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Agronomical management of detention basin

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Abstract. The importance of effective stormwater management through detention basin arrangement has become increasingly evident due to recurring extreme events in recent years. Limitations of the traditional detention basin include a reduced ability of basins to infiltrate water due to compacted soil and the carbon cost associated with the Diesel-powered tractors with lawn shredders. This study aims to compare six different agronomical management approaches for detention basins to improve the water storage capacity and the carbon sequestration potential, including the cultivation of crimson clover, white clover, tillage radish, and two mono-dicotyledonous mixes, against the conventional stable lawn-based approach. The trial was conducted in the detention basin in Castelletti (Firenze, Italy) for one growing season (2020/2021) according to a randomized complete block design with 9 replicates. Soil physical and chemical properties, as well as soil water storage capacity, were assessed to determine the feasibility of agronomical management for detention basins. Results indicated that the different treatments significantly influenced aboveground biomass production, soil organic carbon (SOC) stock, carbon sequestration potential, and water storage capacity. Specifically, crimson clover exhibited the highest aboveground biomass of around 6 t ha^{-1} among the treatments, while tillage radish demonstrated the greatest carbon sequestration potential (4.58 t CO_2 ha^{-1}), stable carbon stock in soil (1.14 t S-SOC ha^{-1}), as well as the highest potential for improving the water storage volume (389 m^3 ha^{-1}) in the topsoil (0-20 cm) of the detention basin. The findings suggested also that the sowing of different mono-dicotyledonous plant mix were poorly effective in improving carbon sequestration potential and water storage volume compared to conventional basin management. To sum up, this experiment has demonstrated that alternative agronomical management practices can enhance the capacity of detention basins to store carbon and stormwater. These results provide valuable insights for improving the sustainability and functionality of detention basins.

Keywords: carbon sequestration potential, stable soil organic carbon, soil water storage, detention basin, drainable porosity.

INTRODUCTION

The recurring extreme events of the last years have highlighted the importance of appropriate stormwater management. Excessive stormwater usually poses problems for rural communities and their livelihoods. The rate of soil impermeabilization, as well as the loss in water storage capacity of agricultural soils, have dramatically soared the water stream flow, determining the increase in soil erosion (Adobati and Garda, 2020). Management plans have been formulated by the European Environment Agency (EEA) to keep the water cycle as sustainable as possible (EEA, 2016). Different strategies accounted for in the best management practices (BPM), have been developed to reduce flooding risk, improve water quality, and recharge groundwater, such as the construction of swales, infiltration basins, retention basins, and detention basins (Davis et al., 2017; Lam et al., 2011). Those basins had been commonly known since ancient times, but with the increase in flooding events, their construction has recently gained attention. Although those ponds' general aim is to reduce stormwater peak flow of torrents and rivers, some distinctions have to be made.

Swales are ditches designed to collect, store, and reduce water runoff both in urban and rural environments, while improving the rate of stormwater that flows toward the groundwater (Sañudo-Fontaneda et al., 2020). Infiltration basins are ponds whose primary function is to improve the amount of water that infiltrates into the soil, hence their design has to facilitate the water flow from the ground surface to the groundwater (Di Lena et al., 2023). Retention basins are the most commonly designed structures for the mitigation of flooding events involving a permanent pool made with landscaped banks and surroundings (Acheampong et al., 2023). Detention basins are designed to temporarily store stormwater, but most of the time of the year they are free from water (Sharior et al., 2019), therefore this lead to their putative use for agricultural purposes outside the rainy season.

Generally, detention basins allow the handling of a higher water volume than that of the usual riverbed; when the river flow is lowered, the basin-stocked water flows back to the river (Emerson et al., 2005). They could be used for managing and treating surface water runoff from impermeable surfaces such as roads (Griffiths, 2017). The conventional management of (dry) detention ponds consists of a soil bed where native plant species capable of tolerating periodic inundation are left to grow up and periodically mowed (Emmerling-DiNovo, 1995). Limitations of the traditional detention basin include a reduced ability of basins to infiltrate water due to compacted soil. One cause of this is that the soil at the bottom of these basins may become overly compacted during construction. Further, these basins are typically planted with turf grass that is shredded and mowed regularly 1-2 times a year to control the growth of aboveground biomass and the formation of shrubs. However, tractor traffic on lawns can have a significant impact on reducing the maximum root number and air-filled porosity in the upper 5 cm of soil, thereby decreasing the soil infiltration rate (Sveistrup and Haraldsen, 1997). Thus, a significant volume of water passes through these basins without the opportunity to infiltrate into the basin soil. Infiltration of precipitation and runoff water is an important green infrastructure goal, since infiltration recharges groundwater, decreases total runoff, and helps remove pollutants from the runoff water. Further, while lawns can function as "carbon sinks," their benefit is often outweighed by the carbon cost associated with their maintenance, specifically Diesel-powered tractors with lawn shredders.

The soil properties of detention basins can be improved by adopting alternative agronomical management while providing environmental and ecosystem services. For example, lawn management can be substituted by the cultivation of a specific crop that might enhance the soil water storing capacity. In this context, the soil in detention basins can be periodically tilled using a chisel plough and harrow to facilitate water accumulation but also to avoid the excessive soil compaction, that compromises detention basin functionality. In addition, the putative crop should produce both high aboveground and root biomass to increase carbon sequestration; previous properties could be satisfied with the sowing of different clover species, which usually occur in frequently flooded habitats (Huber et al., 2009).

However, few studies have been realized on the effect of tillage management on the soil properties of detention basins. Moreover, during the water storage, detention basins represent also a humid area, where some ecosystem functions could be achieved, such as wastewater treatment and the creation of wildlife habitats (Sharma et al., 2023).

The agronomical management of a detention basin could take into account that it is a periodically flooded soil; hence, some soil properties alterations should be observed. According to Schroer et al., (2018), the sediments transported by the water flow toward the detention basins are capable of increasing the carbon, nitrogen, and phosphorus concentration in soil. Accordingly, the basin could also support plant growth and reduce the carbon concentration in the atmosphere. In terms of nutrient load, the analyses of the water inflow revealed a significant amount of phosphorus and nitrogen that could be useful for plant growth (Wissler et al., 2020). In the same study, it was demonstrated that unmaintained detention basins were able to sequester higher amounts of carbon concerning maintained ones over 20 years; however, the maintenance they considered was only the turf grass mowing. Other authors reported an increase in soil particulate organic carbon (POM-C) concentration in a detention basin as a consequence of runoff water flow (Stanley, 1996). On the other hand, no significant changes in organic matter (OM), carbon, and nitrogen concentration were observed in turf-grassed detention basins for the 0-5 and 15-20 soil layers (McPhillips et al., 2018).

Consequently, this work aimed to compare six different management of the detention basin to improve its capacity to stock carbon and store stormwater. Specifically, the sowing of different species of clover, the sowing of tillage radish, and the sowing of two crop mixes made of graminaceous and leguminous plants termed Fascia Tampone and Rustico Dicotiledoni were compared to the conventional management of the detention basin, consisting in the growth of a stable lawn, which is periodically mowed. Some soil physical and chemical properties and soil water properties were measured for the different treatments to assess the feasible agronomical management of the detention basins, which are commonly considered marginal areas.

MATERIALS AND METHODS

Experimental setup

The trial was carried out at the detention basin of Castelletti (Signa, Florence, Italy, 43° 47' 49" N, 11° 4' 51" E) that are managed by the local land requirement consortium (Consorzio di Bonifica 3 Medio Valdarno; CB3MV) , from October 2020 to September 2021. The test site consisted of a surface of 4.2 ha that was subdivided into 15 adjacent watersheds around 2500 m^2 in size. The area was recovered with some projects that aim to restore traditional lowland agricultural hydraulic arrangement patterns and establish areas to promote biodiversity. The experimental design was a randomized completely block design, consisting of 15 blocks identified with the different treatments (3 blocks for treatment); for each block, 3 replicates were considered, hence a total of 9 replicates for treatment were obtained. According to the initial characterization, the soil was silt loam textured as the percentage of sand, silt, and clay were 21.7%, 53.8%, and 24.2%, respectively. The soil pH of the detention basin was neutral (7.19) with an average bulk density of 1.45 t m^{-3}.

Before the arrangement of the trial, the detention basin was managed with a stable lawn, and the soil was periodically tilled with a plough and harrow; before the sowing of different plants, the soil of the detention basin was ploughed and harrowed using moldboard plough and disk harrow, respectively. Six different management of the detention basin were compared: the stable lawn (SL) was considered the control as it was the conventional management before the arrangement of the trial; crimson clover (CC; *Trifolium incarnatum* L.); white clover (WC; *Trifolium repens* L.); tillage radish (TR; *Raphanus sativus* L. var. Longipinnatus); a mono-dicotyledonous mix called OP-Rustico dicotiledoni (RD), a mono-dicotyledonous mix called OP-Fascia tampone (FT). The species description for each treatment is reported in Table 1. No fertilizers and pesticides were applied over the entire field. CC, FT, RD, TR, and WC were sowed at a seeding rate of 25, 35, 55, 18, and 25 kg seeds ha^{-1}, respectively. The TR root system is mainly composed of a taproot with only some fibrous lateral roots. RC and WC have both fibrous lateral roots and a taproot. SL is mainly composed of graminaceous species with fibrous roots, while FT and RD are mixtures comprising both graminaceous species with fibrous roots and leguminous species with both fibrous lateral roots and a taproot. The biomass collection for each treatment was carried out on May 21'. A sampler of 25 cm*25 cm was used to collect the aboveground biomass of the different treatments. The dry weight of the plant biomass was measured after oven drying at 70°C, until reaching constant weight.

Fuel consumption for the different management

The data of diesel fuel consumption (L ha^{-1}) for the specific agricultural operations were provided by CB3MV. The main fuel-consuming activity was ploughing at 30 cm depth because of the high energy requirement for moving a huge amount of soil (Table 2). Also, the preparation of the seedbed for the cultivation of CC, WC, FT, and RD represented a highly energy-consuming activity. The following activity that requires high-energy consumption was the soil disk harrowing, which was null for the conventional management of the detention basin. As regards the management of the aboveground biomass, all the treatments required two grass shredding per year, except the TR which requires only one per year.

Soil sampling and analyses

The collection of soil samples was carried out according to the core sampling method; specifically, three samples for the plot were collected and mixed for 3 different soil depths (0-5, 5-10, 10-20 cm) both as disturbed and undisturbed samples. Disturbed samples were collected to determine some soil chemical properties, while soil

Table 1. Description of the species for the different treatments (SL: stable lawn; CC: crimson clover; WC: white clover; TR: tillage radish, FT: OP-Fascia tampone; and RD: OP-Rustico dicotiledoni).

Herbaceous species in the different treatments					
SL	CC	WC	TR	FT	RD
Bellis perennis L.	*Trifolium incarnatum* L.	*Trifolium repens* L.	*Raphanus sativus* Var.Longpinnatus L.H.Bailey	*Achillea millefolium* L.	*Achillea millefolium* L.
Bromus hordeaceus L.				*Dactylis glomerata* L.	*Leucanthemum vulgare* Lam.
Cynodon dactylon L.				*Festuca rubra* L.	*Lotus corniculatus* L.
Lolium perenne L.				*Lolium arundinaceum* L.	*Medicago sativa* L.
Holcus lanatus L.				*Lolium perenne* L.	*Onobrychis viciifolia* Scop.
Hordeum murinum L.				*Lotus corniculatus* L.	*Phacelia tanacetifolia* Benth.
Plantago Media L.				*Onobrychis viciifolia* Scop.	*Plantago lanceolata* L.
Cichorium intybus L.				*Phacelia tanacetifolia* Benth.	*Salvia pratensis* L.
				Poa pratensis L.	*Silene vulgaris* Moench.
				Trifolium pratense L.	*Trifolium pratense* L.
				Trifolium repens L.	*Trifolium repens* L.

Table 2. Diesel fuel consumption (L ha^{-1}) of the different management of detention basin (SL: stable lawn; CC: crimson clover; WC: white clover; TR: tillage radish, FT: OP-Fascia tampone; and RD: OP-Rustico dicotiledoni) for the different agronomical practices (ploughing, disk harrowing, sowing, first and second shredding operations).

	Diesel fuel consumption per treatment (L ha^{-1})					
	SL	CC	WC	TR	FT	RD
Ploughing (30 cm)		60	60		60	60
Disk Harrowing		33	33	33	33	33
Sowing		6	6	6	6	6
Shredding 1^{st} time	25	25	25	25	25	25
Shredding 2^{nd} time	25	25	25		25	25
Total fuel consumption	50	149	149	64	149	149

physical properties were measured on undisturbed samples. The first soil sampling was carried out in August 2020 for the initial characterization of the soil, and after the soil tillage, the second sampling was performed (October '20); in September '21 after the first growing season, the subsequent soil samples were collected.

The collected samples were air-dried and filtered by a 2-mm sieve. Soil Organic Carbon (SOC; g C kg^{-1}) was measured on disturbed soil samples using the CHNS elemental analyzer (Thermo Fisher Scientific, Waltham, MA, USA). Starting from the SOC it is possible to determine the amount of stable organic C by subtracting the Labile organic C from the SOC; labile organic C is obtained through the addition of particulate-organic carbon (POM-C; g C kg^{-1}) and Permanganate-Oxidable Carbon (POX-C; g C kg^{-1}). The determination of both POM-C and POX-C in soil was assessed through the methods proposed by Cambardella and Elliott, (1992) and Blair et al., (1995). Briefly, POM-C was measured by dissolving 10 g of soil into 30 mL of sodium hexametaphosphate (5 g L^{-1}). The dispersion was left for 15 h on a reciprocal shaker; then the dispersion was filtered through a 53-μm sieve. After various water rinsing, it was dried overnight at 50°C. The resulting dried sample was ground using a mortar and pestle and then subjected to the CHNS elemental analyzer. Regarding POX-C, a solution of $KMnO_4$ (52.625 g L^{-1}) was used for the oxidation of the soil sample. The soil containing 15 mg of SOC was dissolved in 25 mL of the $KMnO_4$ solution and left shaking for 1 h. Afterward, the tubes were centrifugated at 3500 rpm for 5 minutes and the resulting supernatants were diluted to 1:500. The absorbance of the sample was measured at 565 nm using a spectrophotometer. The bulk density (BD; t m^{-3}) of the detention basin for the different treatments was measured on undisturbed soil samples using cylinders of known volume. The SOC stock, the POM-C stock, and the POX-C stock of the 20 cm layer for the different treatments were calculated according to the following formulas:

$$SOC_{Stock} = \frac{(SOC_{Sept'21} * BD * 0.2) - (SOC_{Oct'20} * BD * 0.2)}{100000} \quad (1)$$

$$POM\text{-}C_{Stock} = \frac{(POM-C_{Sept'21} * BD * 0.2) - (POM-C_{Oct'20} * BD * 0.2)}{100000} \quad (2)$$

$$POX\text{-}C_{Stock} = \frac{(POX-C_{Sept'21} * BD * 0.2) - (POX-C_{Oct'20} * BD * 0.2)}{100000} \quad (3)$$

Where $SOC_{Sept'21}$ is the amount of organic C measured in September '21, is the bulk density measured in October '20, $SOC_{Oct'20}$ is the amount of organic C measured in October '20, $POM\text{-}C_{Septs'21}$ is the POM-C measured in September '21, $POM\text{-}C_{Oct'20}$ is the POM-C measured in October '20, $POX\text{-}C_{Septs'21}$ is the POX-C measured in September '21, $POX\text{-}C_{Oct'20}$ is the POX-C measured in October '20 and is the bulk density measured in October '20. The previous parameters were used to calculate the stable SOC stock (S-SOC; t ha^{-1}) as follows:

$$S\text{-}SOC_{stock} = SOC_{stock} - (POM\text{-}C_{stock} + POX\text{-}C_{stock}) \quad (4)$$

The calculation of the drainable porosity (%) for the determination of the water storage volume (WSV; m^3 ha^{-1}) for the different treatments was assessed through the soil water retention curve. Specifically, the water percentage at field capacity was measured through the water retention curve using Richard's plate apparatus (Richards and Fireman, 1943). The estimation of the total porosity was calculated as follows:

$$\text{Total porosity [\%]} = \left[1 - \left(\frac{BD[t\ ha^{-1}]}{2.65\ [t\ ha^{-1}]}\right)\right] * 100 \quad (5)$$

Where BD is the bulk density measured, and 2.65 is the estimated real density. Accordingly, the drainable porosity was calculated as the difference between the total soil porosity and the water percentage in the soil at field capacity. Lastly, the WSV was calculated as the amount of drainable porosity in the topsoil (20 cm).

Statistical analysis

The comparison among the means of different treatments for each variable was assessed according to the one-way ANOVA. The parameters which resulted significantly were compared through a post-hoc Tukey's Test.

RESULTS AND DISCUSSION

Weather description

The climate of the area is Mediterranean with an average annual rainfall and a mean annual temperature of 872 mm and 15.25°C, respectively (Figure 1). No significant differences were observed in the annual rainfall amount between the long-term average (2001-2020) and the 2020/2021 growing season. However, by comparing the monthly data, it was observed that rainfall that occurred during the 2020/2021 growing season exceeded the long-term average in October, December, and January, leading to the flooding of the detention basin for 4 days in December and January. On the other hand, the area experienced a low rainfall amount concerning the long-term average in November 2020 and March 2021. The temperature pattern of the 2020/2021 growing season was quite similar to the long-term trend of temperature, except for the spring months when the average monthly temperature of the 2020/2021 growing season was lower than those reported for the long-term.

Aboveground Biomass yield

The different treatments significantly affected the amount of aboveground biomass (AG-y) produced over the detention basin (Figure 2). The AG-y produced by the different treatments ranged between 2.71 and 6.04 t ha^{-1} of DW. Specifically, CC highlighted the best performance, accounting for 6.04 t ha^{-1} of AG-y. Indeed, Knight, (1985) reported that CC can successfully and

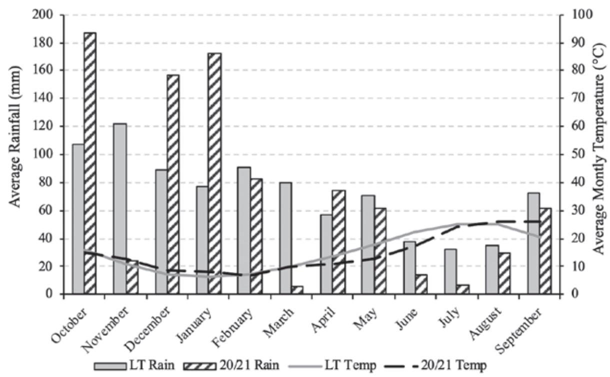

Figure 1. Walter-Lieth diagram of the climatic conditions at Castelletti, Florence, Italy. Grey and striped histograms indicate the rainfall amount of the long-term (2001-2020) and 2020/2021 growing season, respectively; gray and dashed lines show the temperature trend of the Long-Term and 2020/2021 growing season, respectively.

