs values ($p < 0.05$). Applications of BF do not show substantial differences from the ordinary canopy management (C), except at BBCH-079 in 2021, in which C showed higher values, also with respect to ELR. Studies on different plants, including grapevines, have shown that the application of basalt-like covering products (e.g., kaolin), leads to an elevation of stomatal conductance, but only in evaluations carried out under high-stress conditions, while usually the differences are not significant compared to control (Rosati, 2007). Given the absence of significant changes in stomatal conductance in BF, it is plausible to attribute the observed differences of microclimate temperature in 2022 (with lower temperature) not so much to an increase in the cooling effectiveness of evapotranspiration, but rather to an intrinsic reflective property of the product, capable of increasing its albedo (Rosati, 2007; K. C. Shellie and King, 2013).

Leaf chlorophyll content monitoring is reported in Table 7. ELR showed in 2021 and 2022 a delay of leaf senescence (BBCH-089). Leaf removal, promotes a compensatory mechanism, leading to an increase in chlorophyll content later in the growing season, enhancing photosynthesis in remaining leaves, increasing assimilate transport, and redirecting resources to support the vine's sink organs (Chanishvili et al., 2005). BF application showed a more variable impact on Chl. It seems to work better under severe climate conditions, as for the 2022 season, where it concurred to delay leaf senescence. Other studies showed positive effects on leaf pigments and an increase in chlorophyll content in grapevine (Bernardo et al., 2021; Dinis et al., 2017; Rashad et al., 2023) and other plant species (Maletsika and Nanos, 2015; Semida et al., 2023).

Taken together, physiological parameters suggested that management practices have had an impact on leaf functionality and also highlighted the role of environmental conditions, such as water stress or extreme temperature to regulate plant ecological functions.

Seasonal carbon allocation in above-ground biomass

Among ecosystem services of viticultural systems in this study, we considered the carbon sink functions (Brunori et al., 2016): vines remove atmospheric carbon through net growth, which can be monitored and quantified starting from the amount of TOC in the vine above and below biomass.

The percentage of total organic carbon (TOC) in leaves, stems, and berries over three years (2021-2023) of the different management are presented in Table 8.

In general, leaves, stems and berries contribute equally to the carbon storage in vine seasonal organs, also across all management applied.

In 2021 leaves showed lower values of TOC compared to stems across all management. The TOC in leaves ranged from 0.413% (± 0.011) for C to 0.435% (± 0.005) for BF, with no significant differences between the managements. Stems had significantly higher TOC in BF (0.439% ± 0.0) and ELR (0.440% ± 0.0) compared to C (0.425% ± 0.001). Berries exhibited higher TOC values, ranging from 0.447% to 0.448%, with no significant differences among different management practices. In 2022, a higher amount of carbon was found in the leaves, with the highest percentage in C (0.436% ± 0.0), followed by BF (0.432% ± 0.001) and ELR (0.426% ± 0.0). Berries showed TOC percentages ranging from 0.365% (± 0.012) in C to 0.450% (±0.006) in ELR. In 2023, TOC percentages in leaves ranged from 0.423% (± 0.002) for ELR to 0.430% (± 0.002) in C. Stems had higher TOC than leaves in all the managements.

Table 8. *Percentage of total organic carbon (TOC) content for each treatment (control – C; foliar application of basalt flour – BF; early leaf removal - ELR) in each year (2021. 2022, and 2023) in leaves, stems, and berries.*

		TOC (%)					
		Leaves		Stems		Berries	
2021	C	0.413 ± 0.011	ns	0.425 ± 0.001	b	0.448 ± 0.001	ns
	BF	0.435 ± 0.005	ns	0.439 ± 0.000	a	0.447 ± 0.003	ns
	ELR	0.429 ± 0.001	ns	0.44 ± 0.000	a	0.448 ± 0.004	ns
2022	C	0.436 ± 0.000	a	0.425 ± 0.001	ns	0.365 ± 0.012	ns
	BF	0.432 ± 0.001	b	0.425 ± 0.000	ns	0.437 ± 0.005	ns
	ELR	0.426 ± 0.000	c	0.425 ± 0.000	ns	0.45 ± 0.006	ns
2023	C	0.43 ± 0.002	ns	0.454 ± 0.001	ns	0.439 ± 0.005	ns
	BF	0.427 ± 0.001	ns	0.451 ± 0.003	ns	0.446 ± 0.006	ns
	ELR	0.423 ± 0.002	ns	0.459 ± 0.007	ns	0.454 ± 0.003	ns

Note: Data are expressed as mean ± standard error. Lowercase letters indicate significant differences between strategies within the same year. Non-significant differences ($p < 0.05$) are indicated by ns. The analysis was conducted using ANOVA with Tukey HSD post-hoc test.

The average TOC values for the different organs were in line with values found in the literature for the Chardonnay cultivar (Zhang et al., 2021).

In the vegetative biomass, a greater amount of weight was directed toward stems rather than leaves (Figure 6S). Analyzing the dried samples, no significant differences ($p < 0.05$) emerged between the treatments about the percentage of dry matter in the different plant portions. However, a higher accumulation of dry matter was observed in the stems, while the bunch stood out for the higher moisture content (Figure 7S).

Starting from TOC, and according to seasonal biomass quantification, the carbon stored per hectare, in annual vegetative and reproductive biomass, is shown in Table 9.

In 2021 higher values of carbon were stored in reproductive biomass in C and BF, respectively 1.31±0.07 and 1.18±0.22 tC ha^{-1} $year^{-1}$ (4.78±0.25 and 4.32±0.79 tCO_2 eq. ha^{-1} $year^{-1}$), while ERL showed a greater carbon stored in the annual vegetative biomass, with 0.98±0.17 tC ha^{-1} $year^{-1}$ (3.59±0.61 tCO_2 eq. ha^{-1} $year^{-1}$). Greater total carbon sequestration was achieved by C (7.69±0.92 tCO_2 eq. ha^{-1} $year^{-1}$).

In 2022, ELR had a higher carbon stored in the vegetative biomass, with 1.60±0.37 tC ha^{-1} $year^{-1}$ (5.86±1.36 tCO_2 eq. ha^{-1} $year^{-1}$), compared to C and BF, which respectively stored 0.83±0.13 and 0.79±0.17 tC ha^{-1} $year^{-1}$, although without significant differences. The BF strategy showed statistically higher carbon storage in the reproductive biomass, with 0.98±0.11 tC ha^{-1} $year^{-1}$ (4.01±0.43 tCO_2 eq. ha^{-1} $year^{-1}$), while C and ELR stored 0.65±0.03 and 0.68±0.03 tC ha^{-1} $year^{-1}$, respectively. The total carbon storage was highest for ELR, with 2.28±0.38 tC ha^{-1} $year^{-1}$ (8.52±1.41 tCO_2 eq. ha^{-1} $year^{-1}$).

In 2023, ELR showed higher storage in vegetative biomass, with 1.84±0.26 tC ha^{-1} $year^{-1}$ (6.76±0.94 tCO_2 eq. ha^{-1} $year^{-1}$), followed by C with 1.30±0.35 tC ha^{-1} $year^{-1}$ (4.78±1.28 tCO_2 eq. ha^{-1} $year^{-1}$) and BF (4.19±0.51 tCO_2 eq. ha^{-1} $year^{-1}$). Reproductive biomass storage equal amount of carbon for BF and ELR (2.03±0.20 and 2.02±0.17 tCO_2 eq. ha^{-1} $year^{-1}$), and slightly higher with C (2.14±0.21 tCO_2 eq. ha^{-1} $year^{-1}$). Total carbon storage was higher for ELR (8.78±0.79 tCO_2 eq. ha^{-1} $year^{-1}$).

Taken together, data showed that ELR the best sink of grapevine organs were the shoots, that reduce the carbon allocation into the berries (Frioni et al., 2018). The induced-stresses by ELR technique was subjected during the swelling and closing phase of the cluster, as seen with the reduction in g_s and the increase in CWSI, which may in turn have caused a reduction of the assimilative activity and with negative effects on carbon storage of grapes (Tanda and Chiarabini, 2019). In contrast, the BF, with lower thermal stresses and a higher content of photosynthetic pigments, may have increased carbon storage capacity, with a strong tendency to accumulate towards the reproductive organs.

Differences in carbon allocation between vegetative and reproductive biomass, were found in 2023 for BF and ELR.

Table 9. Annual carbon storage per hectare in the annual vegetative biomass and reproductive biomass for each strategy (control – C; foliar application of basalt flour – BF; early leaf removal – ELR).

		Annual vegetative biomass ($tCha^{-1}year^{-1}$)		Reproductive biomass ($tCha^{-1}year^{-1}$)		Total ($tCha^{-1}year^{-1}$)	
2021	C	0.79 ± 0.21	nsNS	1.31 ± 0.07	nsNS	2.10 ± 0.25	nsNS
	BF	0.78 ± 0.07	nsNS	1.18 ± 0.22	nsNS	1.96 ± 0.17	nsNS
	ELR	0.98 ± 0.17	nsNS	0.92 ± 0.08	nsNS	1.90 ± 0.25	nsNS
2022	C	0.83 ± 0.13	nsNS	0.65 ± 0.03	bNS	1.48 ± 0.14	nsNS
	BF	0.79 ± 0.17	nsNS	0.98 ± 0.11	aNS	1.77 ± 0.28	nsNS
	ELR	1.60 ± 0.37	nsNS	0.68 ± 0.03	bNS	2.28 ± 0.38	nsNS
2023	C	1.30 ± 0.35	nsNS	0.58 ± 0.06	nsNS	1.89 ± 0.35	nsNS
	BF	1.14 ± 0.14	nsA	0.55 ± 0.05	nsB	1.70 ± 0.08	nsNS
	ELR	1.84 ± 0.26	nsA	0.55 ± 0.05	nsB	2.39 ± 0.22	nsNS

Note: Data are expressed as mean ± standard error. Lowercase letters indicate significant differences ($p < 0.05$) between strategies within the same year, while uppercase letters denote significant differences in carbon allocation within the same strategy (ns/NS: not significantly different). The analysis was conducted using ANOVA with Tukey HSD post-hoc test.

Overall, the three management practices resulted in an average carbon storage of 0.91(±0.18) tC ha^{-1} $year^{-1}$ in the vegetative biomass and 0.87(±0.06) tC ha^{-1} $year^{-1}$ in the reproductive portion, respectively corresponding to 3.33(±0.66) tCO_2-eq. ha^{-1} $year^{-1}$ and 2.68(±0.22) tCO_2-eq. ha^{-1} $year^{-1}$. These results are in line with those found in the literature (Brunori et al., 2016; Song et al., 2023), and show that with different vineyard management practices, it is possible to keep the carbon sink function active annually through the seasonal organs of the plant that allow them to store carbon shares annually.