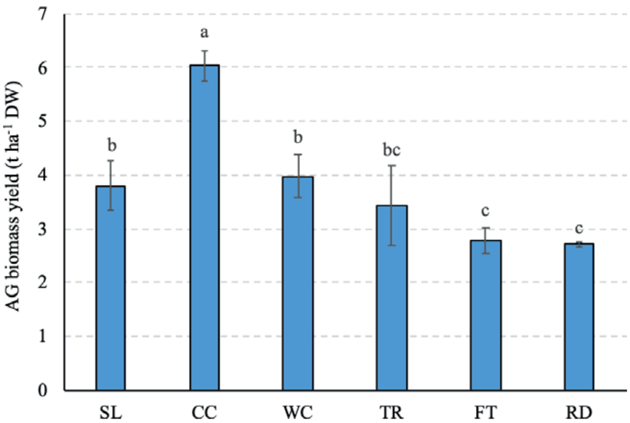

Figure 2. Aboveground biomass yield (AG-y; t ha^{-1} Dry weight) for the different management of detention basin (SL: stable lawn; CC: crimson clover; WC: white clover; TR: tillage radish, FT: OP-Fascia tampone; and RD: OP-Rustico dicotiledoni). Error bars represent the standard deviation (n=9). The letters indicate significant differences between the treatments according to the post-hoc Tukey's test.

rapidly grow in a wide range of climatic and soil conditions. The observed yield of CC was similar to that reported in SARE Outreach, (2007), indicating that crimson clover can reach 7 t ha^{-1} DW in good growing conditions. The AG-y of WC was significantly lower than that of CC, resulting in 34.2% lighter than WC; in fact, WC AG-y was more negatively affected by soil flooding than CC was. The WC susceptibility to flooding was also been described by Huber et al., (2009). The AG-y in SL was significantly lower than that measured in WC but not significantly different from CC and TR. The AG-y in SL, mainly composed of graminaceous plants including common ryegrass, was consistent with the average annual AG-y value of approximately 5 t ha^{-1} reported by several authors for common ryegrass (Vinther, 2006). The AG-y value measured in TR was 3.43 t ha^{-1} and was consistent with that reported by Cottney et al., (2022) for the tillage radish sowed in September. The aboveground biomass of the two herbaceous mixes, FT and RD, were significantly lower compared to the other treatments.

Carbon Stocking capacity

After 1 year, the SOC stock ranged between -0.08 t ha^{-1} in FT to 1.25 t ha^{-1} in TR (Table 2). The TR treatment produce the highest significant increase in SOCstock, followed by CC and WC. The SOCstock variation in SL was not significant, and a not significant negative variation was observed in FT and RD. The labile C stock ranged between -0.08 t ha^{-1} in FT to 0.12 t ha^{-1} in WC. However, no significant differences in labile C stock

Table 3. Changes in SOC stock, Labile C stock, and Stable C stock (S-SOC) for the different treatments (SL: stable lawn; CC: crimson clover; WC: white clover; TR: tillage radish, FT: OP-Fascia tampone; and RD: OP-Rustico dicotiledoni). Standard deviation values are reported in brackets (n=9). The letters indicate significant differences among the treatments according to Tukey's test (p<0.05).

Treatments	SOC stock t ha^{-1}	Labile C stock t ha^{-1}	S-SOC stock t ha^{-1}
SL	0.08 (0.18) c	0.07 (0.1)	0.01 (0.13) d
CC	0.59 (0.12) b	0.05 (0.12)	0.54 (0.14) b
WC	0.47 (0.04) b	0.12 (0.06)	0.35 (0.08) c
TR	1.25 (0.56) a	0.11 (0.26)	1.14 (0.21) a
FT	-0.08 (0.03) c	-0.08 (0.1)	0 (0.09) d
RD	-0.01 (0.02) c	0.04 (0.07)	-0.05 (0.08) d

were detected between the six treatments. The S-SOC stock ranged between -0.05 t ha^{-1} in FT to 1.14 t ha^{-1} in TR. The TR treatment produce the highest significant increase in S-SOC stock, followed in decreasing order by CC and then WC. Further, the S-SOC stock variation in SL, FT, and RD was not significant. These values are consistent with Franzluebbers et al., (2012) who observed that after the conversion of an arable cropping system into perennial grassland the rate of C accumulation down to a depth of 20 cm has an initial value of 0.8 t ha^{-1} y^{-1}. Probably for mixes containing grasses as in FT and RD, the time required to recover the oxidized carbon through soil tillage is longer than a single year of cultivation. As reported by Li et al., (2020) and Liu et al., (2015) the tap-root system may have a higher impact on increasing SOCstock in soil than the fibrous roots. Therefore, the differences between the treatments can be attributable to the different root systems of the plant species in the six treatments.

Carbon sequestration

The annual amount of fixed CO_2 ranged between -0.29 and 4.58 t ha^{-1}, respectively in FT and TR, when considering the whole SOC_{stock} (Figure 3). According to our results, TR was the best treatment in terms of annual carbon sequestration potential, resulting in significantly higher carbon sequestration of 53.65% and 62.43% concerning CC and WC, respectively. The annual carbon sequestration rate SL (0.30 t CO_2 $ha^{-1}y^{-1}$) was significantly lower than that calculated for CC and WC. Lastly, negative values of carbon sequestration were calculated for RD and FT, indicating that the carbon that was released into the atmosphere by these treatments was higher than that incorporated in the soil. Specifical-

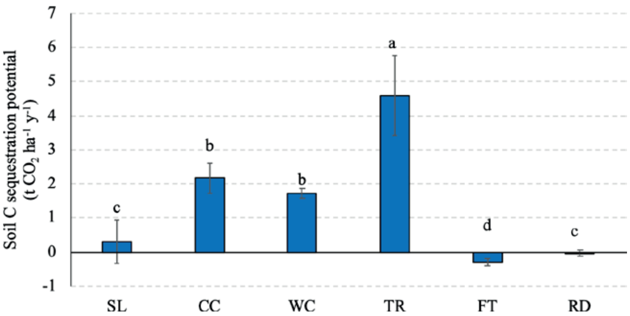

Figure 3. Annual Carbon sequestration rate (t CO_2 $ha^{-1}y^{-1}$) for the different management of detention basin (SL: stable lawn; CC: crimson clover; WC: white clover; TR: tillage radish, FT: OP-Fascia tampone; and RD: OP-Rustico dicotiledoni). Error bars represent the standard deviation (n=9). The letters indicate significant differences between the treatments according to Tukey's test (p<0.05).

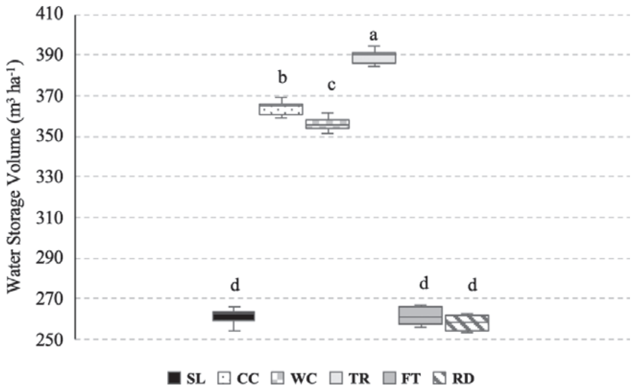

Figure 4. Soil Water Storage Volume (m^3 ha^{-1}) for the different management of detention basin (SL: stable lawn; CC: crimson clover; WC: white clover; TR: tillage radish, FT: OP-Fascia tampone; and RD: OP-Rustico dicotiledoni). The letters indicate significant differences between the treatments according to Tukey's test (p<0.05).

ly, FT showed a significantly lower carbon sequestration potential than RD. The amount of annual CO_2 sequestered by SL was in agreement with that reported by Yang et al. (2019) for topsoil (20 cm) with 8 species making up the grassland system. However, the potential carbon sequestration of the same author for a single species system was lower than we have observed. On the other hand, our results were not consistent with the estimation of carbon balance for Western Europe by Dondini et al. (2023) for an unimproved grassland system of about 4.40 t CO_2 ha^{-1} y^{-1}. However, the value of carbon balance these authors estimated for unimproved grassland was quite similar to the value of the carbon sequestration potential of TR.

Water Storage Volume

The correct management of the detention basin was also assessed through the calculation of its capacity to store water (Figure 4). Our results highlighted significant differences in the WSV among the different treatments, ranging from 258 to 389 m^3 ha^{-1} for RD and TR, respectively. In particular, the highest WSV value was detected in TR, which was significantly higher than CC and WC by 6% and 8% respectively; the average WSV value of CC (364 m^3 ha^{-1}) was significantly higher than that of WC (356 m^3 ha^{-1}). Lastly, the lowest average WSV values were detected in RD, which were not significantly different from that detected in SL and RT, indicating that the behavior of FT and RD in determining the WSV was very similar to that of SL. The WSV values of the latter were quite similar to those reported by Zhu et al. (2022) for the topsoil (20 cm) of mountain grassland. Similarly, the WSV values observed by Otremba et al., (2021) were around 280 m^3 ha^{-1} considering the 0-35 soil layer after one year of alfalfa and orchard grass cultivation. On the other hand, similar results for clover WSV values were obtained by Fang et al., (2023). The good performance in terms of WSV obtained by TR could be determined by the wide holes that taproot leaves in the soil (White and Weil, 2011).

CONCLUSIONS

The different plants in the agronomic treatments were rapidly adapted to the detention basin conditions, especially the crimson clover that produced the highest aboveground biomass yield. Regarding the increase of soil organic carbon, the best performance was obtained by the tillage radish, which could represent a good strategy for increasing soil stable organic carbon. Likewise, tillage radish was also enormously effective in increasing the water storage capacity of the detention basin, followed by the crimson clover and white clover. In summary, the results emphasize the importance of plant selection for the effective management of detention basins. Crimson clover and tillage radish emerged as promising options for maximizing aboveground biomass production, improving soil organic carbon stock, enhancing carbon sequestration potential, and increasing water storage capacity. The findings provided valuable insights for the design and implementation of sustainable and efficient detention basin management strategies, highlighting the role of specific plant species in achieving desired outcomes. Further research and long-term monitoring are needed to fully understand the dynamics and long-term effects of these treatments on the detention basin dynamics.

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Understanding trends and gaps in global research of crop evapotranspiration: a bibliometric and thematic review

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Abstract. Estimating crop evapotranspiration (ET_c) is crucial for ensuring sustainable and efficient agricultural water management. Although this subject has garnered significant attention from the global scientific community, a comprehensive study encompassing the diversity, trends, and dynamics of research themes is currently lacking. To address this knowledge gap, this review employed a combined bibliometric and thematic approach to analyze bibliographic data from 1872 documents retrieved from the Web of Science™ core collection, spanning the period 1987–2022. The main findings of this review are as follows: (1) the scientific landscape is predominantly shaped by institutions from the USA and China; (2) the journal Agricultural Water Management emerged as the most prolific, with the highest number of publications and total citations; (3) a broad range of topics within ET_c research were identified, with a notable emphasis on remote sensing-related subjects; (4) strategic coordination mapping revealed that ET_c and reference evapotranspiration (ET_o) remains an underdeveloped area of study; (5) climate change and machine learning emerged as key topics of significant scientific concern. The results suggest a need for enhanced institutional collaborations and expanded research investigations, particularly in regions grappling with agricultural water scarcity. Furthermore, research investigations should focus on ET_c and ET_o to fill existing knowledge gaps and advance both theoretical understanding and practical applications. Future studies should aim to contribute to the understanding of the impacts of climate change on ET_c by leveraging machine learning techniques and enhancing our understanding of crop water requirements and their application in irrigation management, while also ensuring continuous updates to the existing body of knowledge to meet future challenges.

Keywords: bibliographic coupling, co-authorship and citation networks, crop water requirements, crop evapotranspiration, Web of Science.

INTRODUCTION

Evapotranspiration is the sum of all processes by which water moves from the land surface to the atmosphere via evaporation and transpiration

(United States Geological Survey, 2018). In agroecosystems, it includes transpiration which represents the major use of irrigation and rainfall water by plants and evaporation from the soil (Gowda et al., 2008). Hence, it is crucial to accurately evaluate evapotranspiration in order to avoid excess or deficit irrigation. This can be accomplished through the utilization of models that assess and forecast evapotranspiration rates (Ghiat et al., 2021), or by conducting direct measurements using *in situ* sensors.

Potential evapotranspiration (ET_p) is defined by Jensen (1968) as the rate of evapotranspiration from a well-watered crop having an aerodynamically rough surface like alfalfa with 0.3–0.5 m of top growth. However, the concept of ET_p evolved into that of reference evapotranspiration (ET_{ref}) which was introduced by irrigation engineers and researchers to avoid the confusions that existed in the definition of ET_p (Pokorny, 2019). Reference evapotranspiration is best suited for crop assessments because it is more precise and accounts for crop-related changes (Ghiat et al., 2021). By adopting ET_{ref} (grass [ET_o] or alfalfa [ET_r]), it became easier and more practical to select consistent crop coefficient (K_c) and to make reliable actual crop evapotranspiration (ET_c) estimates in new areas (Pereira et al., 2015; Pokorny, 2019). However, the grass is more often used as a reference crop than alfalfa. ET_o is defined by Allen et al. (1998) as the rate of evapotranspiration from a hypothetical reference crop with an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground. In this definition, grass is particularly defined as the reference crop and is expected to be free of water shortage and diseases. The reference evapotranspiration can be calculated using the standardized Penman-Monteith ET_o (PM-ET_o) equation which remains the commonly used method at present (Pereira et al., 2015; Pereira et al., 2021a).

Crop evapotranspiration is defined by Pereira and Alves (2005, 2013) as the rate of evapotranspiration [mm d^{-1}] of a given crop as influenced by its growth stages, environmental conditions, and crop management to achieve the potential crop production. Thus, the crop water requirements is the sum of ET_c for the entire crop growth period which is defined as the depth of water [mm] needed to meet the water consumed through ET_c by a disease-free crop, growing in large fields under non-restricting soil conditions including soil water and fertility, and achieving full production potential under the given growing environment.

There are many direct and indirect methods of determining ET_c [mm] but the most commonly used method of estimation known as the two-step approach (Eq. 1) requires first calculating ET_o [mm d^{-1}] and then multiplying it with K_c (Paredes et al., 2020; Pereira et al., 2021b; Pokorny, 2019; Todorovic, 2005).

$$ET_c = K_c * ET_o \quad (1)$$

$$K_c = \frac{ET_C}{ET_O} \quad (2)$$

The K_c (Eq. 2) is the crop coefficient for a given crop which is usually determined experimentally and then calculated and inferred from the observed evapotranspiration flux under changing environmental conditions using empirical approaches. The K_c values represent the integrated effects of changes in leaf area, plant height, crop characteristics, irrigation method and water availability, rate of crop development, crop planting date, degree of canopy cover, canopy resistance, soil and climate conditions, and management practices (Ghiat et al., 2021; Pokorny, 2019). Thus, each crop will have a set of K_c for different growth stages: initial, crop development, mid-season, and late season (Pereira et al., 2015; Pokorny, 2019).

To revise the guidelines for computing crop water requirements, the Food and Agriculture Organization (FAO) of the United Nations (UN) introduced the Irrigation and Drainage Paper No. 56 "Crop Evapotranspiration" in 1998 (Allen et al., 1998; Pereira et al., 2015). There are two K_c approaches considered in FAO56. The first is the time-averaged single K_c which includes multi-day effects of soil evaporation in addition to plant transpiration. While the second is the dual K_c (Eq. 3) consisting of a basal crop coefficient (K_{cb}) (Eq. 4) and an evaporation coefficient (K_e) (Eq. 5), where T_c is the crop transpiration and E_s is the soil evaporation (Pereira et al., 2021c; Rallo et al., 2021).

$$K_c = K_{cb} + K_e \quad (3)$$

$$K_{cb} = \frac{T_C}{ET_O} \quad (4)$$

$$K_e = \frac{E_S}{ET_O} \quad (5)$$

The crop coefficient is a key link between ET_c and ET_o which is important for agricultural water management, particularly in determining crop water and irrigation requirements (Paredes et al., 2020; Wang et al., 2023).

Bibliometrics is considered one of the key research tools widely extended to all scientific areas, particularly applicable to fields with large bodies of literature that are difficult to summarize by traditional review methods (Chàfer et al., 2021). This method can demonstrate the current status and developing trends of knowledge through visual network mapping (Chen et al., 2022). Currently, the bibliometric approach has already been used to study trends, gaps, and thematic dynamics of different topics in agriculture and related disciplines including sustainable use of water in agriculture (Abafe et al., 2022), water-use efficiency (Aleixandre-Tudó et al., 2019), agriculture 4.0 (Mühl and Oliveira, 2022), biodynamic agriculture (Santoni et al., 2022), sustainable agriculture (Sarkar et al., 2022), greenery systems (Chàfer et al., 2021), forest ecosystem services (Chen et al., 2022), and application of remote sensing in crop spatial patterns (Xiao et al., 2022). Along with the bibliometric analysis, strategic coordination mapping provides a robust analysis of research topics which allows the researchers to identify interconnections between research frameworks and potential topics for future investigations and evaluate the changes and development of research themes. This approach has also been used by several authors to study thematic evolution and identify research hotspots, topic trends, and knowledge gaps (Abafe et al., 2022; Janik et al., 2021; Mühl and Oliveira, 2022; Sarkar et al., 2022; Zhu et al., 2022). Given these wide and flexible applications, bibliometrics and thematic approaches offer a robust methodology to explore the topic of ET_c estimation.

Many studies on the technical development of the available methodologies and advanced techniques in the estimation of ET_c for agricultural water management have been done. Recent reviews and investigations focused on different aspects of ET_c such as progress and development in FAO56 (Pereira et al., 2015; Pereira et al., 2021a), FAO56 framework for coping with the effects of soil salinity on ET_c and yields (Minhas et al., 2020), assessment of model-estimated crop transpiration and ET_c using satellite-based normalized difference vegetation index (NDVI) (French et al., 2020), machine learning techniques with different meteorological input variables (Yamaç and Todorovic, 2020), updates on the various approaches to determine K_c in its single and dual versions for vegetable crops (Pereira et al., 2021b), field crops (Pereira et al., 2021c), and tree and vine fruit crops (Rallo et al., 2021), determination of ET_c and crop coefficients of sprinkler irrigated canola from lysimeter (López-Urrea et al., 2020) and almond and pistachio orchard using remote sensing (Bellvert et al., 2018), evaluation of the accuracy of a vegetation index-based approach for calculation of ET_c using a well instrumented, drip irrigated sugar beet (Wang et al., 2021), mechanistic and empirical models for open and closed agricultural field applications (Ghiat et al., 2021), and internet of things (IoT) approach to crop water use modeling and prediction for soilless cultivations (Kocian et al., 2023).

After the publication of FAO56 in 1998, ET_c research gained a lot of interest in the scientific community which led to a huge amount of literature in many publication databases. However, there is no comprehensive and exhaustive bibliographic review that has been conducted yet to understand the trends and thematic dynamics of ET_c research at the global scale. Thus, this review intends to fill those knowledge gaps by critically exploring ET_c estimation research using different types of documents in the Web of Science™ (WoS) core collection through a combined bibliometric and thematic approach. The novel findings of this review would provide a synopsis of the current status of research on ET_c estimation globally, identify knowledge gaps and research themes for future research directions, and accentuate the existing collaborations and networks among researchers and institutions in different geographical regions of the world which could be beneficial for future collaborative plans and actions. Specifically, this review aimed to: (1) discuss the *status quo* of research on ET_c estimation and identify geographical-temporal patterns within the literature; (2) analyze the dynamics of major research themes and topics and identify knowledge gaps that could serve as the foundation for future research directions; and (3) infer global relationships between researchers and countries through the analysis of co-authorship, co-occurrence, citation, and bibliographic coupling.

CHARACTERISTICS OF THE BIBLIOGRAPHIC DATA

The WoS™ is one of the world's largest comprehensive and multidisciplinary academic retrieval platforms for citation data and is preferable compared to other databases in terms of data quality (Aleixandre-Tudó et al., 2019; Chen et al., 2022; Sarkar et al., 2022). Only one database was used to reduce the possibility of errors and ease the integration and analysis of data with different software. The academic publications relating to ET_c were retrieved from the WoS™ core collection database using the search pattern TS=(crop evapotranspiration estimation). This query searched the title, abstract, author keywords, and keywords plus of the documents present in the database regardless of the year of publication and subject area. After the search query, the results were exported in plain text (.txt) and binary file (.xls) formats.

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol was adopted as a strategy for the selection of documents for the analysis as it is a well-established method for carrying out systematic reviews and meta-analyses (Haddaway et al., 2022). There were 1879 results in the WoS™ core collection. All of the documents were unique and has no duplication. A total of three unverifiable documents, one retracted paper, one editorial material, one letter, and one meeting abstract were removed from the data set (Appendix Fig. 1). All the bibliographic data with double entries for document type and missing entries for the year of publication were verified manually online. The processed bibliographic data set has 1872 entries and was imported to Biblioshiny and VOSviewer interface for subsequent analyses.

METHODOLOGICAL CONSIDERATIONS FOR BIBLIOMETRIC AND THEMATIC ANALYSES

The documents were assessed in terms of typology of publication, distribution of publications by country and year, categories of distribution topics as well as the frequency of the keyword occurrence, and analysis of citations and collaborations. The annual scientific production was generated by plotting the number of published articles per year using the library(ggplot2) in RStudio to create graphs and density plots. The data were visually represented and analyzed using the VOSviewer and Bibliometrix software package. The Bibliometrix package is an open-source tool programmed in the R language which is capable of performing a comprehensive scientific mapping analysis of scientific literature. In the bibliometrix package, Biblioshiny was utilized which combines the functionality of the bibliometrix package with the ease of use of web apps using the Shiny package environment (Aria and Cuccurullo, 2017). Similarly, VOSviewer is a freely available computer program that collects bibliographic data and builds graphical maps based on co-authorship, co-occurrence of keywords, citation, and bibliographic coupling (van Eck and Waltman, 2017).

Bibliometric analysis was conducted using the visualization of similarity algorithm feature of VOSviewer. For better visualization, a minimum link strength was set for each analysis. The documents or keyword occurrences were used as weights and average publications or average citations as scores to create VOSviewer maps. On the other hand, the trend of the topics was analyzed using the feature of Biblioshiny. In this analysis, the author keywords were used as field of analysis with parameters set to five for word minimum frequency and two for the number of words per year.

The strategic mapping feature of Bibliometrix was used to detect and visualize conceptual subdomains and thematic evolution using the author keywords as field analysis. No text editing was done and parameters were set to 100 for the number of words, five for minimum cluster frequency per 1000 documents, two keywords per cluster, weight index according to inclusion index weighted by word occurrences, minimum weight index to 0.1, and WalkTrap as the clustering algorithm. The number of cutting points was set to three: 1997, 2007, and 2017. This resulted in four time periods namely: 1987–1997, 1998–2007, 2008–2017, and 2018–2022. The same procedure was done to generate the overall thematic evolution map except that no cutting points, five keywords per cluster, and 250 number of words were used for more inclusive analysis.

GEOGRAPHICAL-TEMPORAL PATTERNS OF SCIENTIFIC PUBLICATIONS IN CROP EVAPOTRANSPIRATION

The publication record spans from 1987–2022. The earliest record was a paper by Shih S.F. entitled "Using crop yield and evapotranspiration relations for regional water requirement estimation" which is published in the journal Water Resources Bulletin in 1987. Over the last three decades, the publications increased exponentially with an annual growth rate of 16.19% (Appendix Table 1), indicating strong awareness and engagement of the scientific community in ET_c research. The highest record was in 2021 having 193 documents while the lowest was in 1988 with no recorded document (Fig. 1a). The documents were mostly articles (1596) representing 85.25% of the total publications while only 2 (0.11%) were book chapters. The other documents were conference papers with 230 documents (12.29%) and review papers with 44 documents (2.35%) (Fig. 1b; Appendix Table 1).

The number of articles published by authors in various countries and institutions could be a proxy indicator of research progress and development and to a certain extent, the popularity of the topic. The ET_c research has gained interest among scientific communities from different parts of the world though some counties in Latin America, Asia, and Africa are underrepresented (Fig. 1c). In terms of country production, the documents were dominated by publications from the USA (991), China (973), and India (357). The countries such as Spain (348), Italy (201), France (149), and Germany (126) dominated the European region while Brazil (278), Iran (192), and Australia (134) dominated the regions of Latin America, Middle East, and Oceania, respectively. This geographical pattern was also observed in the bibliometric analysis of research in sustainable agriculture, sustainable water use in agriculture, and water-use efficiency where-

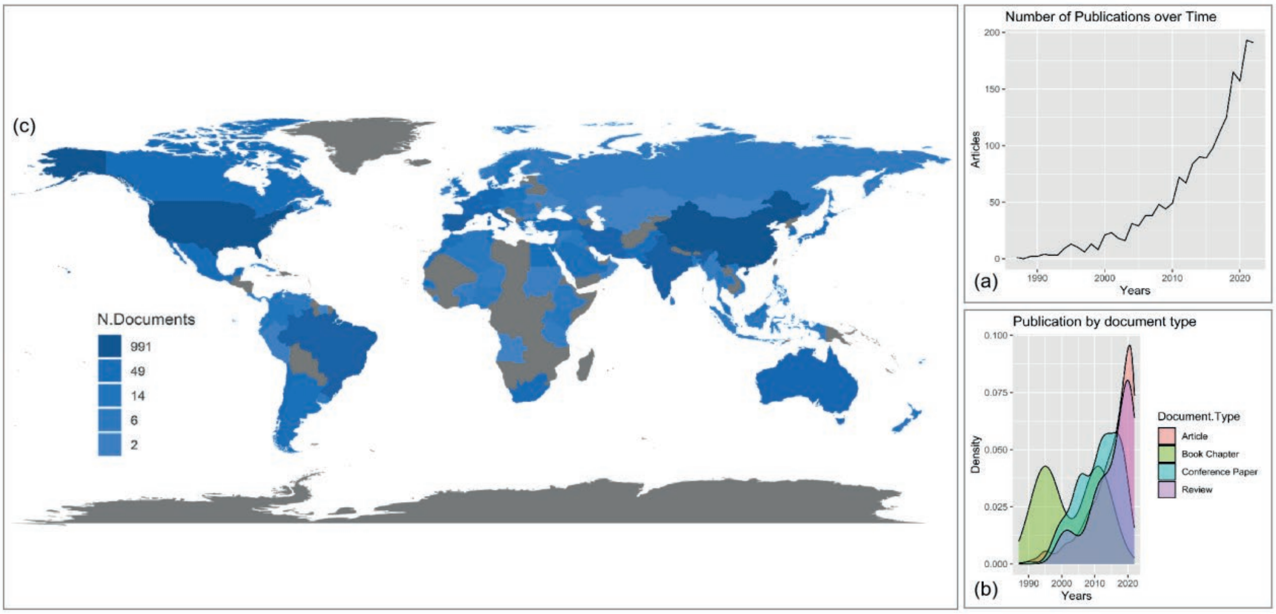

Figure 1. Geographical-temporal patterns of research publications in crop evapotranspiration estimation from 1987-2022 (a) number of publications over time; (b) density plot of document type; (c) worldwide distribution of documents.

in authors reported that the USA, China, Australia, and some European countries have the highest contribution (Abafe et al., 2022; Aleixandre-Tudó et al., 2019; Sarkar et al., 2022).

Co-authorship networks of countries and institutions

International cooperation and exchange play a crucial role in enhancing the research capabilities and academic influence of countries and institutions (Chen et al., 2022). Thus, the co-authorship networks of countries and institutions were analyzed to gain insights into the social networks formed by authors through scientific collaboration. The threshold for the minimum number of documents was set at five for countries and ten for institutions (Janik et al., 2021). Out of the 103 countries and 1967 institutions analyzed, 61 successfully met the threshold criteria. In the network visualization, larger circles indicate a higher number of associated documents, while thicker lines represent greater co-authorship. The colors in the network indicate clustering. Nine co-authorship networks were identified for countries (Fig. 2a), revealing strong collaborative ties and global partnerships among authors from the USA, China, Australia, Iran, India, and various European countries such as Spain, Germany, Italy, The Netherlands, and France. Further analysis highlighted the emergence of newer contributors including Sweden, Georgia, Ethiopia, Egypt, Lebanon, Iraq, Vietnam, and Thailand, while the oldest contributors were France, Belgium, The Netherlands, England, Scotland, New Zealand, Taiwan, Japan, Jordan, Sri Lanka, and Venezuela (Fig. 2b).

The co-authorship network of institutions is composed of six clusters (Fig. 2c) with a strong tendency for collaborations to occur among authors of the same country and institution. This was also observed by Abafe et al. (2022) when they did the same analysis on the topic of sustainable water use in agriculture. The highest total link strengths were observed among academic and research institutions in the USA and China. These institutions include the US Department of Agriculture (USDA) Agricultural Research Service (ARS), Utah State University, Chinese Academy of Sciences, Chinese Academy of Agricultural Sciences, and China Agricultural University. This could mean that both countries place nearly equal emphasis on international cooperation. Despite having relatively high publications, the University of Nebraska, the University of California Davis, Hohai University, the University of Castilla-La Mancha, and the University of Lisbon showed low total link strength, suggesting limited collaborations at the institutional level. On the other hand, Sichuan University, the University of Maryland, and Wuhan University demonstrated high total link strength despite having low publications, indicating good institutional collaboration initiatives. Moreover, the analysis revealed the emergence of several recent institutions conducting research on the

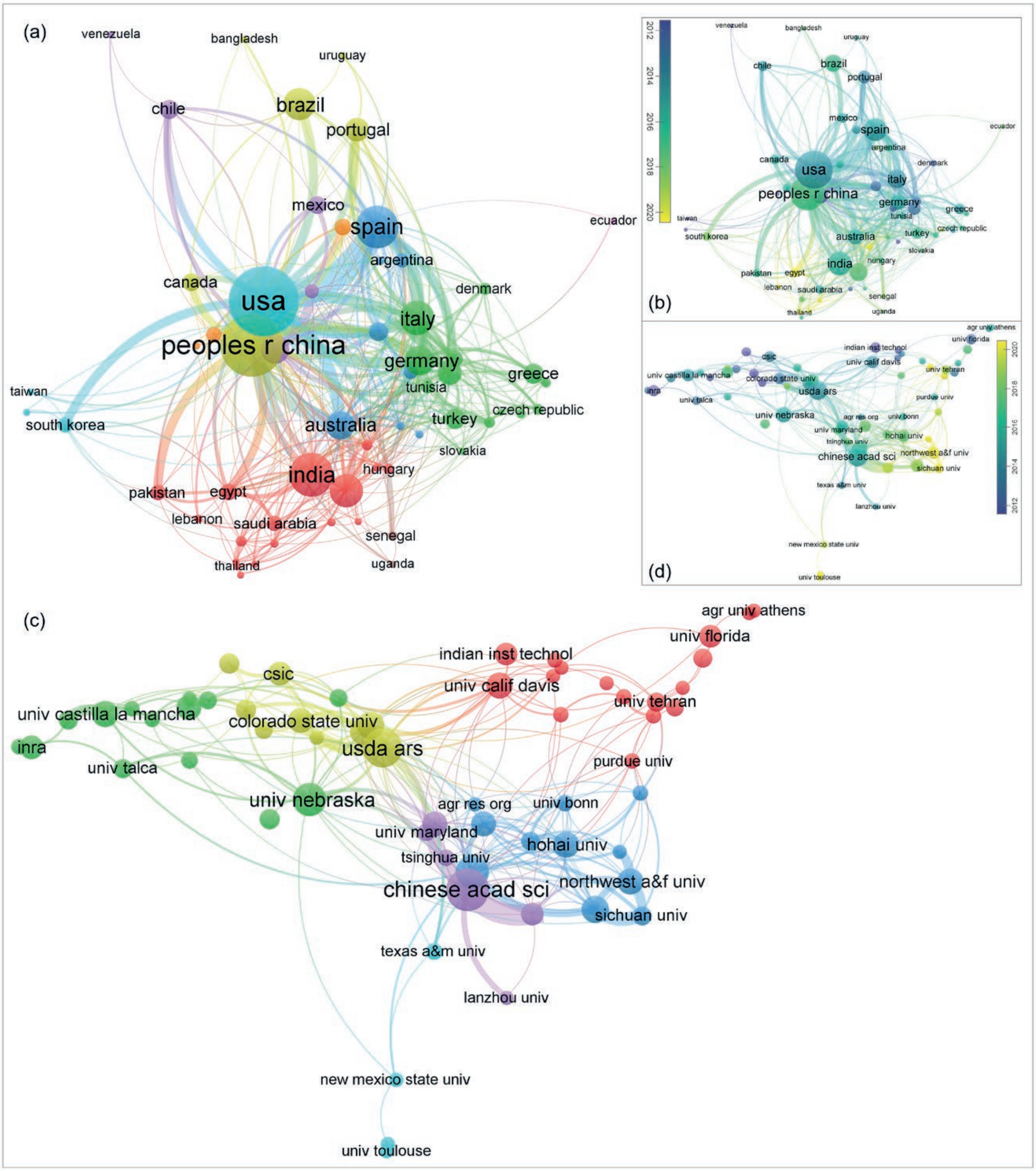

Figure 2. Co-authorship networks of (a-b) countries and (c-d) institutions [minimum link strength: 1].

topic. These include the University of Montpellier and the University of Toulouse in France, New Mexico State University in the USA, University of Chinese Academy of Sciences, Northwest A&F University, Sichuan University, Nanchang Institute of Technology, Nanjing University of Information Science and Technology, and Jiangsu University in China, as well as Mansoura University in Egypt (Fig. 2d).

TREND AND CO-OCCURRENCE NETWORK OF AUTHORS' KEYWORD

There are highly variable keywords in the analyzed documents which highlights the multidimensional and contemporary nature of ET_c research. The keyword with the highest number of occurrences was evapotranspiration (564) followed by remote sensing (219), crop coefficient (119), reference evapotranspiration (118), irrigation (96), eddy covariance (64), energy balance (55), moderate resolution imaging spectroradiometer (MODIS) (46), Penman-Monteith (45), and crop evapotranspiration (44) (Fig. 3a), suggesting that these are among the most commonly discussed areas in ET_c research. Most of these keywords appeared simultaneously three years after the publication of the FAO56 Penman-Monteith ET_o method in 1998. Other authors who conducted bibliometric analysis on related topics such as sustainable water use in agriculture and water-use efficiency also reported a high frequency of the keywords evapotranspiration and irrigation (Abafe et al., 2022; Aleixandre-Tudó et al., 2019). Trend analysis further showed that keywords such as stomatal resistance and irrigation requirements were commonly used by researchers since the early 2000s and remain relevant to the present day. These two keywords are interconnected, with stomatal resistance playing a crucial role in assessing crop water status and estimating transpiration, which are essential for effective irrigation management (Cannavo et al., 2016). The period between 2008 and 2018 exhibited the maximum diversification of authors' keywords, with many terms revolving around soil-plant-atmosphere interactions and decision support systems. Moreover, the term crop modeling paved the way for the emergence of new keywords such as machine learning, random forest, artificial intelligence, and google earth engine which began to gain prominence starting in 2020 (Fig. 3b).

Keywords represent the main contents of existing research and depict the areas studied within the boundaries of a given domain and their co-occurrence highlights the main areas of research (Chàfer et al., 2021). In this context, the co-occurrence network of author keywords was analyzed to gain a better understanding of the main research areas. To ensure a more focused analysis and exclude less significant topics, only keywords with a minimum of 15 occurrences were considered (Janik et al., 2021). Out of the 3739 keywords initially identified, only 59 met this threshold (Fig. 3c). In the co-occurrence network, larger circles and thicker lines represent higher occurrences and co-occurrences in publications, respectively, while colors indicate clustering. The analysis revealed six distinct clusters that represent the primary sub-areas of research in ET_c. Apart from Landsat—a keyword related to space-based moderate-resolution land remote sensing data, the top ten keywords with the highest occurrence also showed the highest total link strength with one another. Recent approaches to estimating ET_c primarily focus on utilizing remotely sensed data (Pereira et al., 2015) and all of these keywords are somehow related to remote sensing. Therefore, it is highly likely that these keywords will continue to exist and co-occur in future publications.

CENTRAL THEMES OF CROP EVAPOTRANSPIRATION RESEARCH

Thematic maps were generated based on the relationship that a network of topics establishes with other networks of topics. The algorithm grouped the topics according to subject areas and distributed them according to different themes based on centrality and density. These themes were classified as follows:

1. Motor - This theme represents well-developed and significant research areas that serve as the foundation for the field. They play a crucial role in structuring the overall research landscape.
2. Niche - The niche theme consists of highly specialized and peripheral topics that cater to specific areas within the field. They address specific, focused aspects that may not receive widespread attention.
3. Emerging or Declining - This theme encompasses topics that are either emerging or declining in importance within the research field. These topics are characterized by evolving trends and changes in relevance.
4. Basic - The basic theme comprises topics that hold importance but are not yet fully developed within the research field. These areas show potential for growth and further exploration.

Centrality is a measure of the extent to which a topic network interacts with other networks within the same discipline. It reflects the interconnectedness and influence of a particular topic grouping. On the other hand, density indicates the internal strength of a network, revealing how closely related the topics within it are. A higher density suggests strong connections between topics, indicating their potential for resilience and improvement (Janik et al., 2021; Mühl and Oliveira, 2022; Sarkar et al., 2022).