A multiple regression analysis was conducted to assess the relationship between the carbon stored in the vegetative annual biomass and reproductive biomass over three different canopy management managements across three vegetation seasons (Figure 12).

In 2021 (Figure 12a), a high positive correlation was observed between vegetative biomass and reproductive, in particular for ELR management (R^2=0.917). In 2022 and 2023 (Figure 12b,c), correlations were noted for BF treatment and ELR management.

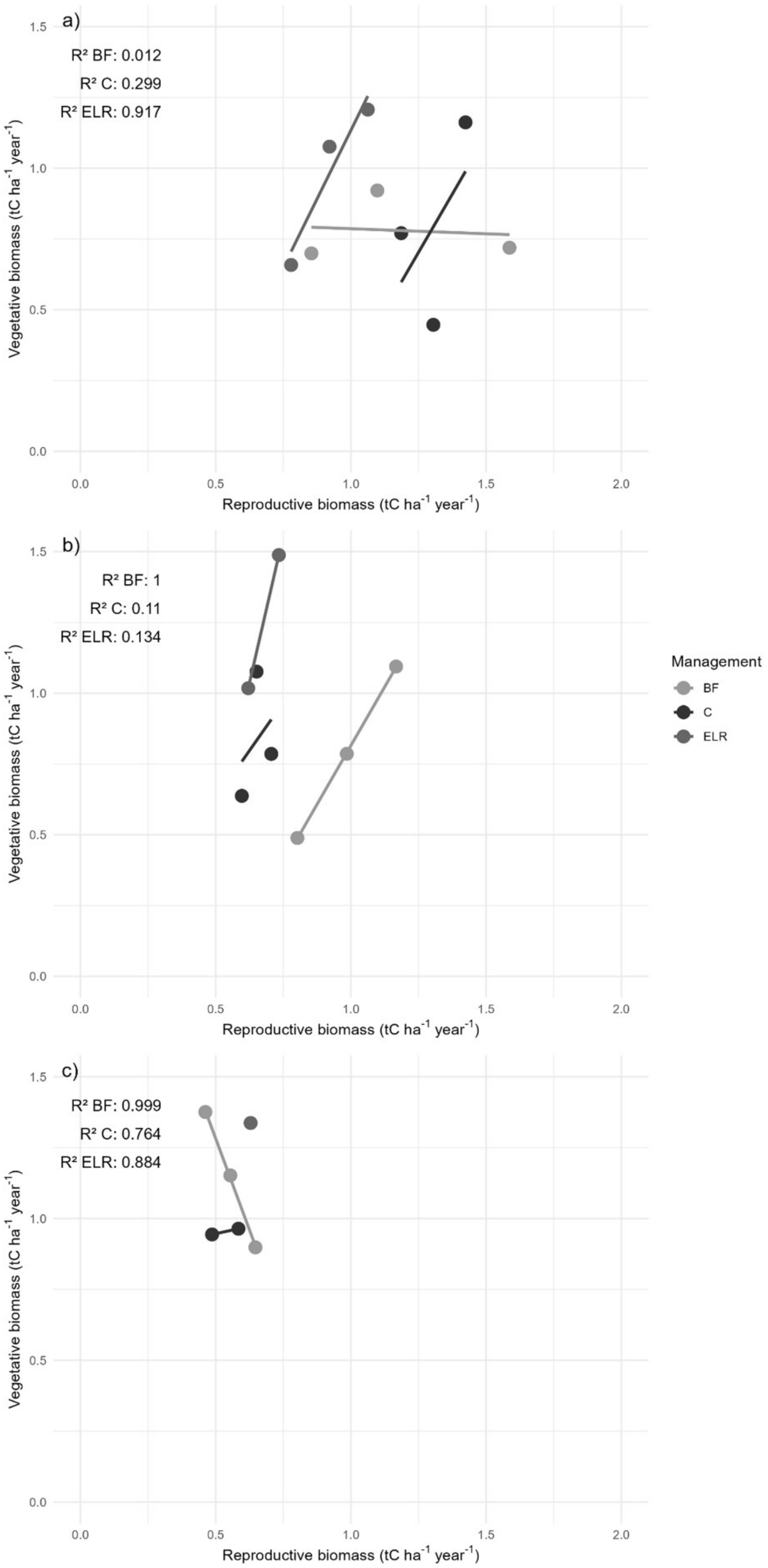

Figure 12. *Multiple linear regression showing the relationship between the carbon stored in the annual vegetative biomass and in the reproductive biomass in each vegetative season for the three management (control – C; foliar application of basalt flour – BF; early leaf removal - ELR).*

Yield and vine's vigor under different vineyard management practices

In addition to evaluating the effects of vineyard management techniques on climate and microclimate alterations, and their impact on vine stress, leaf senescence, and water stress, this study also quantifies their influence on grape production, both in quantitative terms (yield per vine) and qualitative terms (physical and chemical berry parameters). Global warming is causing an increase in sugar levels while simultaneously reducing anthocyanins and acidity in grapes, impacting wine quality. To combat these challenges, climate adaptation strategies are vital for sustainable viticulture. Implementing specific viticultural techniques can delay grapevine ripening, offering a potential solution to heat stress. These approaches are essential for maintaining grape quality and adapting to changing climate conditions.

Quantitative data were monitored for all three consecutive seasons determining the bunch weight (W_{bu}), berry weight (W_{be}), and berries per bunch, shown in Table 10, and yield and vigours (annual biomass weight), shown in Figure 13.

Table 10. *Bunch weight (W_{bu}), berry weight (W_{be}), and number of berries per bunch, in grapevine subjected to the three different management practices (control – C; foliar application of basalt flour – BF; early leaf removal – ELR), measured across three years (2021, 2022, 2023).*

		2021		2022		2023		*p*-value ANOVA (time)
W_{bu} (g)	C	215.99 ± 25.58	nsNS	144.17 ± 9.64	abNS	215.44 ± 24.73	nsNS	0.5
	ELR	139.33 ± 21.32	nsNS	115.66 ± 14.28	bNS	154.61 ± 19.43	nsNS	0.4
	BF	229.56 ± 37.65	nsNS	167.61 ± 14.53	aNS	175.56 ± 11.99	nsNS	0.2
	p-value ANOVA (Management)	0.1		<0.05		0.1		
W_{be} (g)	C	1.49 ± 0.06	bNS	1.48 ± 0.07	aNS	1.23 ± 0.21	nsNS	0.2
	ELR	1.43 ± 0.03	bNS	1.14 ± 0.08	bNS	1.10 ± 0.19	nsNS	0.2
	BF	1.82 ± 0.08	aA	1.55 ± 0.09	aAB	1.28 ± 0.14	nsB	<0.01
	p-value ANOVA (Management)	<0.01		<0.01		0.8		
Berries per bunch (n)	C	145.80 ± 9.35	aAB	96.75 ± 4.40	nsB	168 ± 20.1	nsA	<0.05
	ELR	97.57 ± 7.84	bNS	101.23 ± 7.46	nsNS	135 ± 17.6	nsNS	0.1
	BF	126.75 ± 11.14	abNS	107.72 ± 6.03	nsNS	132 ± 9.4	nsNS	0.4
	p-value ANOVA (Management)	<0.01		0.8		0.2		

Note: Data are expressed as mean ± standard error. Lowercase letters indicate significant differences ($p < 0.05$) between strategies within the same year, while capital letters denote differences between years in the same strategy (ns/NS: not significant - $p > 0.05$). Also, the *p*-values are specified both for differences between management practices and time. The analysis was conducted using ANOVA with Tukey HSD post-hoc.

The ELR reduced W_{bu} compared to the basalt flour (BF) and control (C) treatments. In 2021, this reduction was linked to smaller berry size, with a 21% decrease in W_{be} compared to BF, and fewer berries per bunch, showing a 33% reduction relative to C. In 2022, the W_{be} was again significantly lower under ELR, with a reduction of 20% and 31% compared to C and BF, respectively. ELR's effect on berry size and cluster weight is due to the induction of calibrated photosynthetic stress by removing mature leaves. This stress causes blossom drop and impacts cell division during berry development, leading to looser clusters and smaller berries, ultimately reducing the crop load (Poni et al., 2023; Poni and Bernizzoni, 2010).

In contrast, the BF treatment produced heavier bunches, particularly in 2021 and 2022. In 2022, the W_{bu} under BF was significantly higher than C (by 16%) and ELR (by 45%), which was accompanied by consistently heavier berries across all three years. This aligns with previous studies showing improved yield in grapes and other plant species when treated with basalt or similar silica-based products (Abdallah et al., 2019; Boari et al., 2016; Dinis et al., 2017; Djurović et al., 2016; Laane, 2018).

Over the three years of the study, differences in yield per vine were observed among the three management practices (Figure 13). In both 2021 and 2023, the BF treatment resulted in yields comparable to C and ELR. However, in 2022, BF significantly outperformed the other two practices, with a yield increase of 2.26±0.24 Kg per vine per year, compared to 1.73±0.08 Kg for C and 1.39±0.07 Kg for ELR. These results suggest that BF may provide a cumulative benefit, particularly during stressful growing conditions, that could be attributed to the enhanced chlorophyll content provided by the administration of the product, promoting better fruit development. Other studies conducted on grapevine with the use of different treatments (Popescu and Popescu, 2018; Zhou et al., 2024), have noted that the content of photosynthetic pigments, along with the parameters and efficiency of photosynthesis, plays a crucial role in determining the overall performance and productivity of plants. In addition, The protective effect of basalt flour, which also allows lower temperatures in the canopy and less stress, may have an additional positive effect on the constancy of production between 2021 and 2022.