A total of four clusters were identified in the overall thematic map (Fig. 4a). Two clusters focused on motor themes, with the first cluster pertaining to crop ecophysiological processes, such as transpiration, soil water bal-

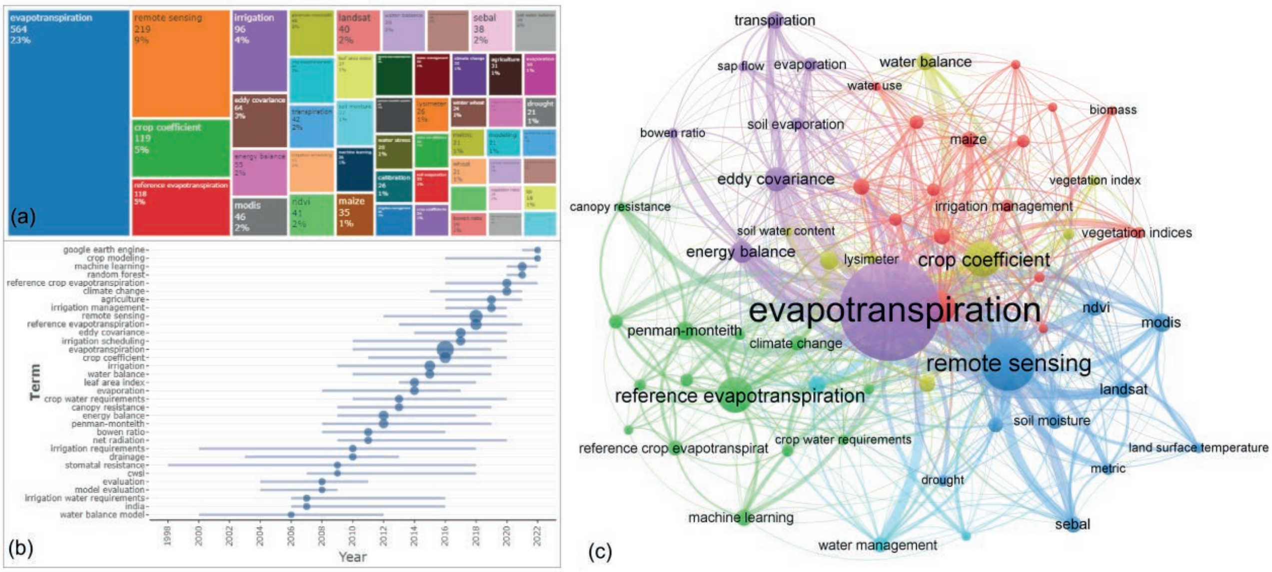

Figure 3. (a-b) Trend analysis and (c) co-occurrence network of author keywords [minimum link strength: 1].

ance, leaf area index, and water stress. The second cluster centered around methods and approaches for estimating ET_c, including remote sensing, crop coefficient, and eddy covariance. Similarly, two clusters were identified as emerging or declining themes. These clusters encompassed a range of conventional and modern methodologies for estimating ET_c, which could signify either sustained relevance or the replacement of conventional methods by modern tools such as machine learning or deep learning techniques. Pereira et al. (2015) emphasized the importance of continuing to use primary data collection systems such as lysimeters, eddy covariance, Bowen ratio, and soil water balance for determining K_c using ET measurements. While the FAO56 method does not explicitly mention the application of remote sensing, there have been significant developments in the past three decades regarding the inclusion of remote sensing data for estimating K_c, K_{cb}, and evapotranspiration, which can greatly support irrigation management (Pôças et al., 2020). In addition, future improvements to the FAO56 K_c-ET_o method for estimating ET_c should take into account the availability of remote sensing observations, particularly in defining crop growth stages at specific locations (Pereira et al., 2021c). Therefore, it is highly likely that the scientific community will continue to investigate these topics in the future.

A comprehensive analysis was conducted to depict the thematic evolution of ET_c research sub-areas over four distinct time spans (Fig. 4b). The initial phase (1987–1997) primarily concentrated on irrigation and transpiration as the main research domains. Subsequently, during the second period (1998–2007), the concept of transpiration underwent significant advancements and expansions. Key developments during this time included the Penman-Monteith equation, reference evapotranspiration, crop coefficients, and water balance. The majority of investigations focused on two prominent crop species, maize and wheat, while new concepts such as climate change also emerged during this period. It is notable that during this period, researchers recognized the importance of *in-situ* sensors in estimating ET_c as marked by the emergence of the term lysimeter. Weighing lysimeters directly measure evapotranspiration by assessing changes in soil and crop mass. These lysimeters are renowned for providing the most precise and dependable measurements of ET_c, making them the standard for evaluating energy and water balance models and calibrating crop coefficients, as outlined in the FAO56 methodology (Ghiat et al., 2021; López-Urrea et al., 2020). The majority of the topics addressed in the second period remained pertinent during the third period (2008–2017), with a particular focus on investigating crop responses to water, such as water stress and crop water requirements. Furthermore, novel concepts emerged, including modeling, MODIS, and latent heat flux, all of which are associated with various approaches for estimating ET_c. Current research (2018–2022) has maintained a strong focus on evapotranspiration, specifically reference and crop evapotranspiration. Pereira et al. (2015) noted that ET_{ref} remains widely used and accepted for practical estimation of ET_c, indicating that these terms

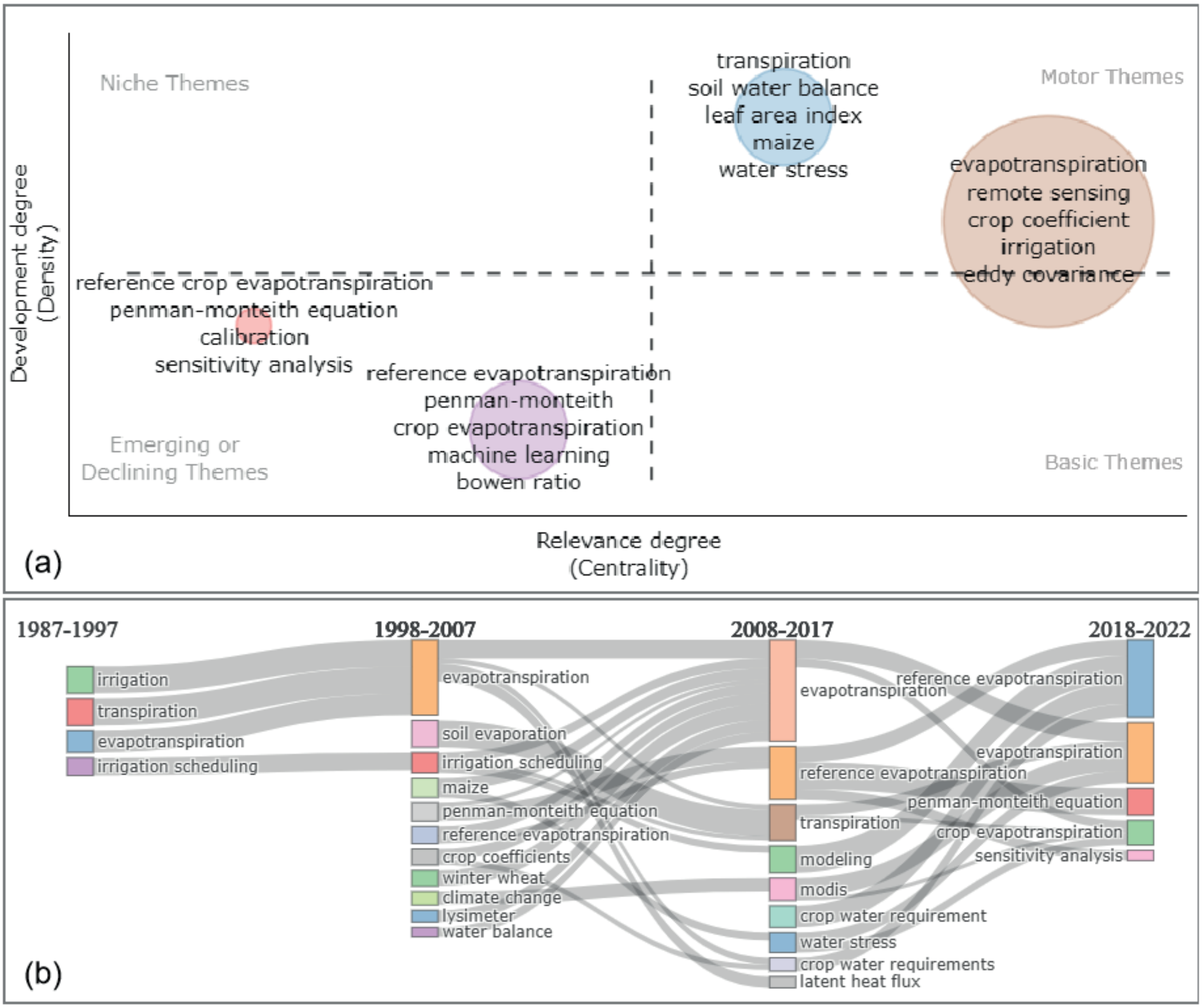

Figure 4. Overall (a) thematic map and (b) evolution of topics over time.

will continue to coexist until new estimation methods for ET_c are developed. Notably, ongoing research in ET_c aligns with advancements in digital tools, such as machine learning, and addresses pressing environmental challenges like climate change. Studies suggest that climate change will negatively impact vegetation water availability, particularly crop water requirements and net irrigation needs (Saadi et al., 2015). Consequently, integrated and sustainable water management becomes crucial to mitigate the vulnerability of agriculture to climate change and its associated environmental consequences (Pereira et al., 2020; Pereira et al., 2021b). Therefore, it is imperative to address these issues concerning ET_c, quantify their impacts, and develop appropriate mitigation and adaptation strategies.

Thematic evolution of topics in crop evapotranspiration research

An in-depth analysis of the evolution of the thematic maps was conducted dividing the studied topics into four categories of themes and time periods previously mentioned. Three themes were identified for the initial period, 1987–1997 (Fig. 5a). The motor themes encompassed studies on evapotranspiration and crop coefficient. The niche themes focused on irrigation scheduling and the crop potato, whereas, emerging or declining themes centered around the concept of transpiration. Notably, during this particular time frame, the diversity of topics was limited due to the nascent stage of ET_c research, which had only begun to capture the attention of the scientific community.

Figure 5. Thematic analysis of topics in four different time periods from 1987–2022: (a) 1987–1997; (b) 1998–2007; (c) 2008–2017; and (d) 2018–2022.

During the second period, 1998–2007 (Fig. 5b), the analysis revealed four main themes, consisting of ten clusters. The motor themes encompassed three clusters that focused on various aspects such as remote sensing, crop coefficient, Penman-Monteith, reference evapotranspiration, water balance, and sap flow. Of these topics, sap flow is of particular interest. It is a method developed to measure transpiration at the individual plant level, and currently, heat tracer-based sap flow techniques are the predominant method of estimation (Wang et al., 2022). The niche themes comprised two clusters that delved into specialized topics related to the prediction and analysis of data associated with spatial or spatiotemporal phenomena, specifically geostatistics and kriging. Two additional clusters were identified as emerging or declining themes, which encompassed topics like evapotranspiration, modeling, soil moisture, and recharge. Similarly, the topic of evapotranspiration, along with irrigation, winter wheat, and NDVI, was classified as a basic theme. Notably, during this period, researchers dedicated significant efforts to exploring the application of remote sensing for indirect measurement of leaf area index, as evident from the co-occurrence of the topics NDVI and remote sensing. Reyes-González et al. (2019) suggested that image-based remote sensing techniques could be employed to estimate leaf area index based on empirical relations with vegetative indices. These vegetative indices could then be incorporated in the surface resistance estimation within the Penman-Monteith model (Ghiat et al., 2021). More recently, French et al. (2020) found that, in most cases, remote sensing of NDVI and modeled K_{cb} accurately estimated K_c and ET_c during the mid-season through senescence. Furthermore, Pereira et al. (2020) provided a comprehensive review on the relationships between single K_c and basal K_{cb} and various parameters, including the fraction of ground cover and height.

In the third period, 2008–2017 (Fig. 5c), the topics energy balance and surface energy balance are located at the center of the strategic diagram which implies that they can be both motor and niche themes. The presence of these topics alongside remote sensing indicates substantial advancements in remote sensing of evapotranspiration, providing a reliable foundation for determining evapotranspiration through surface energy balance (Pereira et al., 2015). China and Iran emerge as niche themes in this period, signifying extensive research efforts related to ET_c in these countries. The topic crop coefficient or single K_c in 1987–2007 evolved to dual crop coefficient as a niche theme in this period. The single K_c only represents typical conditions that can vary with wetting frequency by precipitation and irrigation and with the type of irrigation practiced. This concept was extended by introducing the dual crop coefficient that integrates K_{cb} which is the basal crop coefficient representing primarily plant transpiration and K_e which is the evaporation coefficient that represents the contribution of evaporation from soil to total evapotranspiration (Pereira and Alves, 2013). Over the years, the dual approach significantly improved the accuracy of the evapotranspiration estimate and enabled several entities to update and revise guidelines on evapotranspiration and irrigation water requirements. However, quantifying seasonal variations in the single and dual crop coefficients remains a challenge even today (Pereira et al., 2015; Wang et al., 2023). Pôças et al. (2020) provide a comprehensive review on the application of remote sensing data for assessing K_c and K_{cb} coefficients, particularly focusing on the use of spectral vegetation indices. The other topics under niche themes include the SIMDualKc model, water stress, water-use efficiency, and calibration. Among these topics, the SIMDualKc model is particularly important. It is a model that performs a daily soil water balance at the field scale adopting the dual K_c approach to compute and partition ET_c into T_c and E_s. A recent review by Pereira et al. (2021b) has shown that a well-calibrated and validated SIMDualKc model made it possible to overcome problems related to stress and achieve K_c standardized values. Similarly, Rosa et al. (2016) utilized this model to estimate transpiration rates of maize and sweet sorghum considering the effect of transient salinity stress. Under the basic theme category, one significant topic is the soil water balance, which evolved from the water balance topic in the 1998–2007 period. Extensive research has been conducted on this topic over the years, and it is likely that field and crop-focused soil water balance models will continue to be utilized by farmers and agricultural advisors. Pereira et al. (2020) provide a comprehensive discussion of different approaches to soil water balance modeling. Furthermore, trends in this topic are expected to shift, with traditional models predominantly used for research purposes, while new, fast-responding, and multi-user models based on cloud and Internet of Things (IoT) technologies will be developed for practical farm applications. Kocian et al. (2023) recently employed an IoT approach to predict ET_c of sweet basil in soilless cultivations. Lastly, the other topics falling under the basic themes category include soil evaporation, irrigation, Penman-Monteith, reference evapotranspiration, and evapotranspiration.

In the current period, 2018–2022 (Fig. 5d), topics such as evapotranspiration and remote sensing have become well-developed and are recognized as motor themes. These topics have also been present in previous periods (1998–2017) either as motor or basic themes. One prevalent approach for estimating evapotranspiration using remote sensing involves the utilization of vegetation indices or surface energy balance models based on thermal infrared data (Pereira et al., 2015). This explains the presence of the topic thermal infrared alongside remote sensing. Further analysis showed that researchers exhibit a strong inclination towards topics related to digital agriculture and new technologies in computer science and data analytics. Mühl and Oliveira (2022) observed a similar trend when investigating the dynamics of research topics in agriculture 4.0. Apart from thermal infrared, the niche themes were composed of two clusters which include the topics unmanned aerial vehicle (UAV), solar radiation, and extreme learning machine. One cluster was identified as emerging or declining themes, which include sensitivity analysis and calibration. These topics likely represent emerging themes that highlight the need for fine-tuning and evaluating the robustness of different models available for estimating ET_c. Recent reviews have indicated that many papers fail to satisfy the adopted K_c requirements for various crops, such as vegetable crops, field crops, and fruit trees and vines, in terms of the ET_o computation method or provide solid evidence of measurement accuracy for ET_c. Therefore, future research should prioritize adopting improved accuracy and quality control measures to determine K_c data comparable to currently recognized standard values. This will provide more transferable data to other regions (Pereira et al., 2021b, 2021c; Rallo et al., 2021).

Lastly, the basic themes include interrelated topics such as crop evapotranspiration, climate change, reference evapotranspiration, and machine learning. Despite the substantial amount of research conducted in the past 35 years, it is interesting to note that based on the analysis, these topics are still underdeveloped. Pereira et al. (2015) emphasized that the use of the crop coefficient curve and reference evapotranspiration will live on into the future taking advantage of sophisticated computer language. Future applications of K_c will include the use of thermal-time units such as growing-degree days to establish lengths of periods which is important for assessing the impacts of climate change on future crop water use. Therefore, the scientific community should prioritize future research investigations related to these topics to gain a deeper understanding of the concepts, principles, methodologies, and applications of crop evapotranspiration.

CITATION NETWORK ANALYSIS

The dynamics of citation among authors involved in ET_c research were examined by analyzing the citation networks of countries, institutions, sources, and documents.

Citation network of countries and institutions

In the citation network analysis, the minimum number of documents of a country was set to ten while to 15 for the institution. Among the 103 countries and 1967 institutions considered, 35 met the specified thresholds. The size of the circles in the visual representation indicates the volume of publications, with larger circles representing higher publication numbers. Similarly, the thickness of the lines connecting the circles represents the frequency of mutual citations between the entities.

A total of four citation network groups for countries were identified, with the highest total link observed between USA and China, Spain, Portugal, and Italy. Other countries also showed links with these five countries (Fig. 6a). The analysis further revealed that papers from the USA, Israel, Denmark, Austria, France, Italy, Belgium, and Portugal received the highest average number citations (Fig. 6b). It is worth noting that the first three countries also received a significant number of citations in a previous bibliometric study on water-use efficiency research (Aleixandre-Tudó et al., 2019). The number of citations serves as a metric for assessing the impact of articles on the advancement of the field (Wang et al., 2019). Based on this criterion, papers from these countries can be regarded as highly impactful.

In the citation network of institutions, a total of four clusters were identified, with a strong tendency for institutions of the same country to cite one another (Fig. 6c). In China, the highest links were observed between Northwest A&F University, Chinese Academy of Agricultural Sciences, and Sichuan University. In Portugal, the University of Lisbon showed strong links with the Technical University of Lisbon and the University of Idaho. In the USA, the USDA-ARS displayed strong connections with the Agricultural Research Service (ARS), Utah State University, Colorado State University, and the University of Nebraska. In Spain, the University of Castilla-La Mancha demonstrated a strong link with the University of Valencia. Lastly, in Italy, the University of Palermo showed citation connections with institutions such as the University of Lisbon, Technical University of Lisbon, University of Idaho, University of Nebraska, and ARS. Further analysis revealed that the Technical University of Lisbon and the University of Idaho had the highest average citations thus, making them the most impactful institutions (Fig. 6d). This finding is further supported by the fact that most influential authors in the field are affiliated with these institutions (Appendix Table 2).

Citation networks of sources and documents

The importance of ET_c research is reflected in the type and quality of the sources and documents. Thus, the citation networks were analyzed as a proxy measure of impact and knowledge generation. For this analysis, the minimum number of documents of a source was set to eight while the minimum number of citations of a document was set to 100. Out of 496 sources, 36 met the threshold while out of 1872 documents, 56 met the threshold. However, only 33 documents demonstrated connections within the network.

A total of seven citation networks for sources were identified. The trans- and multidisciplinary nature and diverse subject areas of ET_c has resulted in research findings being published in a wide variety of journals with various aims and scopes. The journal Agricultural Water Management exhibited strong connections with journals specializing in water, irrigation, and remote sensing technologies applications, such as Remote Sensing, Journal of Hydrology, Journal of Irrigation and Drainage Engineering, Agricultural and Forest Meteorology, Water, Irrigation Science, Theoretical and Applied Climatology, Hydrological Processes, and Computers and Electronics in Agriculture (Fig. 7a). These journals also had the highest number of publications and citations highlighting their importance in disseminating research results related to ET_c (Appendix Table 3). Abafe et al. (2022) identified Agricultural Water Management, Water, and Journal of Hydrology as leading journals in advancing research on sustainable water use in agriculture. In addition, Aleixandre-Tudó et al. (2019) identified Agricultural Water Management as the most prolific journal in water-use efficiency research. Further analysis revealed that despite their lower number of publications, the journals Remote Sensing of Environment, Water Resources Research, Ecological Modelling, and Hydrology and Earth System Sciences had the highest average citations, indicating their high credibility (Fig. 7b). Moreover, these journals have high impact factor and are managed by reputable publishers and scientific societies like Elsevier, Springer Nature, Wiley, MDPI, American Society of Civil Engineers, and European Geosciences Union (Appendix Table 3).