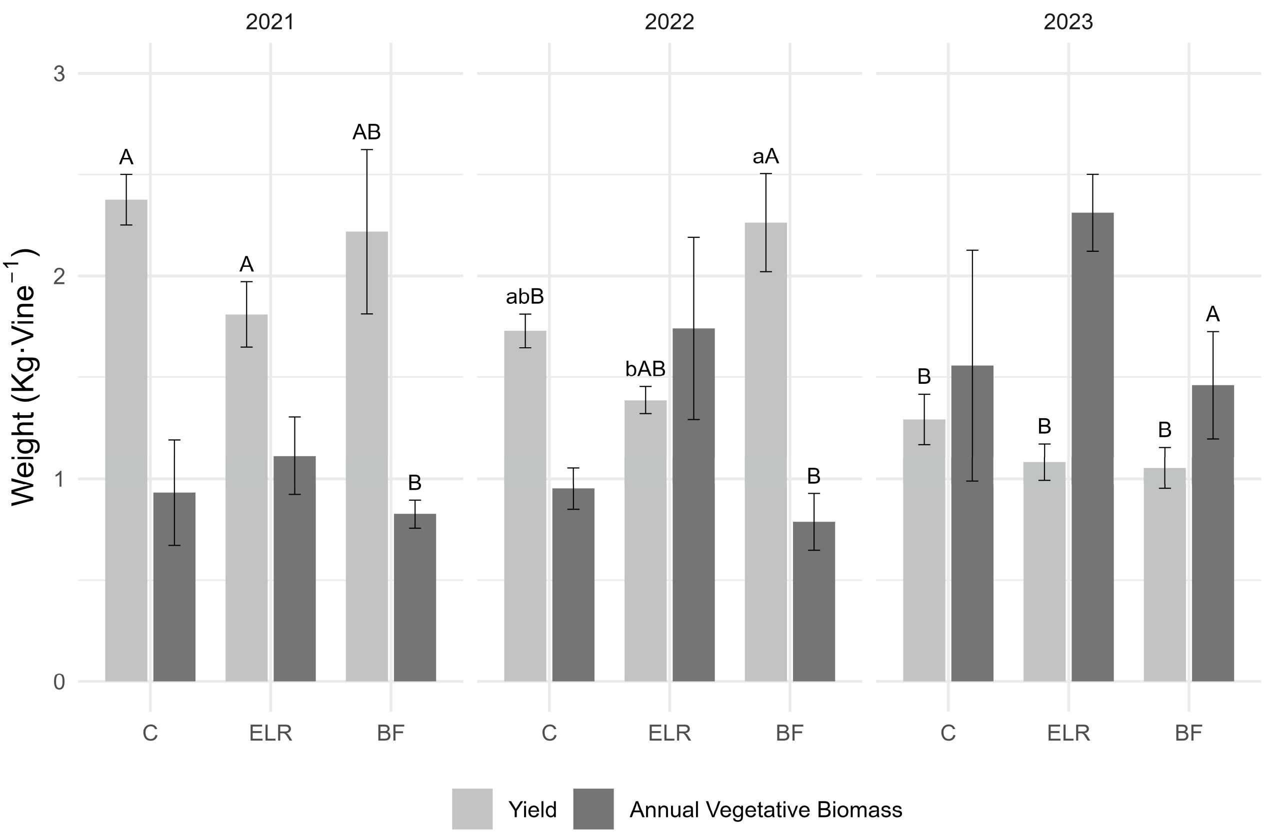

Figure 13. *Yield and annual vegetative biomass per vine (mean ± standard error, n=3) for the three years with different management practices (control – C; foliar application of basalt flour – BF; early leaf removal – ELR). The presence of lowercase letters shows a significant difference ($p < 0.05$) between different management, while uppercase letters show a significant difference ($p < 0.05$) between the years within the same strategy.*

In 2023, a significant reduction in yield per vine was observed across all treatments. This decrease was attributed to a reduced number of bunches per vine (Figure 8S), rather than a decline in bunch weight, which remained stable compared to previous years. The lower yield in 2023 is likely a result of both unfavorable weather conditions in 2022, with heat and water stress in key phenological phases which could have impacted the following year's production (Guilpart et al., 2014), and the climate of the same 2023 that saw high rainfall during the flowering and fruit set periods, which promoted vegetative growth at the expense of reproductive structures and created favorable conditions for pathogen development. These climatic challenges led to widespread yield reductions across the Italian peninsula, as reported by the International Organisation of Vine and Wine (OIV, 2024).

An inverse pattern was observed in the weight of the annual vegetative biomass analysis with lower values for C and BF and higher values for ELR, albeit without significant differences ($p > 0.05$). A general increase in annual vegetative biomass is noted in the early leaf removal strategy. In the final quantity of the vegetation portion, defoliation allows the total reconstitution of the vegetation surface, probably due to the compensation of the loss of the leaf mass removed due to the re-emission of lateral shoots (Palliotti et al., 2011; Poni et al., 2006a). Only BF showed differences through the years, with a constitution of the annual vegetative biomass statistically higher in 2023. These results reflect the source-sink balance and how vines allocate energy between vegetative growth and yield (Holzapfel et al., 2024).

Berry quality

The qualitative analysis of grapes is shown in Table 11.

Chardonnay vine productions intended for white wine are aimed at obtaining a fresh and complex product, characterized by freshness and fruity notes. Brix level between 21° and 23° is generally targeted. The pH values for white wines may be around 3.5 or less, playing a major role in winemaking, affecting different wine parameters (e.g. colour, oxidation rate, tartrate stability, etc; Zoecklein et al., 1999). Lastly, titratable acidity must be in the range of 4.0-8.0 $g \cdot dm^{-3}$ expressed in tartaric acid (Rajkovic et al., 2007).

Harvesting was carried out by the farm on August 26 in 2021 and August 23 in 2023, while in 2022, with more extreme weather conditions, an early ripening occurred, with harvesting carried out on August 16. Grape ripening is highly sensitive to temperature, with warmer conditions accelerating the process. With rising temperatures and prolonged drought periods, the result is an earlier ripening of grapes, stimulated by increased abscisic acid (ABA) and decreased cytokinin, which trigger mechanisms that accelerate ripening (Prada et al., 2024).

Table 11. *Total soluble solid (TSS), pH, and total acidity (TA) of musts of vines under three different management practices (control– C; foliar application of basalt flour – BF; early leaf removal - ELR), measured across three years (2021, 2022, 2023).*

		2021	2022	2023
TSS (°Brix)	C	23.56 ± 0.19 a	22.65 ± 0.003 c	22.67 ± 0.43 ns
	ELR	23.48 ± 0.12 a	24.72 ± 0.007 a	22.37 ± 0.64 ns
	BF	22.82 ± 0.12 b	23.95 ± 0.009 b	23.47 ± 0.82 ns
	p-value ANOVA (Management)	<0.05	<0.001	0.5
pH	C	3.74 ± 0.03 a	3.71 ± 0.003 a	3.47 ± 0.06 ns
	ELR	3.51 ± 0.05 b	3.66 ± 0.003 b	3.67 ± 0.12 ns
	BF	3.48 ± 0.06 b	3.70 ± 0.003 a	3.58 ± 0.05 ns
	p-value ANOVA (Management)	<0.05	<0.001	0.3
TA (mg·L-1 Tartaric Acid)	C	4.88 ± 0.28 ns	4.37 ± 0.003 ns	5.53 ± 0.03 a
	ELR	5.69 ± 0.12 ns	4.30 ± 0.003 ns	5.61 ± 0.04 a
	BF	5.37 ± 0.20 ns	4.47 ± 0.003 ns	5.17 ± 0.08 b
	p-value ANOVA (Management)	0.1	0.33	<0.05

Note: Data are expressed as mean ± standard error. Lowercase letters indicate significant differences ($p < 0.05$) between strategies within the same year (ns: not significant). Also, the *p* -values are reported. The analysis was conducted using ANOVA with Tukey HSD post-hoc test.

Early leaf removal (ELR) treatments produced statistically significant increases in total soluble solids (TSS) in 2021 (23.48°Brix) and 2022 (24.72°Brix) relative to both BF and C management practices. BF exhibited variable results across the study period, with lower TSS values in 2021

(22.89°Brix) and higher TSS in 2022 (23.95°Brix) compared to C. In contrast, C demonstrated the highest pH values across both years, with statistically significant differences noted in 2021 compared to both ELR and BF and in 2022 when compared to ELR alone. Notably, in 2023, TSS and pH values showed no significant differences across treatments, while titratable acidity (TA) was statistically lower in BF.

Previous studies extensively investigate the impact of early defoliation on the ripening progression and aromatic profiles of red grapevines under varying defoliation intensities and timings. The literature generally indicates an advancement in ripening onset due to early defoliation (Mucalo et al., 2021; Palliotti et al., 2011); however, outcomes are highly variable based on defoliation timing and phenological stage. For instance, Frioni et al. (2018) observed that performing two defoliation treatments at full flowering—one lighter (removing six basal leaves) and one heavier (removing ten basal leaves)—resulted in no significant differences in TSS, pH, or TA in the lighter defoliation, but significantly higher TSS and pH with lower TA in the heavier defoliation treatment. Conversely, defoliation at fruit set with the removal of four and eight basal leaves resulted in opposite quality outcomes (Cataldo et al., 2021).

Furthermore, results fluctuate when considering colder climates and white-berried cultivars. For example, in such conditions, early defoliation either produces minimal impact (Verdenal et al., 2019) or even leads to a reduction in °Brix relative to controls (Mucalo et al., 2022). Additional variability arises from the use of protective antitranspirant agents. In a sub-alpine climate, Andreotti et al. (2024) found that a pinolene-based antitranspirant delayed ripening in Sauvignon blanc grapes, whereas kaolin and chitosan treatments showed comparable results to the control. In a study led by Dinis et al. (2020), kaolin applications in another study significantly reduced both °Brix and acidity. Conversely, kaolin treatments at 1% and 3% concentrations on King Ruby seedless grapevines increased TSS and decreased acidity over two consecutive years (Rashad et al., 2023).

In our study, early defoliation influenced °Brix levels, resulting in lower values during wetter years and elevated values during the 2022 season, with opposing trends observed in TA, with a pH generally lower than C. Basalt flour application reduced °Brix in 2021; however, in the warmer, drought-prone seasons of 2022 and also 2023, which is still a year with many dry days before the harvest, it contributed to increased TSS. As expected along the maturation curve, TA levels generally exhibited inverse patterns relative to °Brix, consistent with the typical progression of grape ripening.

Grape ripening is influenced by multiple factors, with plants responding differently across vintages and adapting uniquely to various cultivation practices.

Sustainability assessment

In this study, the environmental impact of crop management, soil management, and plant protection practices was assessed and compared in relation to the three different management strategies and three reference periods.

The highest impact per hectare (Figure 14) for all investigated systems is given by crop management, accounting for approximately 39% of the total CO_2 eq. emissions over the three reference periods. Among the systems analyzed, the ELR system shows the highest CO_2 eq. emissions, primarily due to the use of agricultural machinery for leaf removal, which contributes to adding 30 L/ha of fuel, annually. Compared to the emission per hectare of C and BF systems, ELR system emissions are 21%, 19%, and 13% higher respectively in 2021, 2022, and 2023. The significant contribution of crop management practices to the overall impact is largely attributed to the emissions from numerous high-impact field activities, particularly mechanical harvesting, which, on average, consumes twice as much fuel per hectare as other practices. However, mechanized harvesting reduces harvesting time and machinery use (mainly bank-out trucks) compared to manual harvesting, which could instead lead to an increase in impact per hectare and a decrease in yield (Steenwerth et al., 2015).

Along with crop management, soil management occupies a large portion of the emissions per hectare, with approximately 35% of the total emissions. Among the main factors contributing to diesel input in conventional agriculture are soil tillage and fertilization (Naujokienė et al., 2019). Conversely, the use of conservation tillage and no-till practices could reduce GHG emissions, while the use of cover crops would increase C sequestration in the soil and limit other harmful emissions, such as N_2O (Nistor et al., 2018). Also, it is important to highlight the potential of rethinking waste management practices to reduce CO_2 emissions and enhance the ecosystem service of the vineyards as carbon sinks (Demestihas et al., 2017; Montanaro et al., 2017). For instance, crop residues from pruning, rather than being left in the field, can be utilized for energy generation, offering a more sustainable alternative that significantly lowers the global warming potential (GWP), effectively turning crop residues into a carbon sink (Den Boer et al., 2020; Simões et al., 2023).

In the context of this LCA study, plant protection consistently exhibited the lowest impact per hectare among the evaluated categories, with an average of 25% of the total emissions, when assessed using the IPCC-GWP_{20} method. This lower impact can likely be attributed to the relative efficiency of plant protection activities, which require less operational time and energy, and thus consume less fuel compared to other management practices. Additionally, while plant protection operations are less demanding in terms of energy use, their environmental impact is often linked to the release of pollutants into the atmosphere and toxic substances in soil, and water compartments (Tudi et al., 2021) and their relevant production impacts, above all for fossil resource consumption and GHG emissions. Also, higher impacts are shown for plant protection in the case of the BF system, due to the higher frequency of the basalt flour distribution. Compared to C and ELR systems, BF results in CO_2 eq. emissions per hectare that are 7%, 17%, and 10% higher respectively in 2021, 2022, and 2023 years.

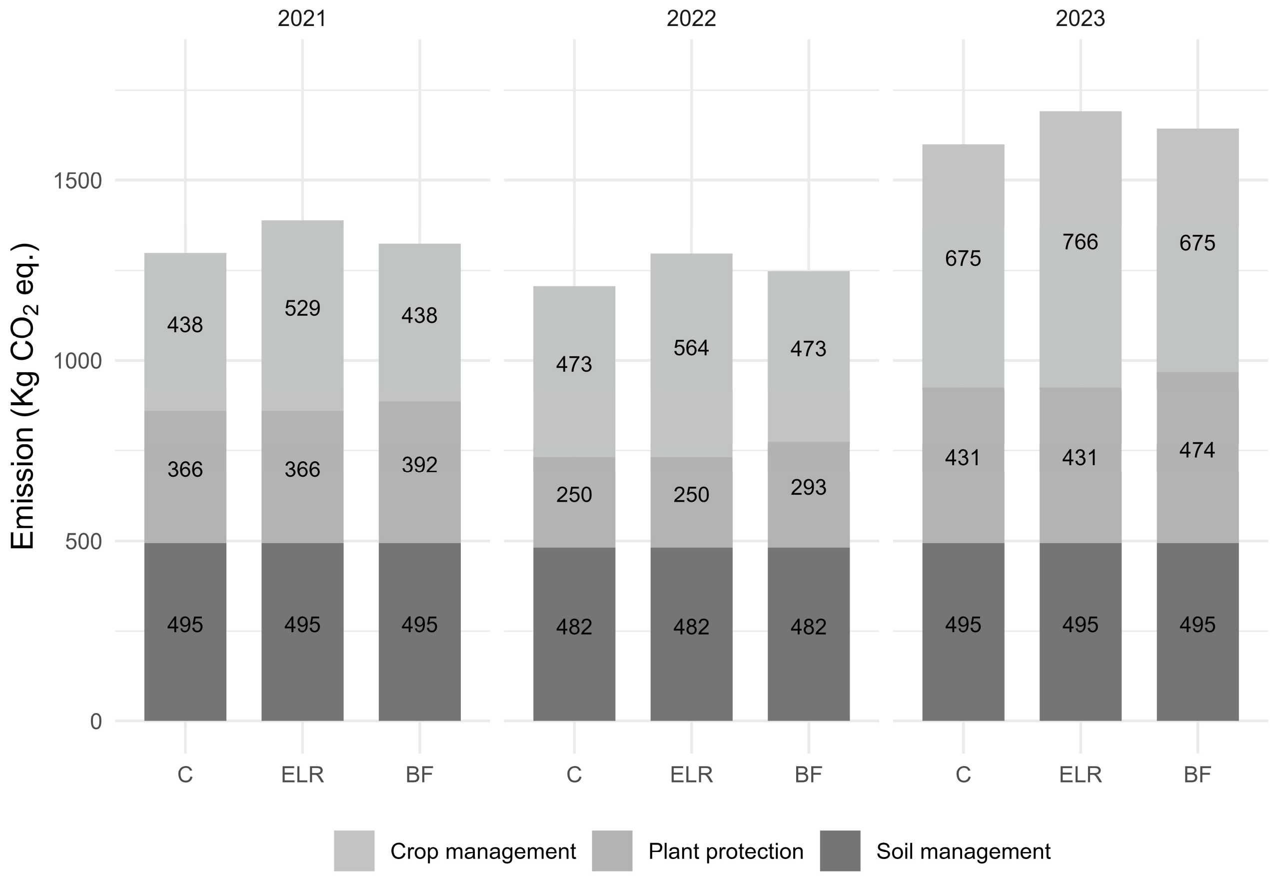

Figure 14. *Emission (Kg of CO_2 eq.) per hectare in the three systems (control – C; foliar application of basalt flour – ELR; foliar application of basalt flour – BF) for the three years (2021, 2022, and 2023).*

In relation to different reference periods, all investigated systems have worsened their environmental performance in 2023 compared with those of both 2021 and 2022, showing a marked increase in their environmental performance. Compared to 2021, C, ELR, and BF emissions for an equal surface unit increased by 23.3%, 21.7%, and 24.1%, respectively. These results probably relate to the increase in 2023 of green pruning practices (topping and suckering) and phytosanitary treatments, as a consequence of the abundant spring rainfall that led to higher growth in vegetation biomass and a microclimate favorable to pathogen attack (OIV, 2024). In 2022, i. fewer green prunings in relation to less favorable environmental conditions and limited vegetative growth, ii. fewer treatments' practices for containing pathogen attacks (Prada et al., 2024; Salinari et al., 2006) and iii. an earlier harvesting led to a slight decrease in CO_2 eq. emissions per hectare compared to those of the other two reference years. These results highlight how the environmental impacts of vineyard management are deeply influenced by seasonal and climatic variability.

In Figure 15 the impacts of producing 1 Kg of grapes (here intended as Kg of CO_2 eq. emissions) of the three investigated systems are shown. By observing results concerning individual production cycles, the C system showed the best environmental performance in the 2021 year, emitting 0.12 Kg CO_2 eq. per kg of harvested grapes. In the same year, for an equal amount of harvested grapes, CO_2 eq. emissions estimated for the ELR and BF systems were 40.4% and 9.2% higher than those of the C, respectively. In 2022 year, the less impacting system was the BF system, with 0.11 kg CO_2 eq. per kg of harvested grapes and 21.6% lower carbon footprint compared to the C system and 42.5% lower compared to ELR one. In 2023 year, CO_2 eq. emissions per kg of harvested grapes by the ELR and BF systems were 0.33 and 0.37 kg CO_2 eq. per kg of harvested grapes, respectively. While the C system showed emissions of 0.26 kg CO2 eq. per kg of harvested grapes in 2023. These results are in line with those found in the literature analyzing other types of vineyard systems considering the same boundaries (Clune et al., 2017; Steenwerth et al., 2015; Vázquez-Rowe et al., 2012; Villanueva-Rey et al., 2014). As pointed out by Ferrara and De Feo (2018), most of the articles dealing with LCA in the vineyard phase also take into account the planting of the vineyard (*cradle-to-gate*). Hence, purely concerning the research area, it is difficult to make comparisons between different studies. Moreover, the functional unit considering a single functional unit criterion is not always unique for all papers. For example, contemplating a product-related indicator, Vázquez-Rowe et al. (2012) considered an FU of 1.1 kg of harvested grapes, while Steenwerth et al. (2015) adopted 1 metric ton of harvested grapes as FU. This leads us to emphasize again, as has been done before by other authors (Clune et al., 2017; Schau and Fet, 2008), the need to establish a standardized functional unit for the same criterion, as well as system boundaries, at least for supporting comparisons between different products. Furthermore, according to Hayashi (2023, 2013), the complementary use of different functional units to compare sustainable cropping systems allows the holistic approach of LCA to be fully exploited. In this context, the present work offers added value, as it allows environmental impacts to be assessed in relation to both area and biomass, providing an overall view of the product's ecological footprint.