Out of the analyzed documents, only 74 were single-authored, with international co-authorship accounting for 30.77% (Appendix Table 1). A total of eight citation networks for the documents (Fig. 7c–d) were identified, with four papers receiving the highest number of citations. The other most cited documents with at least 200 citations can be found in Appendix Table 4. According to Mühl and Oliveira (2022), a highly cited paper is

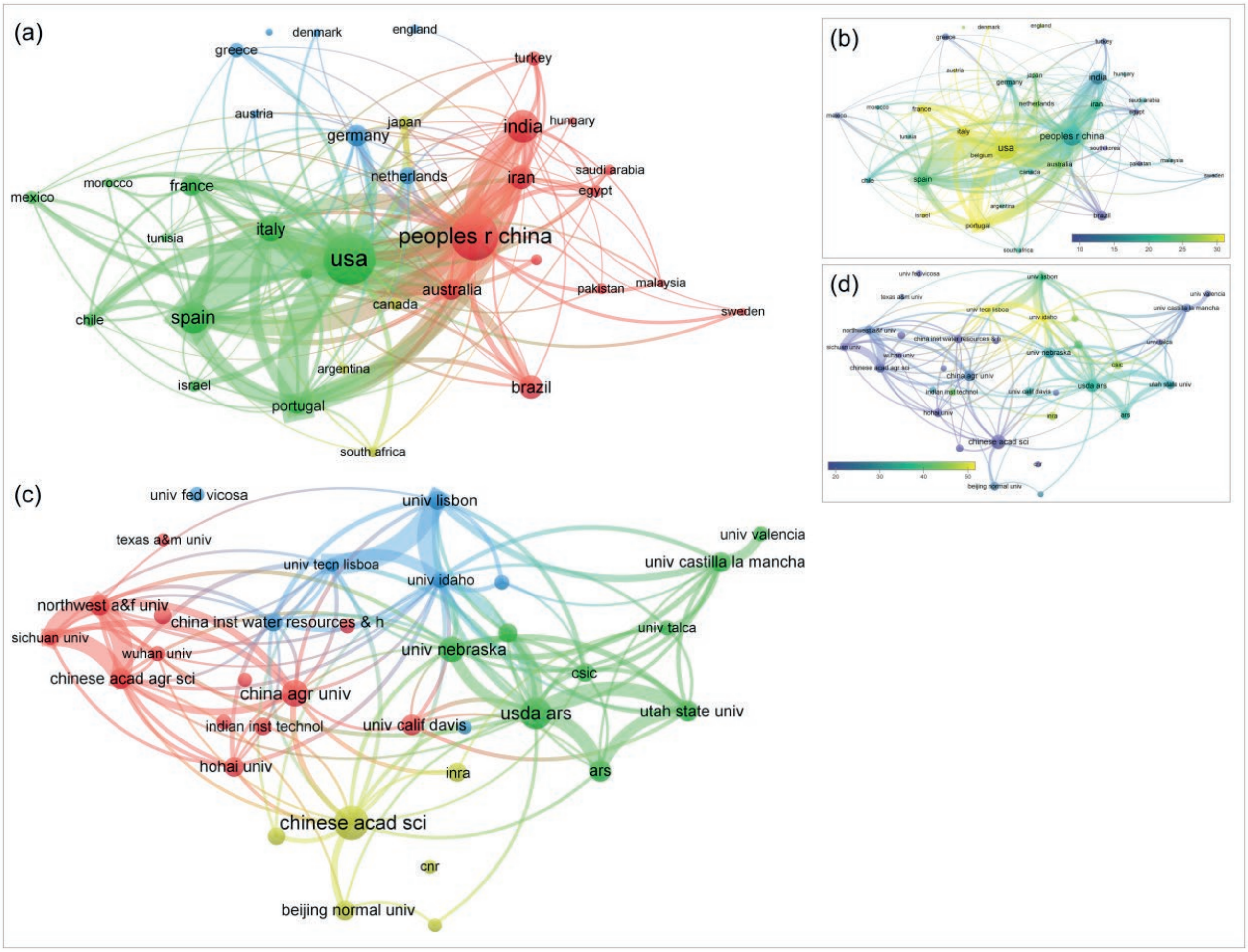

Figure 6. Citation networks of (a-b) countries and (c-d) institutions [minimum link strength: 10].

considered impactful, although impact could also be measured in terms of the number of published papers by authors. The first document is "Evapotranspiration information reporting: I. Factors governing measurement accuracy" by Allen et al. (2011b), published in the Agricultural Water Management journal. This review article discusses the fundamental principles of evapotranspiration measuring systems, common errors, and biases associated with these systems. The second document is also a review paper entitled "Measurement and estimation of actual evapotranspiration in the field under Mediterranean climate: a review" by Rana and Katerji (2000), published in the European Journal of Agronomy. This paper focuses on comparing different methods for estimating evapotranspiration and assessing their accuracy and suitability for arid and semi-arid environments. The third paper is "Crop evapotranspiration estimation with FAO56: Past and future" by Pereira et al. (2015) which is also published in the journal Agricultural Water Management. This review paper provides updated definitions and procedures for computing reference evapotranspiration, discusses the adoption of the dual K_c method for separate estimation of crop transpiration and soil evaporation, and presents improved estimations of ET_c under water, salt stress, and non-standard conditions. The last paper is entitled "Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: a pragmatic synthesis" by McMahon et al. (2013) published in Hydrology and Earth System Sciences. This article serves as a comprehensive guide for estimating actual evaporation from deep lakes and farm dams, potential evaporation for rainfall-runoff models, and reference crop evapotranspiration for small irrigation areas and large irrigation districts. The citation behavior of these four highly cited papers suggests the flow of knowledge between articles. When an article is cited by a large

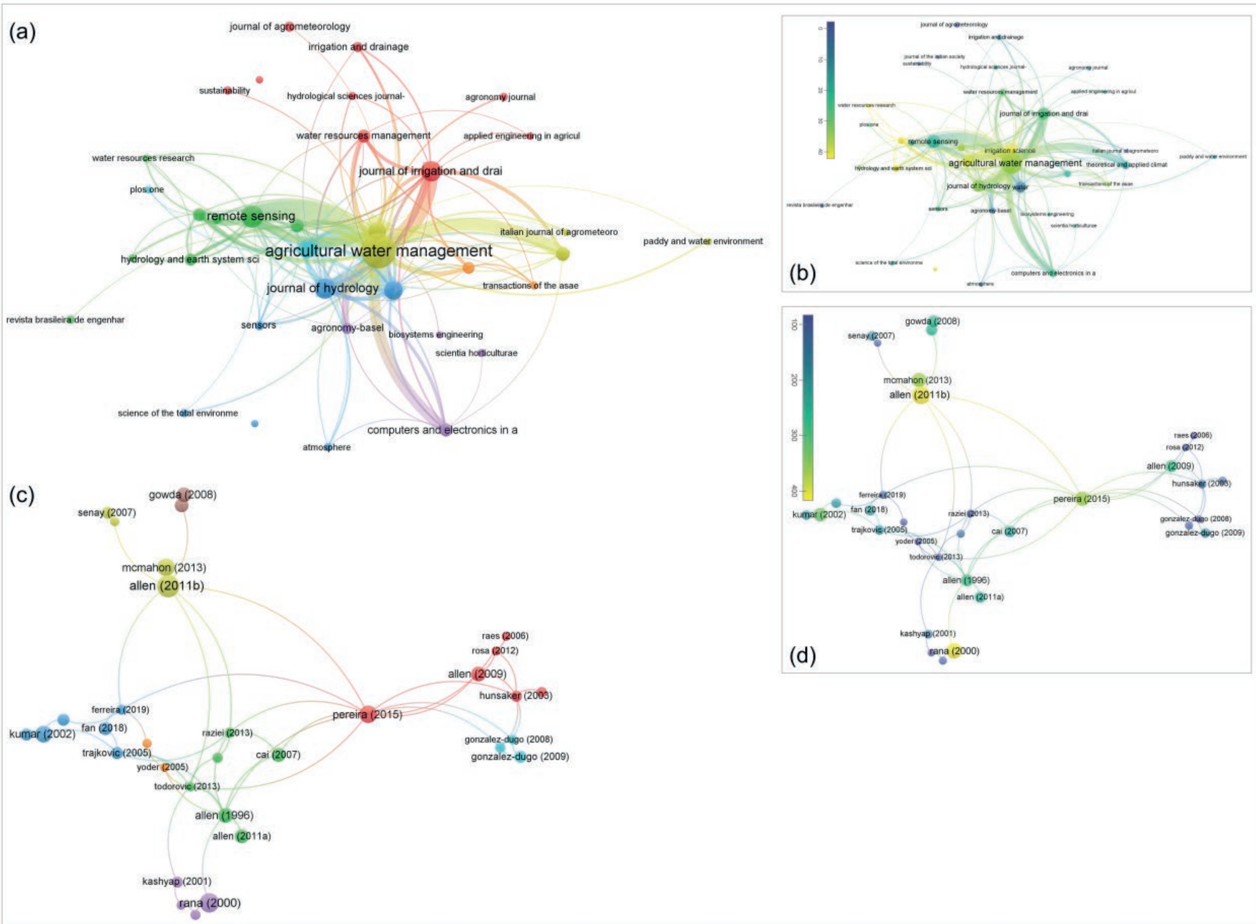

Figure 7. Citation networks of (a-b) sources [minimum link strength: 4] and (c-d) documents [minimum link strength: 6]. For the documents, only the first author is shown by VOSviewer.

number of authors from different countries, institutions, disciplines, and journals, it indicates that the knowledge presented in the article has a significant impact on scientific research conducted by multiple academic entities (Wang et al., 2019).

BIBLIOGRAPHIC COUPLING ANALYSIS

Bibliographic couplings of countries, institutions, sources, and documents were also examined using the same parameters employed in the citation network analysis. Bibliographic coupling refers to the number of shared cited references between two publications, allowing for the identification of publications that are most closely related in terms of their topics (Janik et al., 2021). In general, the findings from the bibliographic coupling analysis complement those obtained from the citation network analysis.

Bibliographic coupling of countries and institutions

Five bibliographic coupling groups for countries were identified (Fig. 8a). Among these groups, the countries that showed strong links with each other were USA, China, Spain, Italy, Portugal, France, Brazil, India, Iran, Australia, Germany, and The Netherlands. The highest link was observed between USA and China, indicating a significant level of collaboration and knowledge exchange between these two countries.

Three bibliographic coupling groups were identified for institutions (Fig. 8b). Chinese institutions, including Northwest A&F University, China Agricultural University, Chinese Academy of Sciences, Chinese Academy of Agricultural Sciences, Sichuan University, as well as US institutions like USDA-ARS, University of Nebraska, Utah State University, University of California Davis, Colorado State University, and University of Idaho, demonstrated strong connections with each other. It is

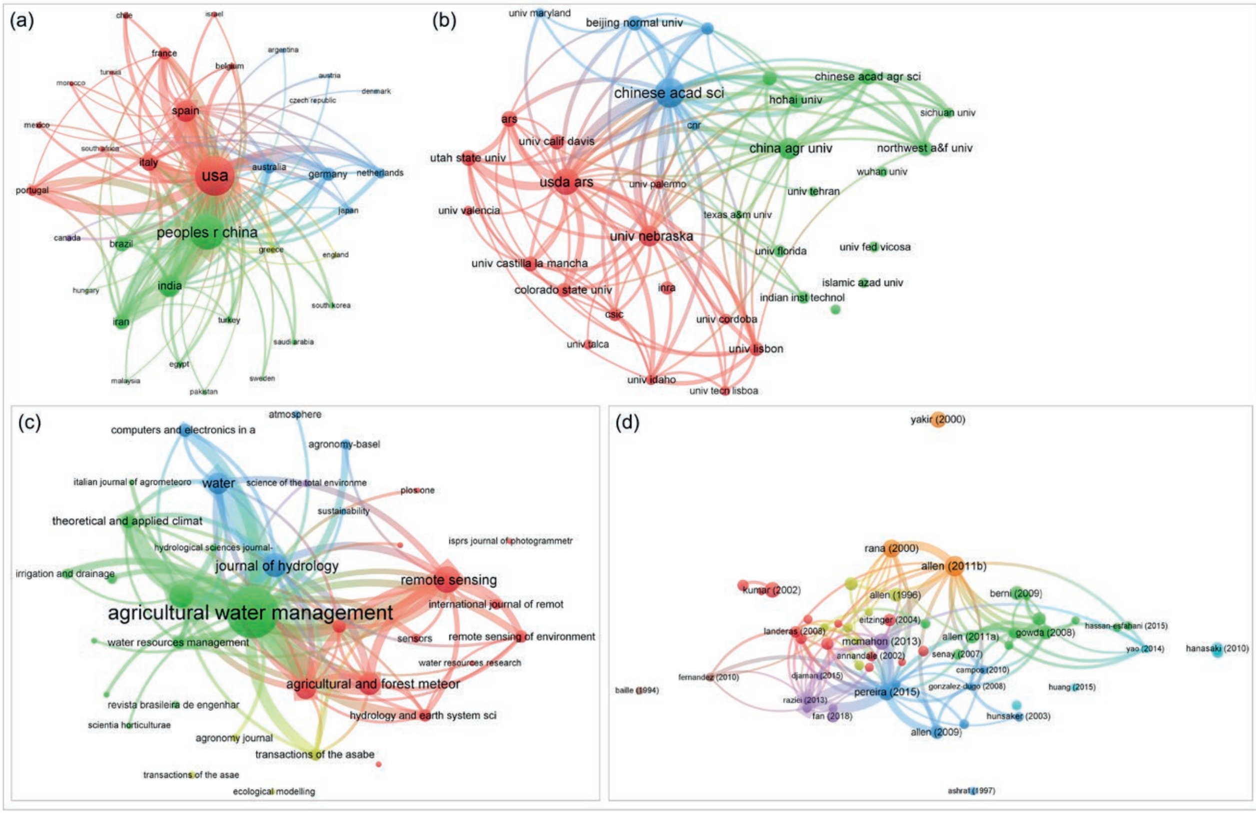

Figure 8. Bibliographic coupling of (a) countries [minimum link strength: 3000], (b) institutions [minimum link strength: 1000], (c) sources [minimum link strength: 1000], and (d) documents [minimum link strength: 5]. For the documents, only the first author is shown by VOSviewer.

worth mentioning that Northwest A&F University and China Agricultural University were also recognized as prominent institutions in producing publications related to sustainable water use in agriculture (Abafe et al., 2022). Lastly, the other institutions that showed strong links were from Spain such as the University Castilla-La Mancha, the University of Valencia, and the University of Cordova, and from Portugal such as the University of Lisbon and the Technical University of Lisbon.

Bibliographic coupling of sources and documents

A total of five bibliographic coupling groups were identified for sources (Fig. 8c). The journal Agricultural Water Management exhibited strong links with the Journal of Water Resources Management and with all the journals identified as impactful in the citation network analysis, except for Hydrological Processes. For documents, a total of eight bibliographic couplings were identified (Fig. 8d). The documents by Rana and Katerji (2000), Allen et al. (2011b), Pereira et al. (2015), McMahon et al. (2013), Gowda et al. (2008), Allen et al. (2011a), Raziei and Pereira (2013), Todorovic et al. (2013), and Rosa et al. (2012) showed strong links with one another but the highest link was found between Raziei and Pereira (2013) and Todorovic et al. (2013). Most of these papers were authored or co-authored by Luis S. Pereira from the University of Lisbon in Portugal, who is also the most locally cited author. However, Rana and Katerji (2000), McMahon et al. (2013), and Gowda et al. (2008) were authored by other researchers. In addition, the first four documents were also identified as the most impactful papers in the citation network analysis.

CONCLUSIONS AND LIMITATIONS

This review provided a comprehensive overview of contemporary research topics in ET_c estimation from 1987 to 2022. The USA and China were the two world-leading countries in ET_c research which could potentially influence future research direction since most of the institutions working on this topic are located in these countries. There is a wide range of journals for publication of research results on ET_c but the Agricultural Water Management has gained great importance because most authors are publishing and citing papers in this journal. The growth of ET_c research is increasing and the findings demonstrate a widespread collaboration between the authors, institutions, and countries around the world indicating that ET_c is a well-established topic. However, there are some underrepresented countries in the analysis. It is important to note that this review focused only on documents where the term "crop evapotranspiration estimation" appeared in the title, abstract, or keywords, which poses some limitations on the comprehensive representation of the research topic. Despite these limitations, rigorous efforts were made to conduct this research accurately following the PRISMA protocol. Due to the difficulty of merging bibliographic data from different sources, only the WoS™ publication database was utilized which implies that it cannot be assumed as complete. Nevertheless, this review provides a valuable overview of the current state of global research on ET_c. With the inclusion of documents that can be found in other databases like Scopus®, the results could deviate a little bit from what is presented in this review. Moreover, the number of publications and the number of their citations were utilized as proxy measures of the quality and quantity of the analyzed documents regardless of their actual scientific value.

The analysis revealed the complexity and broadness of ET_c research while emphasizing the significance of transdisciplinary and multidisciplinary approaches to investigate related research questions. Over the past 35 years, research themes have diversified, new concepts have emerged, and researchers worldwide have employed various approaches, tools, and methodologies to address research questions in this field. Thematic analysis indicates that topics such as crop evapotranspiration and reference evapotranspiration are still underdeveloped, suggesting the need to focus on these areas to fill existing knowledge gaps and advance both theoretical understanding and practical applications. The findings regarding leading authors, countries, and academic and research organizations can serve as a foundation for establishing meaningful scientific collaborations in the future, fostering further research growth and scientific advancements. Additionally, as the topics of crop evapotranspiration research rapidly evolve, addressing the lack of basic information on crop water requirements becomes crucial for improving water use efficiency and irrigation management. Therefore, future research efforts should contribute to enhancing our understanding of crop water requirements and their application in irrigation management, while also ensuring continuous updates to the existing body of knowledge to meet future challenges.

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AUTHOR CONTRIBUTIONS

Wilfredo B. Barrera Jr.: Conceptualization, Methodology, Formal analysis, Visualization, Writing- Original draft, Writing- Reviewing and Editing.

Anna Dalla Marta: Conceptualization, Supervision, Writing- Reviewing and Editing.

Roberto Ferrise: Conceptualization, Supervision, Writing- Reviewing and Editing.