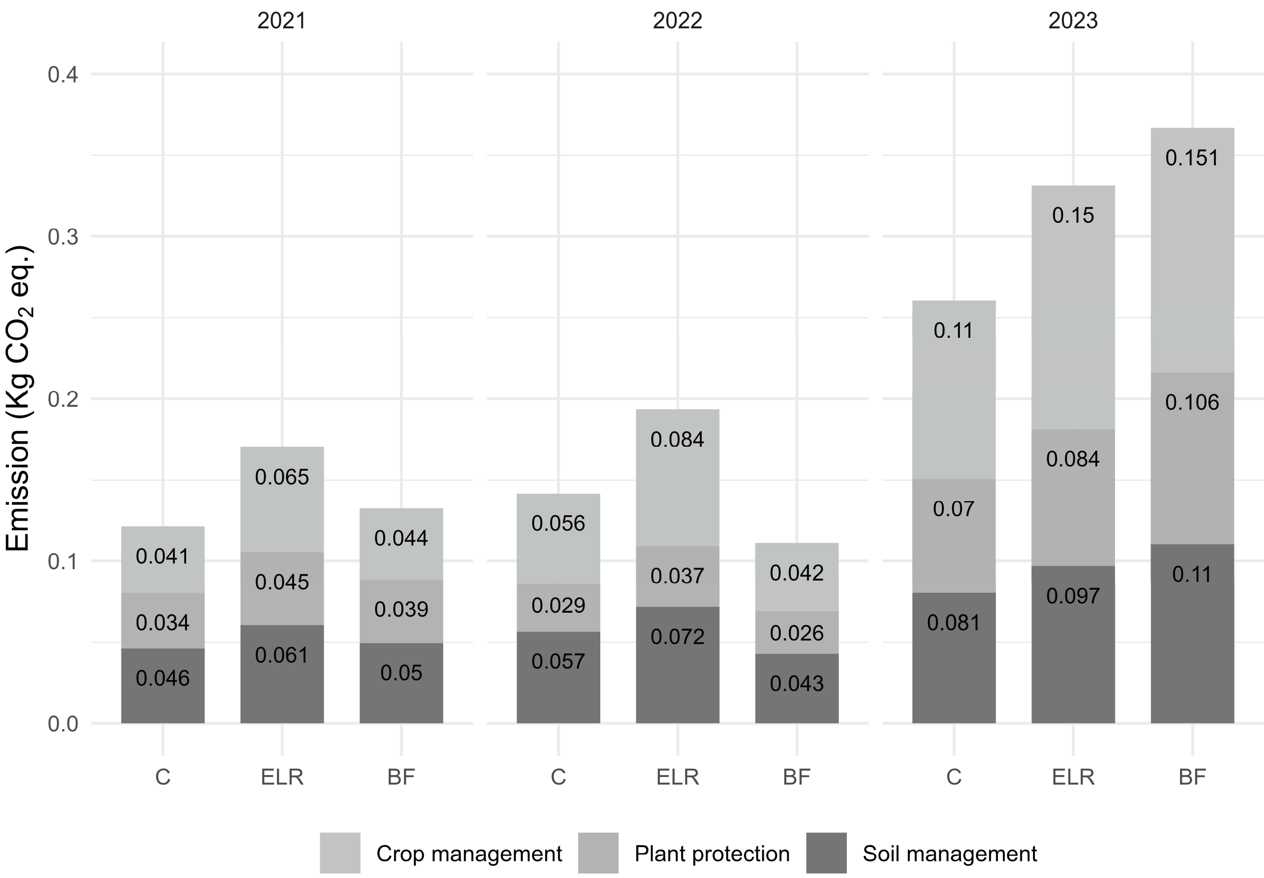

Figure 15. *Emission (Kg of CO_2 eq.) to produce 1 Kg of grapes in the three systems (control – C; early leaf removal – ELR; foliar application of basalt flour – BF) for the three years (2021, 2022, and 2023).*

Compared to the C system, the ELR system recorded lower yields in all three years, as a consequence of the same leaf removal, while increasing its impacts. This might lead to thinking that this technique may be disadvantageous both environmentally and economically for farmers. However, parameters such as product quality are not taken into account in the present LCA. As for other agricultural products, viticulture yield needs to be correlated with the quality of wine, with less yield considered a tool for the production of high-quality wines (Foerster et al., 2024). Early leaf removal is a particularly effective strategy with multiple benefits. Reducing vegetative growth, improves the canopy microclimate and optimizes the distribution of sugars between shoots and ripening grape berries (Alatzas et al., 2023). This practice is especially advantageous for grape varieties such as Chardonnay, which has thin skins and compact clusters prone to pathogens attack, thus making early leaf removal an effective means of reducing attacks (Benetti et al., 1989; Mundy et al., 2022; Wurz et al., 2022). Additionally, early leaf removal positively impacts berry composition. Reducing berry sizes, and higher skin-to-pulp ratio will be achieved by the berries, positively affect aroma and flavor compounds (Alatzas et al., 2023). In addition, this practice substantially increases berry color and phenolic content (Tardaguila et al., 2010). Overall, early leaf removal, even if it increases the environmental impact, benefits both grape health and wine quality, thus confirming the push towards research approaches that carefully evaluate the trade-offs between quantity and quality of production.

Results of the LCA analysis displayed that for the 2022 year, C and ELR systems increased their CO_2 eq. emissions per unit of harvested grapes by 16.8% and 13.6%, respectively, compared with their emissions in 2021. Otherwise, the CO_2 eq. emissions of the BF system for an equal amount of harvested grapes decreased in the year 2022 by 16.1% with respect to their CO_2 eq. emission in 2021. This decreased impact of BF could be attributed to the higher yield which in turn led to a redistribution of impacts per hectare. Significantly lower yields per hectare in 2023 contributed to an increase in the impact in this reference year, considering the emissions per kg of grapes produced. Recent studies (Laane, 2018; Rashad et al., 2023; Slim et al., 2020; Wang et al., 2022) have highlighted the potential of basalt flour and similar products to have benefits for pest management, creating physical barriers that control pests and enhance plant health. Moreover, it represents a sustainable agricultural amendment (Conceição et al., 2022; Oppon et al., 2023; Rodrigues et al., 2024). Moreover, the use of alternative products in organic and eco-friendly farming systems aligns with the European Union recommendations in order to limit copper usage in agriculture due to its negative environmental impacts (EC, 2018). While copper, a widely used fungicide and bactericide, has significant downside effects (Lamichhane et al., 2018), basalt flour offers a safe, non-toxic alternative compatible with organic farming standards, constituting a valuable sustainable solution.

In addition, rather than focusing on annual variations in production, we chose to evaluate the cumulative impact values over the three years, treating them as a single production cycle. This approach allows us to assess the overall impacts across the three years, providing a more comprehensive comparison of the environmental performance of the systems. Such an analysis could be particularly relevant for companies interested in understanding the long-term effects of adopting the strategies we propose across multiple agronomic cycles. The results (Figure 9S) indicate that, at the end of the three years, the total emissions of ELR in relation to a biomass unit increased by 0.219 kg of CO_2 eq., which is 35% higher compared to the C system (0.162 kg of CO_2 eq. per kg of harvested grapes). In contrast, the BF system showed a minimal overall increase in impacts of only 1%, with even lower emissions associated with soil and plant management, resulting in total emissions of 0.164 kg of CO_2 eq. per kg of harvested grapes.

All these findings underscore the importance of adopting mitigation management practices that are also responsive to climatic conditions (adaptive), aiming not only to reduce emissions but also to optimize resource use and maintain yield and quality characteristics under changing environmental scenarios. Such an approach could help mitigate the dual challenges of minimizing environmental impact and ensuring sustainable agricultural production in the face of a changing climate. Moreover, farm decisions cannot always be guided solely by criteria of immediate convenience, but should be directed toward more sustainable strategies that consider the importance of reducing environmental impacts throughout the entire life cycle of products.

4. CONCLUSIONS

Climate change poses a significant challenge to viticulture, exposing vineyards to abiotic stresses such as rising temperatures, extreme weather events, and water scarcity, which disrupt vine development and productivity. In this context, adopting effective management practices to ensure both high yields and quality while promoting environmental sustainability, is essential.

This study explored different short-term vineyard management practices aimed at mitigating the effects of climatic stresses on both productivity and grape quality. Additionally, it assessed the environmental impacts of these practices, examining the trade-offs between viticultural production and environmental sustainability.

The analysis revealed that ELR increased maximum temperatures at the bunch level but generally reduced minimum temperatures in warm and rainy years compared to the control. Physiologically, ELR had a significant effect on stomatal conductance (gs) during the critical bunch closure period. It also improved grape quality by increasing total soluble solids (TSS) and reducing pH, thereby enhancing grape composition. However, ELR led to yield reductions and shifted carbon storage towards vegetative parts, such as the shoots, rather than the berries.

In contrast, BF maintained lower temperatures, effectively mitigating water stress, and enhanced photosynthetic pigment accumulation, supporting the grapevine activity and yield production, particularly during hot and arid seasons. BF also promoted consistent carbon storage in the reproductive biomass, ensuring optimal yield without compromising the vine's carbon sink potential.

The Life Cycle Assessment (LCA) provided insights into the environmental impact of both practices. ELR resulted in higher CO_2 emissions due to intensive machinery use and lower yields, which increased emissions per unit of production. Conversely, BF maintained lower emissions by supporting constant yields and distributing emissions more efficiently. While ELR offered notable benefits for grape quality, BF emerged as the more sustainable option, highlighting a trade-off between environmental impact and quality enhancement.

These findings highlight the need for further research to refine and expand sustainable vineyard management practices. For example, the potential of basalt flour to replace traditional treatments like copper in organic farming systems as a protective measure against pests and diseases remains an underexplored area. Developing alternative solutions for plant protection that are both effective and environmentally friendly is crucial to reducing the reliance on copper-based applications.

Moreover, agronomic policies play a pivotal role in promoting the adoption of eco-friendly farming practices. Policies that reduce the costs of environmentally friendly techniques, like basalt flour, could encourage broader adoption and enhance sustainability across the viticultural sector. However, it is critical that these management decisions are contextualized, as their effectiveness depends on local conditions and seasonal variations. Flexible, adaptive management approaches tailored to specific contexts will be key to ensuring both immediate and long-term sustainability in viticulture.

Future studies should focus on expanding the understanding of basalt flour's applications, optimizing its use, and integrating it into holistic vineyard management frameworks. By aligning agronomic research with supportive policies, the viticultural sector can better navigate the challenges posed by climate change and drive meaningful progress toward sustainability.

5. SUPPLEMENTARY MATERIALS

5.1 Supplementary tables

Table 1S. *Chemical composition of basalt flour XF (More info at https://farinadibasalto.it/farina-di-basalto-tipo-xf-stimolante-fogliare/).*

Mineral elements	Medium content
Silicondioxide (SiO_2)	47%
Potassium oxide (K_2O)	9%
Ferric oxide (Fe_2O_3)	6.85%
Calcium oxide (CaO)	8%
Magnesium oxide (MgO)	2.25%
Sodium oxide (Na_2O)	3.55%
Phosphorus pentoxide (P_2O_5)	0.65%
Titanium dioxide (TiO_2)	0.60%
Manganese (Mn)	363 mg/Kg
Sulfur (S)	536 mg/Kg
Boron (B)	81 mg/Kg
Copper (Cu)	51 mg/Kg
Zinc (Zn)	68 mg/Kg

Table 2S. *Physical properties of the three soil profiles (P1 – foliar application of basalt flour; P2 – control; P3 – early leaf removal). The denominations of the soil horizons were determined according to the Soil Survey Staff (1999).*

Profile	P1			P2			P3	
Horizon denomination	Ap2	Abk	Bw	Ap2	Bk	BC	Ap2	Bk
Horizon depth (cm)	5-25	25-40	40-60	10-35	35-55	55-100	10-55	55-80
Sand [%]	28	28	24	32	37	24	31	40
Silt [%]	37	40	41	35	35	39	37	33
Clay [%]	35	32	35	33	28	37	32	27
Textural class*	CL	CL	CL	CL	CL	CL	CL	L