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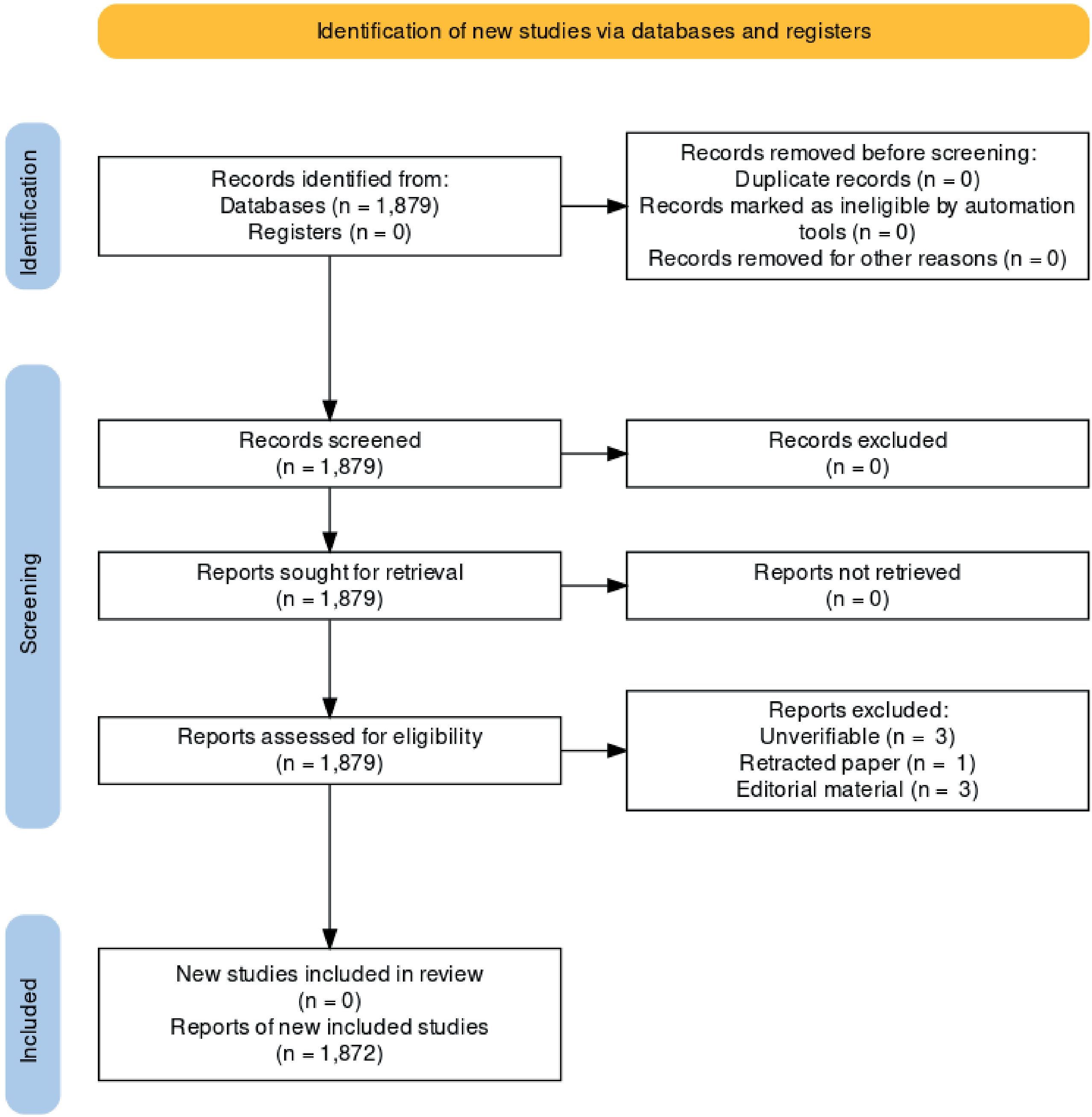

Appendix Figure 1. Procedure applied for document selection for the bibliometric review and thematic analysis (PRISMA protocol).

Appendix Table 1. General information of the bibliographic data.

Description	Results
Timespan	1987-2022
Sources (journals, books, etc.)	496
Documents	1872
Annual growth rate (%)	16.19
Document average age	8.4
Average citations per document	19.97
References	44639
Keywords plus	2389
Author's keywords	3739
Authors	5480
Authors of single-authored documents	70
Single-authored documents	74
Co-authors per document	4.56
International co-authorships (%)	30.77
Article	1596
Book chapter	2
Conference paper	230
Review paper	44

Appendix Table 2. Number of publication and citation metrics of the most influential authors with at least 15 documents. The affiliation of author was retrieved from Scopus database through 'author search'. Legend: TC-total citations; NP-number of publications; SYP-start of the year of publication.

Author	h index	g index	m index	TC	NP	SYP	Affiliation
Pereira LS	25	36	0.9620	2883	36	1998	University of Lisbon
Kustas WP	17	29	0.8100	1063	29	2003	U. S. Department of Agriculture, Agricultural Research Service
Irmak S	11	21	0.5240	466	26	2003	Pennsylvania State University
Neale CMU	12	22	0.5220	741	22	2001	University of Nebraska
Paredes P	19	22	1.5830	1026	22	2012	University of Lisbon
Anderson MC	13	21	0.6190	995	21	2003	U. S. Department of Agriculture, Agricultural Research Service
Allen RG	16	20	0.5710	2243	20	1996	University of Idaho
Gowda PH	13	20	0.7650	697	20	2007	U. S. Department of Agriculture, Agricultural Research Service
Howell TA	14	18	0.5830	1346	18	2000	U. S. Department of Agriculture, Agricultural Research Service
Prueger JH	13	18	0.8130	605	18	2008	U. S. Department of Agriculture, Agricultural Research Service
Chavez JL	11	17	0.6470	658	17	2007	Colorado State University
Cui NB	8	17	1.1430	293	17	2017	Sichuan University
Kang SZ	13	16	0.7650	554	16	2007	China Agricultural University
Nieto H	8	16	0.7270	300	16	2013	Institute of Agricultural Sciences, ICA-CSIC
Olioso A	9	16	0.3100	419	16	1995	Ecologie des Forêts Méditerranéennes (URFM)
Ortega-Farias S	7	16	0.3500	332	16	2004	Universidad de Talca
Calera A	8	15	0.4000	367	15	2004	Universidad de Castilla-La Mancha
Gonzalez-Dugo MP	8	15	0.4440	438	15	2006	Centro IFAPA Almeda del Obispo
Lopez-Urrea R	7	15	0.3890	309	15	2006	Info Instituto Tecnico Agronomico Provincial de Albacete
Raghuwanshi NS	11	15	0.4230	746	15	1998	Indian Institute of Technology Kharagpur

Appendix Table 3. Number of publications and citation metrics of sources with at least eight documents. The impact factor of the journal was retrieved from the 2021 Journal Citation Reports (Clarivate Analytics, 2022). Legend: TC-total citation; NP-number of publication; SYP-start of the year of publication; AC-average citation; IF-impact factor; NR-no record.

Sources	h index	g index	m index	TC	NP	SYP	AC	IF	Publisher
Agricultural Water Management	46	74	1.438	7503	221	1992	33.95	6.611	Elsevier-ScienceDirect
Remote Sensing	20	36	1.429	1498	80	2010	18.73	5.349	Multidisciplinary Digital Publishing Institute (MDPI)
Journal of Hydrology	26	46	0.897	2216	69	1995	32.12	6.708	Elsevier-ScienceDirect
Journal of Irrigation and Drainage Engineering	22	40	0.667	1730	68	1991	25.44	NR	American Society of Civil Engineers
Agricultural and Forest Meteorology	27	46	0.931	2253	59	1995	38.19	6.424	Elsevier-ScienceDirect
Water	12	17	0.857	416	58	2010	7.17	3.530	Multidisciplinary Digital Publishing Institute (MDPI)
Irrigation Science	24	46	0.8	2211	53	1994	41.72	3.519	Springer Nature
Theoretical and Applied Climatology	12	20	0.857	448	31	2010	14.45	3.410	Springer Nature
Hydrological Processes	14	28	0.467	949	28	1994	33.89	3.784	Wiley
Computers and Electronics in Agriculture	14	24	1.167	623	28	2012	22.25	6.757	Elsevier-ScienceDirect
Remote Sensing of Environment	19	26	0.576	1765	26	1991	67.88	13.850	Elsevier-ScienceDirect
Hydrology and Earth System Sciences	16	25	1.067	1003	25	2009	40.12	6.617	European Geosciences Union
Water Resources Research	6	9	0.286	412	9	2003	45.78	6.159	Wiley
Ecological Modelling	7	8	0.269	324	8	1998	40.50	3.512	Elsevier-ScienceDirect

Appendix Table 4. Most cited documents (only documents with at least 200 citations are presented). Legend: TC-total citation; TCY-total citation per year; NTC-normalized total citation.

Authors	Title	DOI	TC	TCY	NTC
Allen et al. (2011)	Evapotranspiration information reporting: I. Factors governing measurement accuracy	10.1016/j.agwat.2010.12.015	561	43.15	19.17
Rana et al. (2000)	Measurement and estimation of actual evapotranspiration in the field under Mediterranean climate: a review	10.1016/S1161-0301(00)00070-8	425	17.71	7.24
Pereira et al. (2015)	Crop evapotranspiration estimation with FAO56: Past and future	10.1016/j.agwat.2014.07.031	351	39.00	14.61
Mcmahon et al. (2013)	Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: a pragmatic synthesis	10.5194/hess-17-1331-2013	350	31.82	10.82
Kumar et al. (2002)	Estimating Evapotranspiration using Artificial Neural Network	10.1061/(ASCE)0733-9437(2002)128:4(224)	317	14.41	5.61
Allen (1996)	Assessing Integrity of Weather Data for Reference Evapotranspiration Estimation	10.1061/(ASCE)0733-9437(1996)122:2(97)	274	9.79	5.85
Allen and Pereira (2009)	Estimating crop coefficients from fraction of ground cover and height	10.1007/s00271-009-0182-z	273	18.20	7.02
Berni et al. (2009)	Mapping canopy conductance and CWSI in olive orchards using high resolution thermal remote sensing imagery	10.1016/j.rse.2009.06.018	266	17.73	6.84
Gowda et al. (2008)	ET mapping for agricultural water management: present status and challenges	10.1007/s00271-007-0088-6	255	15.94	5.63
Drexler et al. (2004)	A review of models and micrometeorological methods used to estimate wetland evapotranspiration	10.1002/hyp.1462	250	12.50	7.28
Norman et al. (2003)	Remote sensing of surface energy fluxes at 10^1-m pixel resolutions	10.1029/2002WR001775	248	11.81	4.90
Allen et al. (2011)	Satellite-based ET estimation in agriculture using SEBAL and METRIC	10.1002/hyp.8408	237	18.23	8.10
Cai et al. (2007)	Estimating reference evapotranspiration with the FAO Penman–Monteith equation using daily weather forecast messages	10.1016/j.agrformet.2007.04.012	221	13.00	6.64
Hanasaki et al. (2010)	An estimation of global virtual water flow and sources of water withdrawal for major crops and livestock products using a global hydrological model	10.1016/j.jhydrol.2009.09.028	215	15.36	6.77
Fan et al. (2018)	Evaluation of SVM, ELM and four tree-based ensemble models for predicting daily reference evapotranspiration using limited meteorological data in different climates of China	10.1016/j.agrformet.2018.08.019	205	34.17	12.05

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Transpiration by sap flow Thermal Dissipation Method: applicability to a hedgerow olive orchard

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Abstract. The climate change requires thrifty use of water resources in agriculture since irrigation is became common also for those crops like olive orchard that were traditionally grown in rainfed conditions. The water requirement is imperative in semi-arid conditions of the Mediterranean basin especially if the olive orchards are cultivated in super high density. For a correct irrigation scheduling, methods to measure transpiration (Tr) at plant level are used. Among the most spread methods to determine Tr, the thermal dissipation method (TDM) has been applied on a hedgerow olive orchard considering: (i) species-specific local calibration, (ii) wound effects, (iii) azimuth correction, and (iv) radial gradient corrections. The performances of the corrected TDM method have been evaluated with respect an independent method, the water balance at weekly scale. If any correction nor specific calibration is carried out, the underestimation of the actual transpiration calculated by TDM was of about -18% with respect to the water balance method.

Keywords: *Olea europaea* cv. *Arbosana*, semi-arid climate, wound effect, radial gradient effect, azimuthal effects, water balance.

HIGHLIGHTS

- Transpiration (Tr) on olive orchard was measured by thermal dissipation method (TDM)
- calibration, wound effects, azimuth and radial gradient corrections were applied
- Tr by uncorrected TDM was of about -18% with respect to Tr by water balance method

1. INTRODUCTION

The increasing instabilities of precipitation regimes, together with the stable increase of air temperature due to the global warming, requires the adaptation of agronomic techniques to climate change. Irrigation is common also for those crops that were commonly grown in rainfed conditions. In the Mediterranean basin, the case of olive is emblematic: this fruit tree crop is notably efficient to face drought, and although it is very well adapted to the arid and semiarid climates (Tognetti et al. 2009), it is often irrigated to save the production and the oil quality (Iniesta et al. 2009). Since last decades of the past century olive growing moved towards great intensification, with the large diffusion in Mediterranean region of the super high density (SHD) cropping systems. These full mechanized olive groves, known as hedgerow orchards, as well, are characterised by a density over 1,200 trees per hectare and by continuous fruit harvesting and show positive both economic and environmental impacts compared to rainfed traditional olive orchards (Russo et al. 2015).

The Mediterranean region is known to be strongly negatively affected by air temperature increase and changes of seasonal rainfall distribution (Katerji et al. 2017). In these weather conditions, SHD olive cropping systems significantly decrease water use under irrigated conditions, with an estimated reduction in water footprint of one half with respect to the traditional ones (Pellegrini et al. 2016).

To correctly evaluate the water requirement of a crop, it is necessary to determine with high accuracy the actual evapotranspiration (Katerji et al. 2008), particularly complex for orchards, since the water follows complex paths for tree transpiration (Tr) and soil evaporation, separately (Scanlon and Kustas 2012). The micrometeorological methods generally resulted the best way to measure evapotranspiration (ET) with a suitable accuracy, but measurements must be carried out above large surfaces (Lee et al. 2004). When large surfaces are not available or are not homogeneous, methods to measure transpiration at plant level are preferred, and the most spread methods to determine Tr are the techniques based on the measurement of the sap flow density (Rana and Katerji 2000). The thermal dissipation method (TDM) (Granier 1985) has been frequently used to determine actual transpiration of olive orchards in different situations (Masmoudi et al. 2011; Cammalleri et al. 2013; Agüero Alcaras et al. 2016; Conceição et al. 2017). However, while TDM-type sap flow sensors are surely suitable to monitor the dynamics of the sap flow or for comparing different treatments in relative terms, they cannot be used to quantify water losses by trees in absolute terms, unless species-specific calibration has carried out (Fuchs et al. 2017; among others). Furthermore, systematic underestimations of the transpiration determined by TDM approach (see Flo et al. 2019 for a review) occur, due to: (i) wound effects (Wullschleger et al. 2011; Wiedemann et al. 2016); (ii) errors due to azimuthal variations (Molina et al. 2016; Shinohara et al. 2013); and (iii) errors caused by differences in radial gradient sap flux density profiles (Clearwater et al, 1999; Cohen et al. 2008; Bush et al. 2010).

The general objective of this study was to analyse the applicability of TDM to olive trees (cv. *Arbosana*) grown in a hedgerow orchard submitted to full irrigation regime. Sap flow density was monitored by TDM for 15 weeks in 2022 in a Mediterranean region (southern Italy), considering the species-specific local calibration, the wound effects, the azimuth correction, and the radial gradient corrections. This TDM transpiration was compared with an independent method (soil water balance) and the percentage correction was quantified with respect to the TDM application without considering all these corrections.

2. MATERIALS AND METHODS

2.1 The experimental site

The study was carried out in the period 26 June – 30 September 2022, including the most evaporative demanding periods in the site (Katerji et al. 2017). The olive orchard (cv. *Arbosana*) is located at the University of Bari experimental farm, southern Italy (41°01'N; 16°45'E; 110 m a.s.l.), on a shallow sandy clay soil (sand 630 g kg^{-1}; silt 160 g kg^{-1}; clay 210 g kg^{-1}) classified as a Typic Haploxeralf (USDA) or Chromi-Cutanic Luvisol (FAO). At 0.5 m of depth is present a parent rock that reduces the capacity of the root systems to expand beyond this layer. The site is characterised by typical Mediterranean climate with a long-term average (1988-2018) annual rainfall of 560 mm, two third concentrated from autumn to winter, and a long-term average annual temperature of 15.6 °C. The olive grove has been planted in early summer 2006; the self-rooted trees were trained according to the central leader system and spaced 4.0 m × 1.5 m (1,667 trees ha^{-1}) with a North–South rows orientation. Trees were 1.75±0.46 m high. Routine nutrition and soil management, pests and diseases control practices were set up as described by Camposeo and Godini (2010). Irrigation was scheduled following the FAO56 guideline (Allen et al. 1998), restoring 86% of crop evapotranspiration. The plots were irrigated by a dripline equipped with 2.5 L h^{-1} emitters, 0.6 m apart.

Air temperature (T_{air}, °C) and vapour pressure deficit (D, kPa) through air relative humidity, global radiation (R_g, W m^{-2}) and precipitation (P, mm), wind speed (u, ms^{-1}) were collected at a standard agrometeorological station 120 m far from the experimental field. Net Radiation R_n in Wm^{-2}, was calculated following Allen et al., (1998) as Rana and Katerji (2009):

$$Rn = (1-\alpha)R_g - \sigma\left(\frac{T_{max}^4+T_{min}^4}{2}\right)\left(0.34-0.15\sqrt{e_a}\right)\left(1.35\frac{R_g}{R_{g0}}-0.35\right) \quad (1)$$

where α is the albedo of the crop, directly determined on the orchard as mean of hourly daytime values (0.27) from January to December 2021; T_{max} and T_{min} (K) are maximal and minimal air temperatures; σ (4.903 10^{-9} MJ K^{-4} m^{-2} day^{-1}) is the Stefan-Boltzman constant; e_a (kPa) is the actual vapour pressure; R_g (MJ m^{-2}) was integrated in the time interval and R_{g0} (MJ m^{-2}) is the calculated clear-sky radiation (Allen et al. 1998). After a local calibration of twelve months (January-December 2021), soil heat flux, G, was considered as a constant at daily scale and equal to 0.09 R_n.

Soil water content in volume (θ, m^3 m^{-3}) was measured by capacitive probes (5TM, Decagon Devices Inc., USA). Three points were monitored following the protocol described in Campi et al. (2020): two points in the rows to intercept the dynamics of θ below the dripping lines, and one point among the rows. At each point, two capacitive probes were installed horizontally into the soil profile and transversely to the row, at -0.12 and -0.37 m from the soil surface. All sensors were connected to data-loggers (Tecno.el srl, Italy) and acquired at hourly scale; daily soil water content was determined for the soil profile (0.5 m) by integrating the values measured at each depth, since each probe was supposed to detect the water content in a 0.25 m soil layer. θ measurements from the three points were pooled to obtain a single average value for each treatment.

2.2 The TDM method

The transpiration at tree level, as determined by TDM, foresees the measurement of difference in temperature (ΔT, °C) between two probes placed in the conducting xylem of the stem; when the sap flow is low, or close to zero, a maximum difference in temperature (ΔT_{max}) is recorded and the variable K [unitless] was calculated as:

$$K = \frac{\Delta T_{max}-\Delta T}{\Delta T} \quad (2)$$

ΔT_{max} was determined using night-time measurements, separately for each sensor, according to Lu et al. (2003) and Peters et al. (2010).

Commercial 20 mm sap flow probes (SFS2 Type M, UP, Steinfurt, Germany) were installed at 0.30-0.40 m height above the ground. Probes were installed in each sampled tree in the north side to avoid direct solar heating; to prevent thermal interference, the heated probe was inserted 0.10 m above the unheated one; the probes in each sampled tree were covered by a reflecting radiation screen which also protected them from rain. ΔT was continuously monitored by a data loggers (CR10X, Campbell Scientific, Utah, USA) every 10 s, and the average values recorded every 10 min, to be further averaged at hourly scale.

The sap flow density (J_{s0}, gm^{-2}s^{-1}) was determined by the relation (Granier 1985; Lu et al. 2003):

$$J_{s0} = aK^b \quad (3)$$

with a and b determined by specific calibration as detailed in the following. Measurements were carried out in three replicate trees chosen to be representative of the olive orchard, considering the similar vigour, according to frequency distribution of trunk diameters and tree size of whole plot.