*CL=Clay-Loam; L=Loam

Table 3S. *Chemical properties of the three soil profiles (P1 – foliar application of basalt flour; P2 – control; P3 – early leaf removall). The denominations of the soil horizons were determined according to the Soil Survey Staff (1999).*

Profile	P1			P2			P3	
Horizon denomination	Ap2	Abk	Bw	Ap2	Bk	BC	Ap2	Bk
Horizontal depth (cm)	5-25	25-40	40-60	10-35	35-55	55-100	10-55	55-80
Limestone [%]	23.9	28.7	28.1	28.1	34.5	23.9	28.1	35.1
pH	8.2	8.3	8.4	8.4	8.4	8.5	8.4	8.4
CEC [meq/100 g]	28.64	23.05	26.04	24.19	20.35	28.48	21.54	20.29
Organic matter [%]	0.99	0.46	0.33	0.66	0.39	0.33	0.92	0.33

Table 4S. *Available water content (AWC), and air capacity (AC), bulk density in different soil horizons at varying depths for the three soil profiles (P1 – foliar application of basalt flour; P2 – control; P3 – early leaf removal). AWC and AC are expressed as percentages of total soil volume.*

Profile/Horizontal depth (cm)	AWC (%)	AC (%)	Bulk density ($g\cdot cm^{-3}$)
P1/25	18.43	9.1	1.59
P1/60	17.14	5.3	1.46
P2/50	18.51	6.94	1.55
P2/80	14.22	6.73	1.49
P3/40	16.8	6.9	1.5
P3/70	18.12	6.24	1.54

Table 5S. *Classification, composition, and dosages of farming aids used in the four investigated systems in the three reference years.*

ID TRETMENT	PRODUCT /A.I.	DOSAGE	INPUT	OUTPUT
Fertilizer (2021-2023)	NPK (12-8-16) compound	250 kg/ha	Production and consumption mix of 250 kg NPK fertilizer	45 kg of nitrogen, 20 kg of phosphorous, 40 kg of potassium
Fertilizer (2022)	NPK (14-7-17) compound	250 kg/ha	Production and consumption mix of 250 kg NPK fertilizer	
Sucjering	Carfentrazone-ethyl	3.5 kg/ha	Production and consumption mix of 3.5 kg of herbicide	0.21 kg of carfentrazone-ethyl
Treatment 1	Metiram	2 kg/ha	Production and consumption mix of 31 kg of fungicide and 1.5 kg of herbicide	3.15 kg of metiram, 0.1125 kg of cymoxanil, 0.286 kg of meptyldinocap, 0.7 kg of mandipropamid, 0.04 kg of fluxapyroxad, 0.04 kg of oxathiapiprolin, 1.2 kg of folpet, 0.04 kg of tetraconazole, 6.56 kg of sulfur, 0.06 kg of amisulbrom, 0.025 kg of cyflufenamid, 0.015 kg of emectin benzoate, 1.2 kg of copper sulfate
	Cymoxanil	250 g/ha		
	Meptyldinocap	400 ml/ha		
Treatment 2	Metiram	2.5 kg/ha		
	Meptyldinocap	400 ml/ha		
Treatment 3	Mandipramid	2.5 kg/ha		
	Fluxapyroxad	150 ml/ha		
Treatment 4	Oxathiapiprolin	200 ml/ha		
	Folpet	1.5 kg/ha		
	Tetraconazole	1.75 kg/ha		
Treatment 5	Oxathiapiprolin	200 ml/ha		
	Amisulbrom	3.75 ml/ha		
	Tetraconazole	1.75 kg/ha		
Treatment 6	Mandipramid	0.5 kg/ha		
	Cyflufenamid	0.5 l/ha		
	Emectin benzoate	1.5 kg/ha		
Treatment 7	Copper sulfate	2.5 l/ha		
	Sulfur	3 l/ha		
Treatment 8	Copper sulfate	1.5 l/ha	Production and consumption mix of 10.5 kg of fungicide	1.8 kg of copper sulfate, 1.2 kg of sulfur
	Sulfur	3 l/ha		
Treatment 9	Copper sulfate	3 l/ha		
	Sulfur	3 l/ha		
Treatment 10	Copper sulfate	1 l/ha	Production and consumption mix of 10 kg of fungicide	2.4 kg of copper sulfate, 1.2 kg of sulfur
	Sulfur	3 l/ha		
Treatment 11	Copper sulfate	3 l/ha		
	Sulfur	3 l/ha		
BF treatment	Basalt flour XF	400 l/ha (3% conc.)	Production and consumption mix of 12 kg of basalt rock flour	5.7 kg of silicon min., 2.6 kg of aluminium, 1.1 kg of potassium, 0.8 kg of iron, 1 k of calcium, 0.25 kg of magnesium, 0.4 kg of sodium, 0.15 kg of phosporous

Table 6S. *Carbon content (kg/ha) of dry mass of residues left on the ground after pruning, canopy management and leaf-removing practices in the four investigated systems in the three reference years.*

SYSTEM	YEAR	PRACTICE	ORGANIC CARBON RELASED (kg/ha)
C	2021	*Pruning*	941
		Tipping + topping	221
	2022	*Pruning*	959
		Tipping + topping	354
	2023	*Pruning*	1072
		Tipping + topping	596
ELR	2021	*Pruning*	1107
		Tipping + topping	271
		Leaf- removing	307
	2022	*Pruning*	1827
		Tipping + topping	630
		Leaf- removing	225
	2023	*Pruning*	2336
		Tipping + topping	1298
		Leaf- removing	396
BF	2021	*Pruning*	931
		Tipping + topping	225
	2022	*Pruning*	923
		Tipping + topping	299
	2023	*Pruning*	1168
		Tipping + topping	649

5.2 Supplementary figures

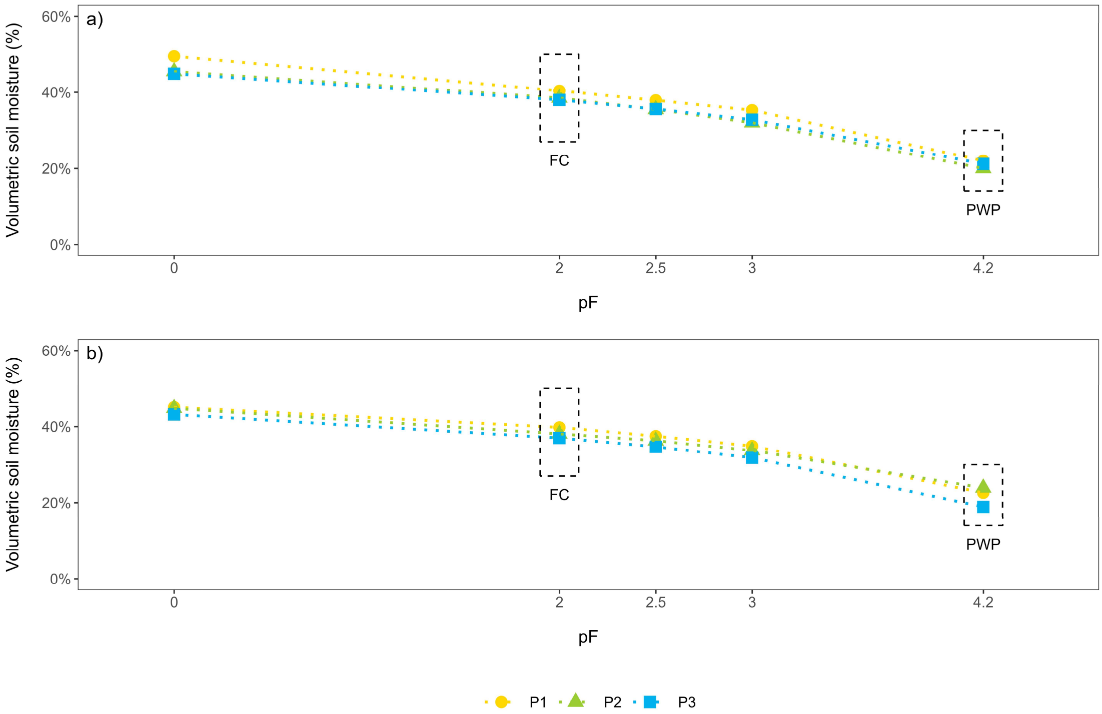

Figure 1S. *Water retention curves for the three pits (P1 – foliar application of basalt flour; P2 – control; P3 – early leaf removal) and for the upper (a) and deepest (b) horizons. The FC (field capacity) and PWP (permanent wilting point) are shown at their respective matrix potential points.*

Figure 2S. *Minimum temperature in canopy (CH) and bunch zone (BH) treated by different management practices: (control – C; foliar application of basalt flour – BF; early leaf removal - ELR). In the graphs is also shown the precipitations occurred during the berry development in the seasons 2021 and 2022 (DOY – day of year).*

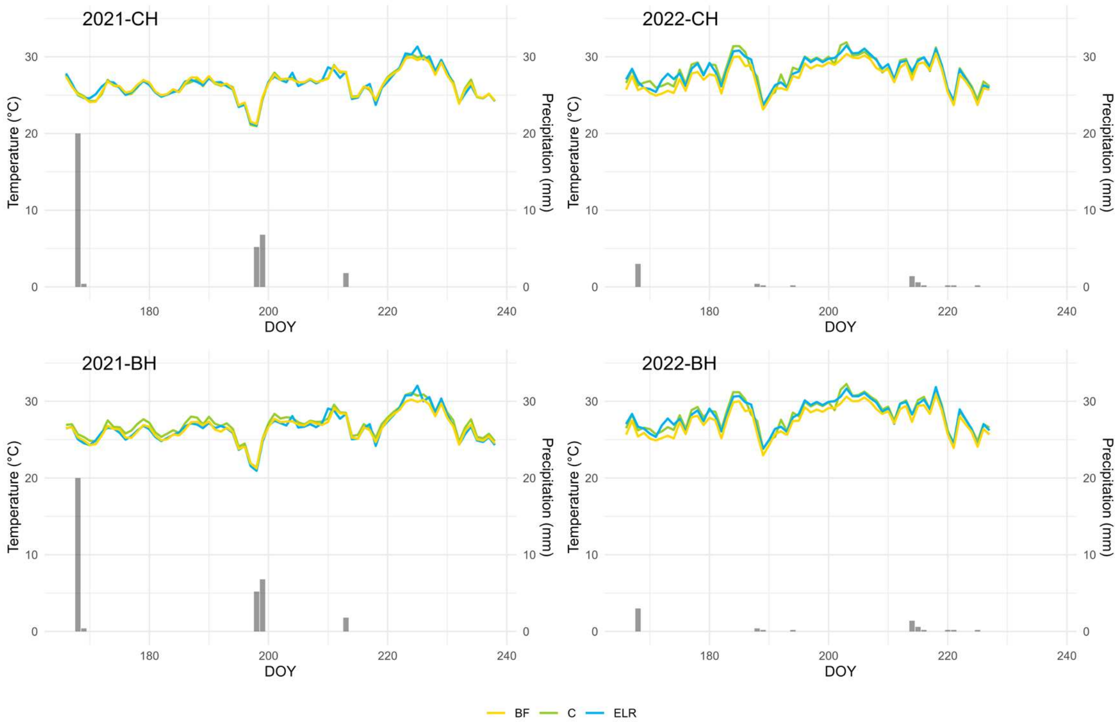

Figure 3S. *Average temperature in canopy (CH) and bunch zone (BH) treated by different management practices: (control – C; foliar application of basalt flour – BF; early leaf removal - ELR). In the graphs is also shown the precipitations occurred during the berry development in the seasons 2021 and 2022 (DOY – day of year).*