2.3 The TDM species-specific local calibration

According to Alarcón et al. (2005), McCulloh et al. (2007) and Zhou et al. (2017), the calibration to find the specific coefficients a and b in the Eq. (3) was carried out on three 5-year-old trees of the investigated variety (*Arbosana*) cultivated in pots placed in plastic cylindric pots (diameter 0.45 m, height 0.66 m) filled by the same soil of the experimental field and mulched by a plastic film to avoid soil evaporation. Sap flow density J_{s0} was computed as

$$J_{s0} = \frac{Tr_m}{SWA} \quad (4)$$

where Tr_m is the measured transpiration (g s^{-1}) determined by recording the weight loss in the pots at 150 minutes intervals, for one week (15 – 21 July 2022) during daytime, with an electronic balance (Radwag, Poland, model C315.150.C5.K). Every 150 minutes, the pot weights were obtained by averaging measurements carried out every one minute for 10 minutes; the pots were placed in open air, close to the experimental field to avoid differences in the mean meteorological conditions. SWA is the sapwood area determined by measuring sapwood depth on a core collected, at the end of the experiment, with a 5-mm-diameter increment borer at the middle between the two probes in the north side of monitored trees (Rana et al., 2019). At the same time, ΔT was continuously monitored by the same type of TDM sap flow probes used in the field, following the same protocol, recording data every 10 s (data logger CR10X, Campbell Scientific, Utah, USA), with the average values recorded every 10 min. In post processing, the 10-minute values were averaged to meet the interval times of the pot weight determination. By using these measurements of temperature, K values were determined. The calibration curve is obtained plotting the J_{s0} of eq. (4) vs the K values.

2.4 The TDM corrections

To assure the correctness of the TDM in the sap flow density measurement at tree level, J_{s0} was corrected for: (i) the damages caused by the trunk wounds by the probes set up, (ii) the azimuth variations (iii), the radial gradient of sap velocity in trunks.

2.4.1 The wound effect

A coefficient C_w was determined to correct the sap flow density for the wound effects (Wiedemann et al. 2016). For this aim, a couple of TDM probes (20 mm) were installed in parallel to the already measuring probes (installed in the first part of January 2021) in two trees, at the same height and 20 mm from the already installed ones, in the period 23 June – 23 August 2022. Hence, since the wound effect is due to the probe insertion in the trunk and then, affects the measured ΔT, correction is limited to the K parameter (see eq. 2) and the sap flux density becomes:

$$J_{s0} = a(C_w K)^b \quad (5)$$

2.4.2 The azimuth effect

The azimuthal variations of sap flux density were analysed in two sampled trees, by adding two couples of TDM probes (20 mm) at 120° and 240°, in the period 23 June – 23 August 2022. For taking into account this azimuth effect, a correction coefficient due to azimuthal variations, C_a, was introduced following Shinohara et al. (2013), to extrapolate sap flux density in the north direction, using the north sensor as a reference to the three integrated directions (averaged over the three directions). Hence, C_a is calculated as the ratio of the mean sap flux density in the three directions to sap flux density in the north direction; therefore, the sap flow density is now:

$$Js_0 = C_a a(C_w K)^b \quad (6)$$

2.4.3 The radial gradient effect

Finally, to account for radial gradient in sap flux density, following Ford et al. (2009) the whole sapwood depth of each sampled tree was divided in a set of 20 mm increments and a 3-parameter Gaussian function (Ford et al. 2004) was applied to estimate the sap flux density in each increment. In this application, the denominator of the exponent in Eq. (5) is inversely related to the rate of decrease in sap flux density with radial depth; the fitting of this parameter allows that the rate of radial decrease varied from tree to tree and with time (Ford et al. 2004). In this case, as suggested by Pataki et al. (2011), for angiosperms the used function is:

$$J_{si} = 1.033 J_{s0} \exp\left[-0.5\left(\frac{x-0.09963}{0.4263}\right)^2\right] \quad (7)$$

where J_{si} (g m^{-2} s^{-1}) is the sap flux density in each increment i, x is the normalized depth of each sapwood increment ($0 \le x < 1$) and J_{s0} is calculated using Eq. (6).

Here, to test the used function (Eq. 7) over the active sapwood (Rana et al., 2019), two new set of TDM probe were installed in parallel to the already measuring probes in two sampled trees, at the same height and 20 mm from the other ones, in the period 23 June – 23 August 2022. In this case, beyond the 20 mm probes, commercial sap flow probes of 10 mm length (SFS2 Type M, UP, Steinfurt, Germany) were installed. From the sap flow density measured from the couple of probes, the J_{s0} values in the layer 10–20 mm of the sapwood depth was derived according to Iida and Tanaka (2010) as follows:

$$J_{s10\text{-}20} = \frac{J_{s\,0-20} - \alpha J_{s\,0-10}}{\beta} \quad (8)$$

where α and β are the proportions of the sapwood area from depths of 0–10 mm to that of 0–20 mm, and from depths of 10–20 mm to that of 0–20 mm, respectively.

2.5 The transpiration at field scale

Finally, the whole tree transpiration of each sampled tree (Tr_{tree}, g s^{-1}) was determined as:

$$Tr_{tree} = \sum_{i=0}^{m} J_{si} SWA_i \quad (9)$$

where m is the number of 20-mm increments in sapwood depth (m=2 for the sapwood depth measured in this case), J_{si} is the sap flux density determined by Eq. (7) and SWA_i is the sapwood area at each depth increase i. SWA was determined as above described in pot experiment.

Since Tr_{tree} measurements were referred to the projected canopy area, transpiration by TDM at field scale was calculated as

$$Tr_{TDM} = A_p \overline{Tr_{tree}} \tag{10}$$

where Tr_{TDM} is expressed per unit of projected canopy area, i.e., kg m^{-2} or mm, with $\overline{Tr_{tree}}$ the mean of the monitored trees and A_p (m^2) the area occupied by the mean vertical projection of each tree, (Lu et al. 2003).

A_p was calculated using a digital surface model (DSM) obtained from an automatic flight of an Unmanned Aerial Vehicle (UAV); a Phantom 4 multispectral with RTK system was used. The flight was planned at 40 m altitude with 85% overlap in vertical and horizontal. The acquired images were processed with Pix4d software to obtain the orthomosaic and DSM. The DSM was then used in QGIS environment to extract the canopy surface in accordance with Albuquerque et al. (2022) and Torres-Sanchez et al. (2017) (Figure 1). A value of A_p equal to 0.25 was used in eq. (1).

Transpiration on daily time scale was calculated by integrating transpiration at daytime (i.e., when $R_g > 10$ W m^{-2}).

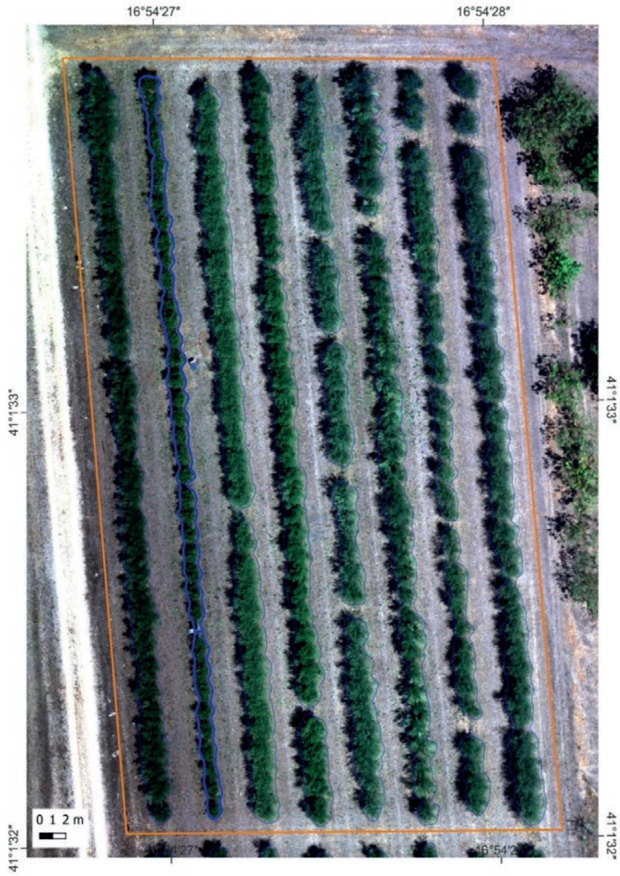

Figure 1. Canopy surface of the Valenzano experimental olive grove obtained with DSM processed from Phantom 4 drone images. The row outlined in blue is the one relating to the species analysed in this study.

2.6 Soil water balance

According to Fujime et al. (2021) the test and performance evaluation of the transpiration determined by the applied TDM has been carried out by comparing the transpiration Tr_{TDM} (mm) calculated by the Eq. (10) and the transpiration calculated from soil water balance Tr_{WB} (mm). In this Mediterranean site, characterised by shallow soil irrigated by localized drip irrigators, the soil water balance can be written:

$$ET_{WB} = P_{eff} + Ir \pm \Delta SWC \tag{11}$$

with ET_{WB} evapotranspiration (mm), P_{eff} effective rain (mm), Ir irrigation (mm); ΔSWC (mm) the difference of soil water content in the time interval; the deep percolation, runoff and capillary rising terms were considered neglectable (Rana and Katerji 2000). Due to the relatively high soil infiltration rate and the flat field, all rainfall over 0.2 mm was considered as effective precipitation (Villalobos and Fereres 2017).

Tr_{WB} comes from subtracting soil evaporation (E_S) from ET_{WB} as

$$Tr_{WB} = ET_{WB} - E_s \tag{12}$$

According to López-López et al. (2018), E_S was calculated following Bonachela et al. (2001), who modelled this term specifically for drip irrigated olive orchards. E_s is the sum of three terms: the water evaporated from the not wetted area (Bonachela et al., 1999), the water evaporated from the wetted area by emitters and a term which accounts for the advection effects increasing the evaporation from wetted zones.

3. RESULTS AND DISCUSSION

3.1 The TDM species-specific local calibration

The calibration curve obtained by the pots' experiment is shown in Figure 2, where the sap flow density values are fitted by a power function of K with specific coefficients a and b (see Eq. 3) equal to 140.0 and 1.118, respectively; this curve is robust (R^2 = 0.856) and slightly different from the original Granier (1985) calibration curve also reported in Fig. 2 . The new calibration curve had a slightly steeper slope and higher J_{s0} values along the whole K domain than the original Granier curve (a=118.9, b 1.231). This discrepancy resulted in overall underestimation of actual J_{s0} values by the original Granier curve.

Often, the used methods to calibrate the TDM species-specifically are based on gravimetrically induced flows through a stem segment (Roberts 1977; Vertessy et al. 1997; Bush et al. 2010; Sun et al. 2012). Although these cut-tree methods can be considered as the only way to directly obtain gravimetric measurement of water circulation for large trees at suitable time scale, Merlin et al. (2020) showed that these complex apparatus and studies present many disadvantages and limitations, mainly due to the separation of the crown and stem from the root system, which can much alter the correct evaluation of water uptake by trees. Conversely, weighting lysimeters, which are quite similar to the system pot plus balance here used, can provide suitable TDM calibration (Merlin et al. 2020) for young olive trees.

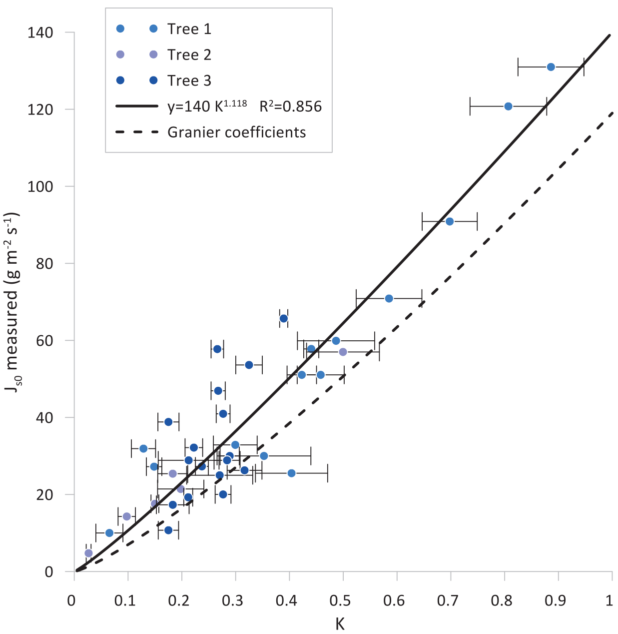

Figure 2. Calibration curve of the Thermal Dissipation Method (TDM). J_{S0} is the sap flow density measured by using eq. (4) in the text. K values have been obtained by TDM and eq. (2) in the text. The original Granier curve (a=118.9, b 1.231) is also reported.

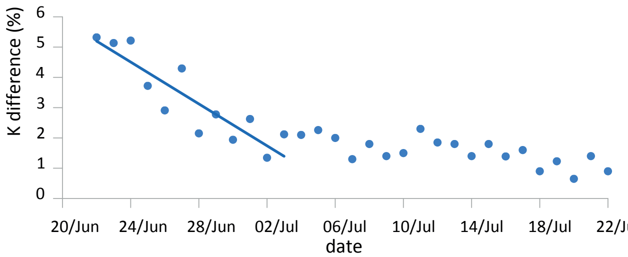

Figure 3. The relative difference between K values (see eq. 2 in the text) measured by the probes just installed and the oldest ones.

3.2 The TDM corrections

Regarding the wound effects, the relative difference between the K variable measured by the probes just installed and the probes installed in the first part of January 2021 is shown in Figure 3, from which a correction factor C_w=1.06 was calculated on K daily values. The correction factor due to wound effects is strongly dependent on the species (Wiedermann et al., 2016): in this case study, the found value is in the range reported by Reyes-Acosta et al. (2012) for another diffuse porous species (*Fagus sylvatica* L.). Moreover, the wound effects seem to vanish in around two weeks (see Fig. 3) against the four weeks reported by Wiedermann et al. (2016).

To evaluate the azimuthal corrections, the relationship between J_{s0} averaged for all probe directions ($J_{s0\text{-}avg}$) and J_{s0} at north direction ($J_{s0\text{-}North}$) is reported in Figure 4. The slope of this robust linear regression (R^2= 0.999) was used as azimuthal correction (C_a =1.29 in Eq. (6)). López-Bernal et al. (2010) found a variation of azimuthal sap flow density higher (C_a=1.58) in mature olive trees well irrigated; similar azimuthal variations were found in young olive trees by Vandegehuchte et al. 2012. Since azimuthal variability were mainly dependent on the structure of the sapwood (Vandegehuchte et al 2012) and variation of soil water content in the root zone (Fernández et al. 2001), the results of this study, with a lower correction coefficient for azimuthal variations, could be due to the regular structure of the olive orchard and the well localized drip irrigation.

The comparison between the adopted Gaussian function (Eq. 7) and the actual measurements of J_{s0} in the two sampled trees in the two layers (0-10 and 10-20 mm) is shown in Figure 5, using all available data at daily time

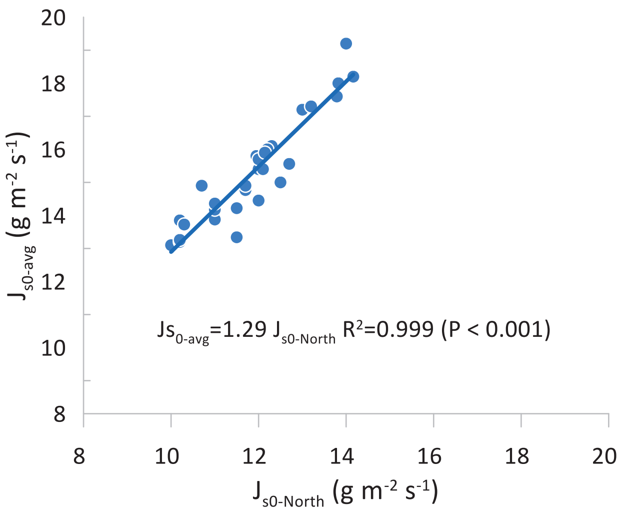

Figure 4. Relationship between sap flow density J_{s0} averaged for all probe directions ($J_{s0\text{-}avg}$) and J_{s0} at north direction ($J_{s0\text{-}North}$).

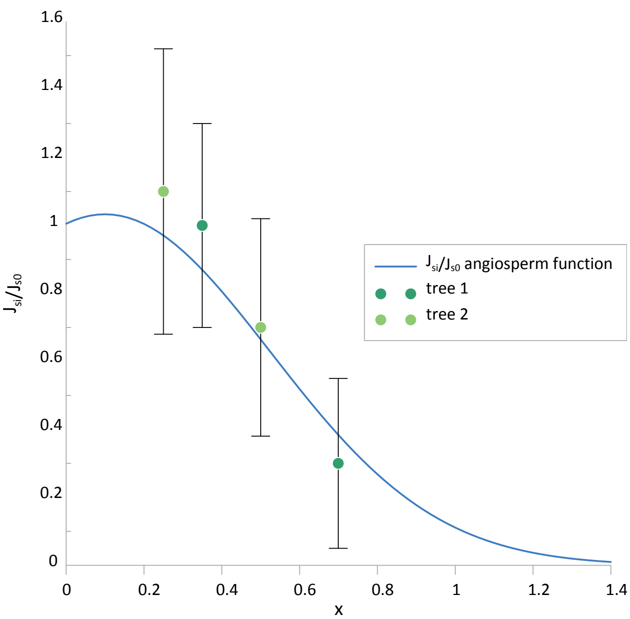

Figure 5. Sap flow density J_{s0} ration in the two sampled trees in the two layers of 0-10 and 10-20 mm vs x, the normalized depth of each sapwood increment.

scale. From this figure it seems clear that the used function to consider the gradient sap flow density over the sapwood works well enough in the present study. These results are supported by Rana et al. (2019), who successfully used the same function in mature olive trees under similar pedoclimatic conditions in urban environment.

Figure 6 presents the comparison between the two methods of determining *Tr* at weekly scale, TDM (spe-

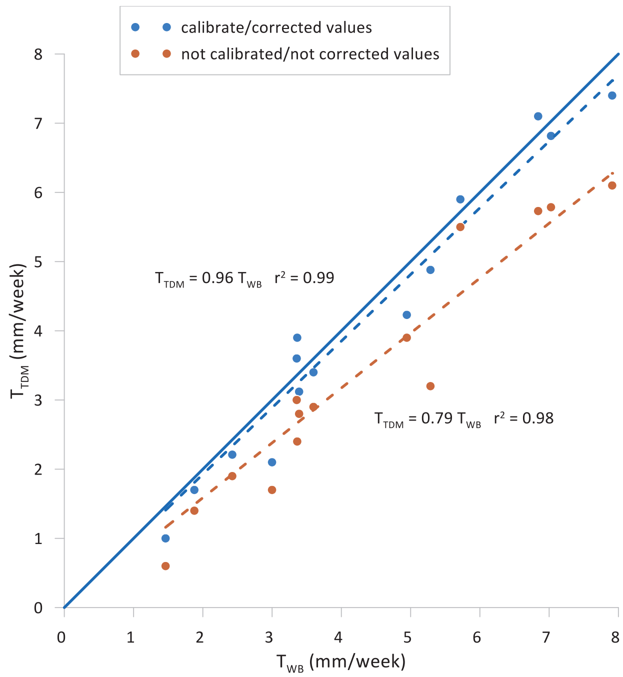

Figure 6. Transpiration by TDM method (T_{TMD}) vs Transpiration by water balance method (T_{WB}). The line 1:1 is also reported.

cies-specific local calibrated and corrected for all the above-mentioned effects) and soil water balance. Generally, both methods agreed in the estimates of transpiration at field scale, with a slight underestimation of the TDM with respect to the soil water balance; the cumulated values were 57.4±3.4 and 60.2±4.1 mm for the TDM and soil water balance, respectively, with an underestimation of about -5% for the cumulated values in the whole considered experimental period. Other publication compared soil water balance and sap-flow methodologies (Oren et al., 1998; Kang et al.,2003; Gong et al., 2007), but without a suitable independent estimation of soil evaporation. López-López et al. (2018), with a similar approach in the separate estimation of soil evaporation, found that the Compensation Heat Pulse sap flow technique applied to an almond crop overestimates the water balance transpiration values of about 10%.