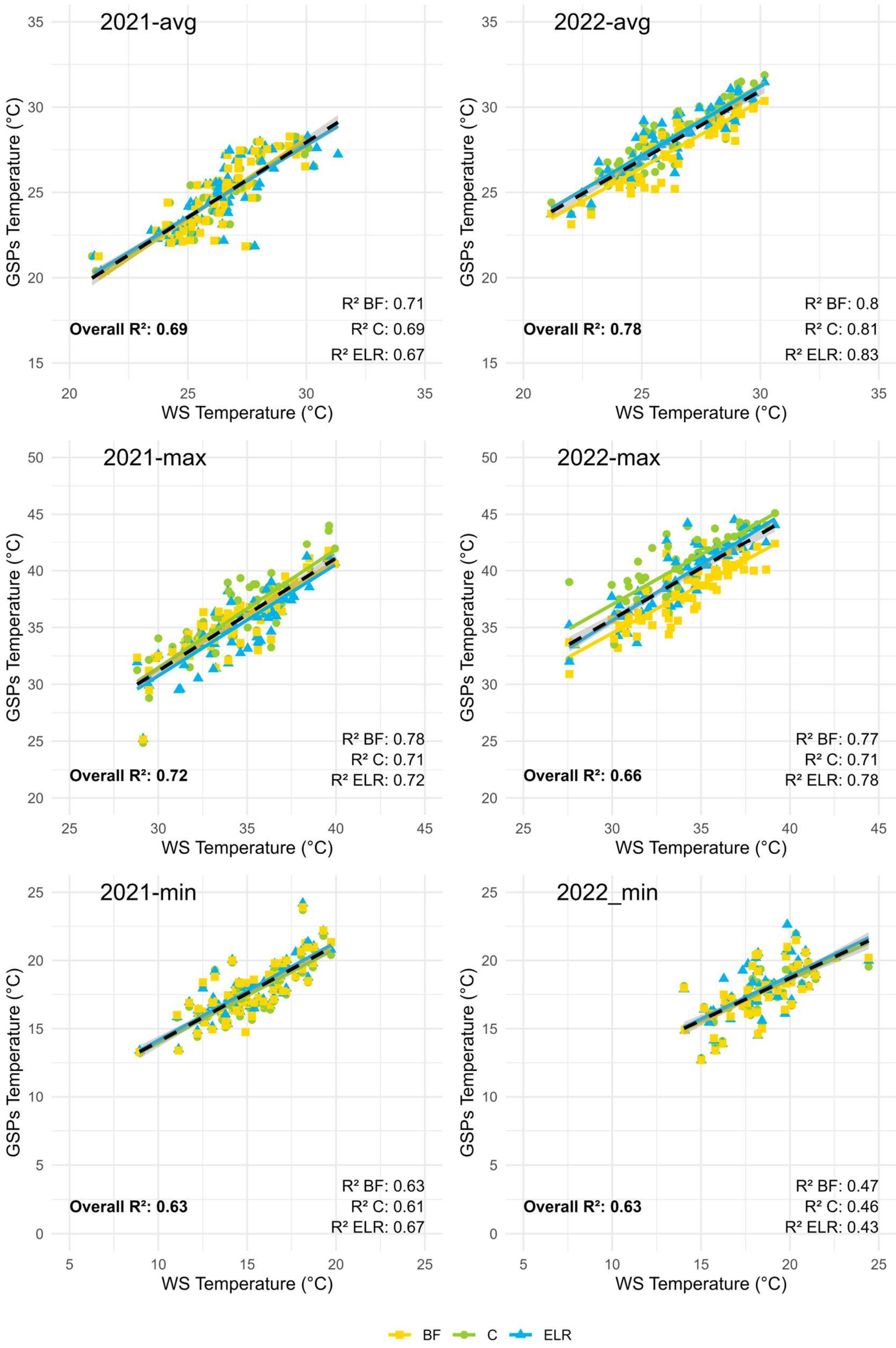

Figure 4S. *Linear regression between average (avg), maximum (max), and minimum (min) daily temperature of the weather station (WS) and the air temperature at 150 cm (CH) of the ground sensor platforms (GSPs) of the three management practices (non-defoliated and not treated with basalt flour – C; foliar application of basalt flour – BF; early leaf removal – ELR).*

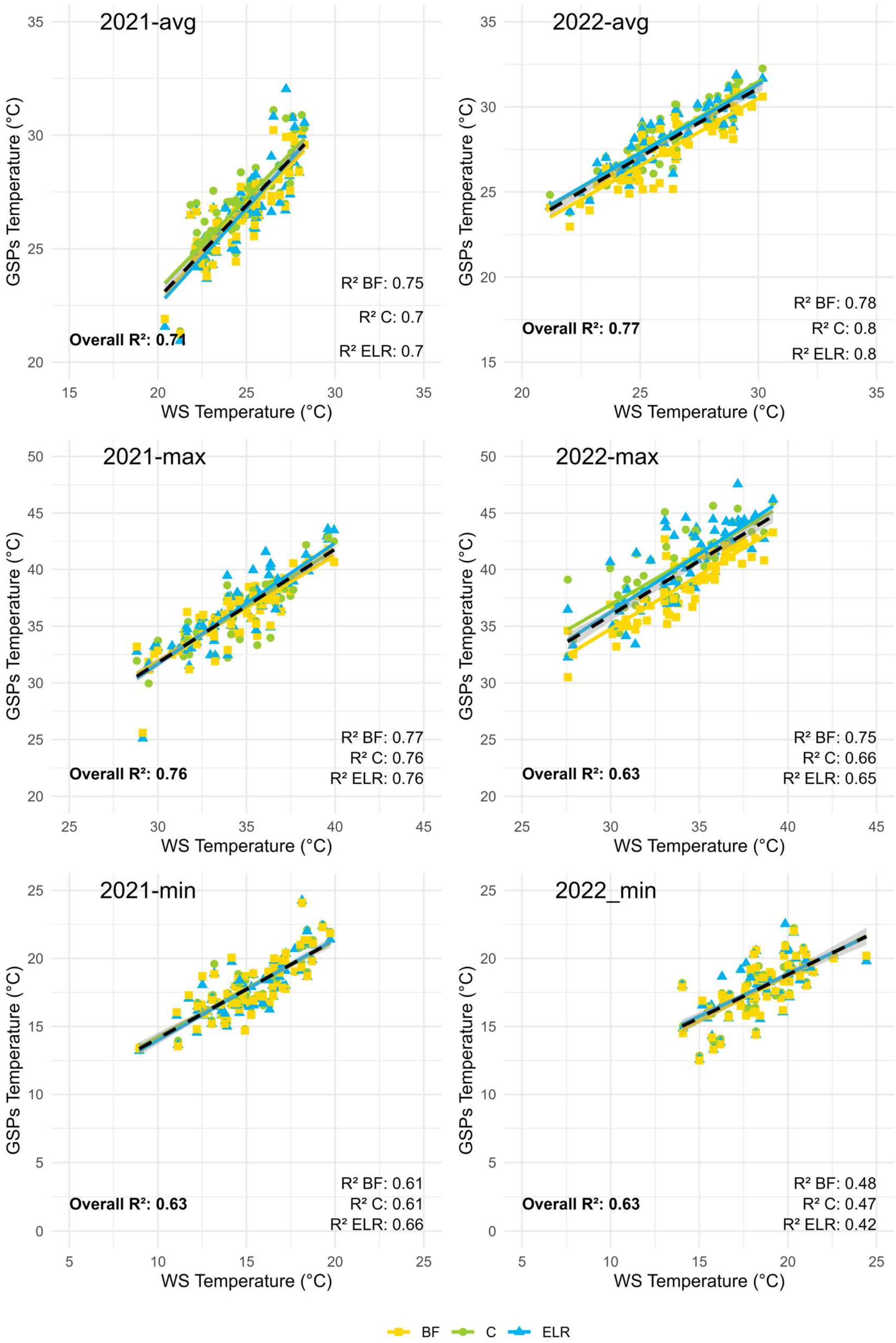

Figure 5S. *Linear regression between average (avg), maximum (max), and minimum (min) daily temperature of the weather station (WS) and the air temperature at 100 cm (BH) of the ground sensor platforms (GSPs) of the three management practices (non-defoliated and not treated with basalt flour – C; foliar application of basalt flour – BF; early leaf removal – ELR).*

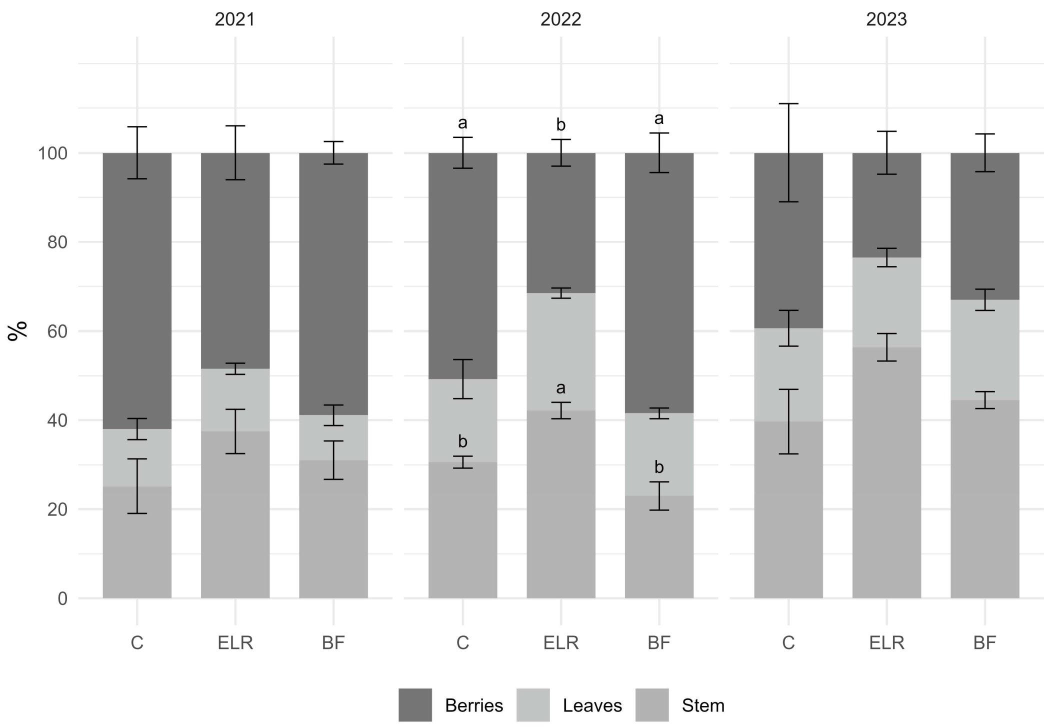

Figure 6S. *Partitioning between annual above-ground biomass (berries, stem, and leaves) of the three management management practices (control – C; foliar application of basalt flour – BF; early leaf removal – ELR) in the three years of study (2021-2023).*

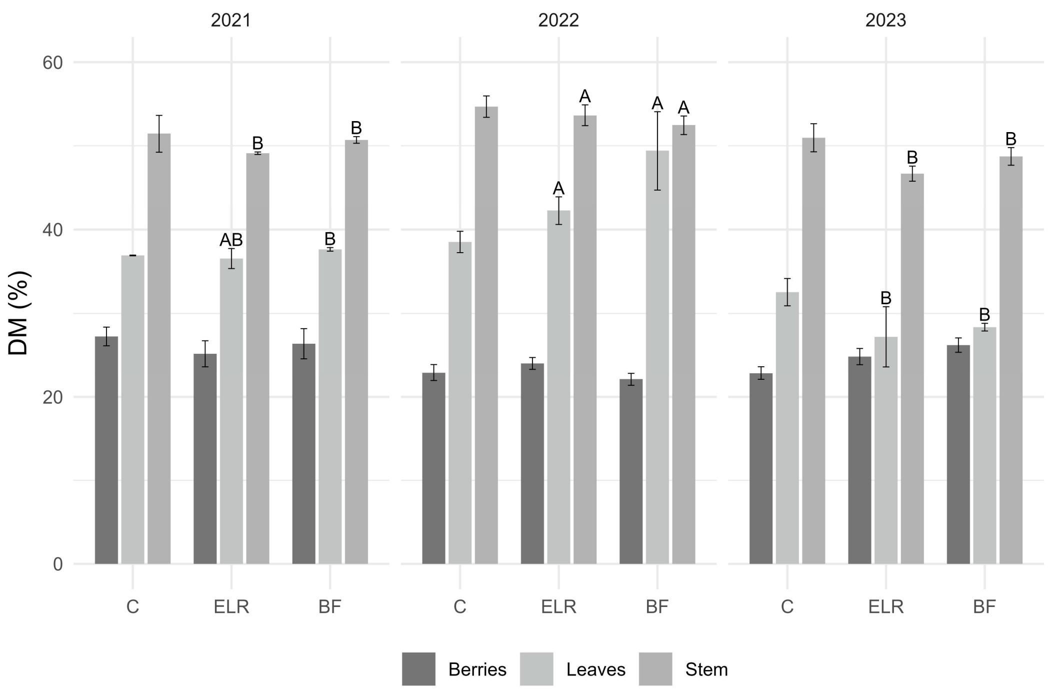

Figure 7S. *Mean dry matter content (± standard error) of berries leaves, and stems each management practices (control – C; foliar application of basalt flour – BF; early leaf removal – ELR) in each year. Capitol letters denote significant differences (p < 0.05) between the years of the same strategy. The absence of the letters denotes the absence of significant differences (between treatments or years).*

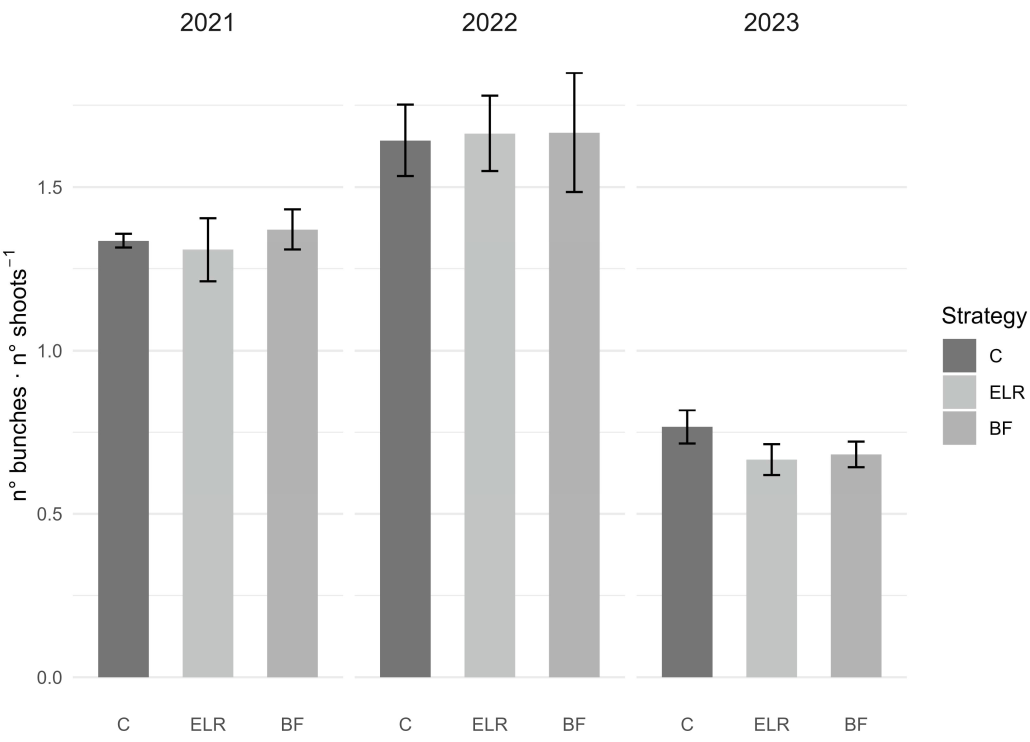

Figure 8S. *Real fertility for the three management practices (control – C; foliar application of basalt flour – BF; early leaf removal – ELR) in the three years. The absence of letters of significance denotes the lack of it (p > 0.05).*

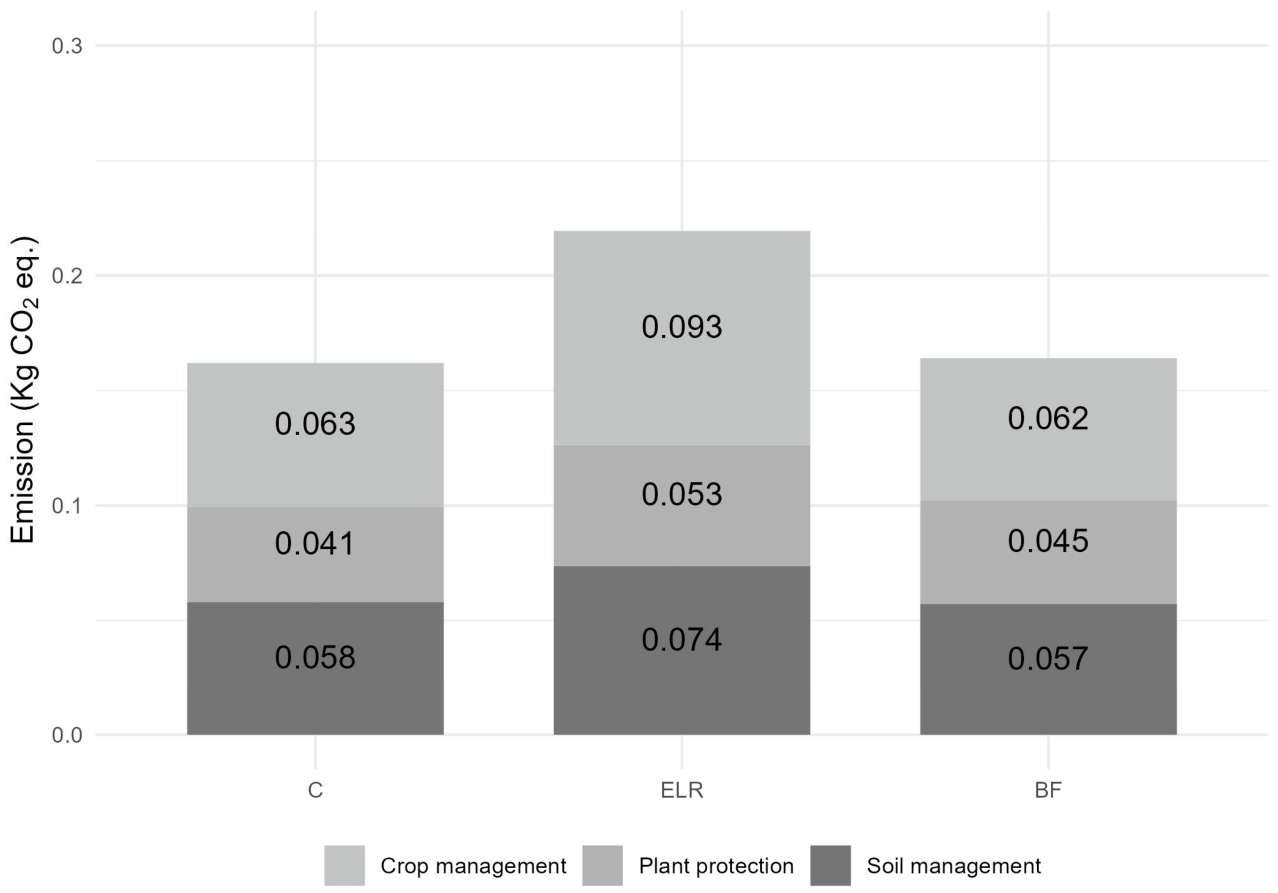

Figure 9S. *Emission (Kg of CO_2 eq.) to produce 1 Kg of grapes in the three systems (control – C; early leaf removal – ELR; foliar application of basalt flour – BF) reported on the cumulative impact of the three years.*

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