In Figure 6, also the comparison between Tr determined by TDM without specific calibration and corrections and soil water balance: in this case the underestimation of TDM is quite high, with cumulated value equals to 46.9 mm for the uncorrected and uncalibrated TDM.

4. CONCLUSIONS

This study proved that the thermal dissipation sap flow method applied to a super high-intensive hedgerow olive orchard can be used to quantify the actual transpiration only after several suitable species-specific characterizations. In particular: (i) the species - specific calibration was carried out by comparing TDM transpiration values with those directly measured in pots; (ii) the correction for the wound effects of the probes in the tree trunk was made by measuring the sap flow density with new probes on the same tree; (iii) the correction for the azimuth variability was estimated by measuring the sap flow density at different oriented trunk sectors; and finally (iv) adoption of a suitable Gaussian function to take into account the radial gradient variation of sap flow density over the sapwood area. If any correction nor specific calibration is carried out, the underestimation of the actual transpiration calculated by TDM was of about -18% with respect to the Tr estimated by a suitable water balance method, with the evaporation from the soil modelled by a specific olive orchard method.

The presented results support the widely accepted conclusions that: (i) for thermal dissipation method it should not be assumed that the original calibration is appropriate in all cases; (ii) corrections are necessary to mitigate the invasiveness of the probe use; (iii) the interaction between probes and sapwood could be suitably modelled.

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Italian winegrowers' and wine makers' attitudes toward climate hazards and their strategy of adaptation to the change

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Abstract. This study reports the results of a survey disseminated to Italian winegrowers and wine makers to understand their attitude toward the main climate risk factors on grape and wine productions and their willingness to proactively act in facing the related consequences. A general noticeable concern about the future effects of climate change and variability emerged, even with some differences between stakeholders operating in different geographic and climatic areas. Current signals of adaptation mostly emerged at technological level, but they also included the varietal choice, with evidence to a switch from traditional varieties to others showing better pest and drought tolerance. In addition, some climate-smart cultural practices are considered ranging from water-saving irrigation methods to sustainable energy management.

Keywords: climate change, grapevine, wine, adaptation, survey.

HIGHLIGHTS

- Climate change concerns currently appear to be as relevant as the economic ones in the wine sector.
- Concern for climatic hazards strongly increases for the future scenarios, compared to the present situation.
- In the choice of varieties, the preference of market-driven ones prevails over the "climate-resilient" ones.
- Impact of climate change on wine quality is clearly less perceived in the southern Mediterranean.
- To date, weather event insurance as a tool for farm income stability seems still poorly appreciated.

1. INTRODUCTION

Climate is a determinant forcing factor on grapevine vegetative and productive growth (Van Leeuwen et al., 2004; Neethling et al., 2019), with a greater effect on vine development and fruit composition (Van Leeuwen and Darriet, 2016). CC effects on wine production, and their quantitative and qualitative socioeconomic impacts at stake, have been investigated for few decades (Jones et al., 2005; Ashenfelter and Storchmann, 2010; Webb et al., 2012; Droulia and Charalampopoulos, 2022). In the Mediterranean area, the change entails an overall temperature increase, local changes in precipitation patterns, but also the increase in the frequency of extreme event e.g. heat waves, hailstorms, late frost spells, and excessive rainfall events negatively affecting all crops, and particularly highly specialized ones as grapevine (Bindi et al., 1996; White et al., 2006; Fraga et al., 2013a; Mosedale et al., 2015). In addition, the vegetative cycle of plants is already taking place in warmer and drier conditions, showing a general anticipation of some phenological stages over time. The earlier budding timing thwarts the potential reduction of frost risk, enhanced by a possible higher temperature variability (Mosedale et al., 2015), and the dynamics of diseases and pests may be influenced (Castex et al., 2018; Van Leeuwen et al., 2019). On the other hand, earlier ripening induces a change in the composition of the grapes and their qualitative potential, with direct influence on higher sugar and lower acidity levels, but also on secondary metabolites, affecting wine quality (Tate, 2001; Mira de Orduña, 2010).

A major consequence of CC is the negative trend in water availability (Fraga et al., 2018; Weiler et al., 2019). Grapevine itself can tolerate moderate drought events as vineyards have been traditionally grown on relatively dry and scarce soils, allowing to favor the production of high-quality wines (Koundouras et al., 1999, Chacón-Vozmediano et al., 2021).

The concept of *terroir*, conceived for typical wine production bound to their geographic, environmental, and cultural contexts, represents the linkage uniqueness between wines and territories in the agricultural sector (Jones, 2006). It is implicit that CC may become a strong challenge to the permanence of the optimal conditions of grapevine production in their original areas (Van Leeuwen et al. 2004; White, 2020). In general, the idea that specific grapevine varieties will be permanently linked to their original areas might be subject to a revision in the future, and model simulations involving the future development of grapevine growing witness the interest in such prognostic exercises (Jones, 2006; Malheiro et al., 2010; Moriondo et al., 2011; Hannah et al., 2013; Eccel et al., 2016; Alikadić et al., 2019). In the wine sector, the existence of a climate-driven risk is particularly evident (Seccia et al., 2016), with an expectation of a further change in the configuration of the Italian grapevine cultivation areas. The Mediterranean region is in fact a climate “hot spot”, with temperature increase higher than in other geographic regions (Fraga et al., 2013b; Cos et al., 2022). Heterogeneous impacts of climate changes are envisaged across vine varieties and regions, leading to conditions that might turn out too warm to produce specific Protected Designation of Origin wines (Bernetti et al., 2012; Jones et al., 2006; Alikadić et al., 2019), pointing out the relevance of the adoption of adaptation and mitigation strategies and policies. Such measures should strategically regard the entire value chain, including those enabling to deal with the future impact on grape processing (Droulia and Charalampopoulos, 2021).

Current technical information campaigns aimed at adaptation, that also take into account specifically tailored local climate scenarios, have proven to be successful in increasing the resilience of winegrowers and wine makers, as shown from the California (Babin et al., 2022). Thanks to the economic importance and to its historical tradition, the wine sector, more than other agricultural ones, has always been characterised by a strong capacity of autonomous adaptation, due to the high attention of winegrowers to the environment and, specifically, to climate (Battaglini et al., 2009). However, the strong linkages with cultural and market capital calls for a major effort aiming at an adaptation to the increasing difficulties for farmers and producers imposed by an unprecedented changing environment (Fraga et al., 2013b; Santillán et al., 2019). De Salvo et al. (2019) highlights how, in the specific case of “climate risks”, the adoption of protective measures makes winegrowers more aware of hazard probability, increasing their perception of “residual risk”.

Surveys may be reliable and powerful sources of data and information to provide bases for analysis of the actual and perceived risks, fostering their engagement in supporting adaptation and mitigation strategies. For instance, in Bois et al. (2017), the information retrieved worldwide on the presence of grapevine pests and cryptogamic diseases were used to map their incidence according to present and future climate conditions. Aigrain et al. (2019) utilized an expert-consultation method associated with a bottom-up participatory approach as a foresight exercise to design adaptation policies to CC. Battaglini et al. (2009) depicted the state of awareness and the concerns about CC in the viticultural regions of France, Germany, and Italy, while Teil (2020) focused on the adaptation of the wine supply chain in two viticultural regions of France, and Carroquino et al. (2020) in Spain. Wheeler and Marning (2019) designed a survey on specific water-related and irrigation management issue in arid vine-growing Australian regions – pointing out differences in the behavioural adaptation strategies between conventional, organic, and biodynamic growers. Consultation with farmers may also lead to unexpected results; as in the case of Italian Emilia – Romagna (Merloni et al., 2018), where a countertrend perception of the water issues emerged, as farmers highlighted their concern for water-excess seasons.

A particular aspect of resilience enhancement in agricultural farms is the adoption of insurance policies. In Sicily, Sgroi and Sciancalepore (2022) pointed out that, despite of the positive benefits deriving from the adoption of insurance policies (see, e.g. Russo et al., 2022), the viti-vinicultural enterprise adherence to this opportunity remains below the expectations. It is then urgent to adopt appropriate adaptation policy schemes, to obtain the sector actors' feedback to understand their concern and risk perception, as well as their proactive attitude.

With this aim, under the MEDCLIV project, an European project co-funded from EIT Climate-KIC, a survey was disseminated to the actors of the vine and wine value chain in six EU countries (France, Spain, Italy, Portugal, Cyprus and Slovenia) in their respective national languages. The present work focuses on the results for the Italian community.

2. MATERIALS AND METHODS

2.1 The survey design

The link to the survey was nationally disseminated from May to November 2020 and was extended to winegrowers and wine makers operating in all regions. The questionnaire was accessible online and designed using PHP scripting language.

Survey dissemination strategies were implemented with the objective to reach the largest number of participants and operated with a range of supports. To be mentioned, the collaboration of some larger firms in wine industry which provided their networks to connect with a large community of winemakers and winegrowers, the publication of the survey through articles in specialised journals and magazines and social networks, such as the Facebook page of the project, individual emails to winegrowers and wine producers using addresses published online.

2.2 Questionnaire

Survey firstly informed about preliminary general questions on gender, age and region of production of responders, then addressed questions differently tailored for winegrowers and wine makers.

The questionnaire consisted of a total of 32 questions, 13 for winegrowers (Tab 1.) and 16 for wine makers (Tab. 2), plus three final questions, posed to both categories (Tab 3).

Some questions were single-choice (yes/no), while almost all the others were multiple-choice; this explains, for some answers, percentages higher than 100%. For two questions a five-point Likert scale was used.

The questionnaire was designed by authors and shared with a panel of project experts, with the aim to make it easy to understand, quick to answer and suitable for all countries. In order to minimize early drop-outs of the questionnaire, excessive details and long lists of options were intentionally avoided. For example, the question on the "choice of new varieties" included in the options only some of those indicated in literature as relevant for improving vineyard adaptation to CC (Mozell and Thach, 2014; Fraga et al., 2016; Van Leeuwen and Destrac-Irvine, 2017) and no distinction was made between scion or rootstock.

A five-point Likert scale was used to assess the degree of danger of the listed grape pests (1= no threat; 5 = greatest threat), chosen as the most relevant for MEDCLIV partner countries among those indicated in the EIP-AGRI "Focus Group Diseases and pests in viticulture" (March 2019), by Mira de Orduña (2010) and by Bois et al. (2017). Similarly, only a limited selection of practices recognized in literature as capable to improve CC vineyard resilience were included in the list addressed to winegrowers (Celette et al., 2009; Palliotti, et al., 2013; Van Leeuwen and Destrac-Irvine, 2017).

When questioning about insurance, multi-peril insurance was also included in the list as it is already available in several parts of Europe (Santeramo and Ford Ramsey, 2017), but participants were not asked to further detail the kind of risks included in the insurance cover. To avoid excluding entrepreneurs with more recent business activity, the question about the reference time frame was not posed, leaving respondent free to refer to shorter or longer temporal distance when comparing the past insurance status with present conditions.

The changes in wine characteristics listed in the wine makers questionnaire (i.e., pH and alcoholic content increase and changes in aromatic profile) were those most likely impacting wine quality and its typicality in the future (Van Leeuwen and Destrac-Irvine, 2017).

Table 1. List of questions and their respective variables for winegrowers; SCq = Single choice question; MCq = multiple choice 157 question; LSq = Likert scale question.

N.	Questions for winegrowers	Answer options	Type of response
1	*Total agricultural surface of your vineyard (in hectares)*	< 1 ha; 1 – 5 ha; 6 – 10 ha; 11 – 25 ha; > 25 ha	SCq
2	*What kind of formal viticulture do you practice?*	Conventional; Integrated; Organic; Biodynamic	MCq
3	*Have you introduced in the last years additional varieties in your vineyard?*	Yes; No; No, but I plan to do soon	SCq
4	*Which type of new varieties did you introduce in your vineyard in the last years?*	Pest resistant; drought resistant; cold tolerant; late ripening varieties; early ripening varieties; market demand	MCq
5	*Do you have potential access to water resources in the perimeter of or near your vineyard?*	Yes; No; Partially	SCq
6	*Are your vines irrigated?*	Yes; No; Partially	SCq
7	*If so, which irrigation system do you have?*	Drip; sub-surface (underground); surface; sprinkler; flood	MCq
8	*Would you consider having, implementing or modifying the irrigation system in the future?*	Yes; No; Partially	SCq
9	*Indicate the danger intensity of the following items. Please rate each item on a 1-5 scale, with 1 being no threat and 5 being the greatest threat in a "normal" year.*	Downy mildew (*Plasmopara viticola*) Powdery mildew (*Erysiphe necator*) Grey mould (*Botrytis cinerea*) Grapevine trunk diseases Black–rot (*Guignardia bidwellii*) European grapevine moth (*Lobesia botrana*) Smaller green leafhopper (*Empoasca vitis*) Med. Mealy bugs *(Planococcus ficus)* Brown marmorated stink *bug (Halyomorpha halys)* Citrus flatid planthopper (*Metcalfa pruinosa*) Mites (different sp) Thrips (*Thrips tabaci/Frankliniella* sp.) Flavescence dorée (*Candidatus Phytoplasma vitis*) Pierce's disease (*Xylella fastidiosa*)	LSq
10	*Indicate the cultivation techniques that you employ now and that you did in the past.*	Thinning; use of anti-transpirants; green pruning; leaf removal practices; row cover cropping; late shoot topping (July, August).	MCq
11	*Do you have any insurance?*	Yes; No	SCq
12	*Did you have any insurance in the past?*	Yes; No	SCq
13	*Indicate the insurance policies that you have now compared to those that you had in the past*	Hail; late frost; wind; flooding; drought; wild animal; multi risk	MCq

Questions concerning the adoption of measures in favour of energy saving – and consequently facilitating CO_2 emission reduction – spanned over the main topics included in the survey described by Carroquino et al. (2020).

The three final questions, posed to both categories, addressed the main long-term concerns about one's own firm business and the perceptions of the impact of CC. The list proposed economic and regulation issues, as well CC-related problems; a five-point Likert scale was used to assess the degree of concern (1= no concern; 5= greatest concern).

2.3 Data analysis

Only fully-completed questionnaires were included in the analysis. All the responses were aggregated according to three main Wine Growing Zones (WGZs) identified in European Union (2013) – Appendix I: CI (Trentino-Alto Adige, Val d'Aosta), CII (Abruzzo, Campania, Emilia – Romagna, Friuli – Venezia Giulia, Lazio, Liguria, Lombardy, Marche, Molise, Piedmont, Tuscany, Umbria, Veneto), CIII (Basilicata, Calabria, Apulia, Sardinia, Sicily). This classification, considering the thermal-climate regimes of the regions, appropriately relates to the local influence on the required grape maturity at harvest and the levels of sugar reached.

Table 2. List of questions and their respective variables for winery owners; SCq = Single choice question; MCq = multiple choice question.

N.	Questions for wine makers	Answer options	Type of response
14	*Which category does your winery fall in?*	Single-member property; Cooperative winery; Noncooperative winery	SCq
15	*Average annual production*	< 100 hl/year; 100-1000 hl/year; 1 000-10000 hl/year; >10000 hl/year	SCq
16	*Have you noticed an increment in pH levels in the past 5 years?*	Yes; No; Do not know	SCq
17	*Have you noticed an increased alcoholic content in your wines compared to the past?*	Yes; No; Do not know	SCq
18	*Have you noticed any change in the aroma profile?*	Yes; No; Do not know	SCq
19	*Have you recently had an analysis of the cost/energy consumption/water consumption of your winery?*	Yes; No	SCq
20	*Will you consider having one in the future?*	Yes; No; Do not know	SCq
21	*Have you recently invested in equipment/infrastructures to optimize energy use for your winery?*	Yes; No	SCq
22	*If yes, have you invested in renewable energy?*	Yes; No	SCq
23	*In which type of renewable energy did you invest in your winery?*	Thermal solar panel; photovoltaic solar panel; wind power; bio digester; provider of renewable energy	MCq
24	*Do you plan to adopt renewable energy in the future?*	Yes; No; Do not know	SCq
25	*Have you recently invested in equipment/infrastructures to optimize water consumption of your winery?*	Yes; No	SCq
26	*Are you planning to invest in equipment/infrastructures to optimize water consumption of your winery in the future?*	Yes; No; Do not know	SCq
27	*Do you have any temperature and humidity control in your winery?*	Yes; No	SCq
28	*If yes, please mention which temperature and humidity control system you have in your winery*	Ventilation; insulation; air-conditioning; humidifier; dehumidifier	MCq
29	*Are you considering installing or implementing it in the future?*	Yes; No; Do not know	SCq

Table 3. Final questions and their respective variables; SCq = Single choice question; MCq = multiple choice question; LSq = 163 Likert scale question.

N.	Questions for both categories	Answer options	Type of response
30	*Which are your main concerns for your professional activity in the long term? Please rate each item on a 1-5 scale, , with 1 being no concern and 5 being greatest concern*	Reduction of profitability of grape and wine production Increased pests and diseases Difficulty finding skilled labour Reduction of public aid and increased regulation Water stress Economic crisis and decreased in wine demand Climate change Reduction of quality and loss of typicity Unpredictable weather Increased barriers to export	LSq
31	*How do you rate the effect of climate change on your activity?*	No effect; Positive effect; Negative effect	SCq
32	*How do you rate the effect of climate change on your activity in the future?*	No effect; Positive effect; Negative effect	SCq

For data analysis, 'stats' package of R software was used (R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/).

Categorical responses (both single and multiple-choice) were processed by applying Pearson's chi-square test to point out significant differences in the frequencies of responses among all WGZs ($p < 0.05$). When significant, a pairs Pearson's chi-square test (CI vs CII; CI vs CIII; CII vs CIII) was performed to remark the association among the WGZs.

Since Bartlett's test proved there was not homogeneity of variance across populations, Kruskal-Wallis H test was applied when dealing with Likert-scale answers to examine the diversity among the three WGZs ($p < 0.05$). The Kruskal-Wallis H test is a non-parametric method for checking three or more sets of scores that come from different groups and it is equivalent to the one-way ANOVA but does not apply the ANOVA normality assumption (Kruskal and Wallis, 1952). Pairwise comparisons using Wilcoxon rank sum test with continuity correction was also performed.

3. RESULTS

364 fully completed responses had been received by the survey deadline. Most of respondents (75.3%) were both winegrowers and wine producers, while 18.7% of interviewed were exclusively winegrowers (for a total of 342 winegrowers) and 6% winery owners (for a total of 296 wineries). The gender of most responders was male (71.7%), and only 21.4% female. Ages were most represented in the two ranges of 30-45 years old (32.7%) and 46-60 years old (46.2%).

The highest percentage of answers (76.6%) came from the CII zone, which includes the largest number of Italian regions (12), while 16.5% were from CIII zone (5 regions) and 6.9 % from CI, including only 2 regions (Tab. 4 and Fig. 1).

3.1 Winegrowers

Table 5 shows the profile of grapevine farmers responding to the survey (questions 1 and 2). The vineyard extensions were evenly divided among 4 size classes (1-5 ha; 6-10 ha; 11-25 ha and > 25 ha); only 1,8% of participants declared a farm size less than 1 ha.

The farmers in the sample primarily declared a management of their vineyard by integrated or organic protocols, while representatives of conventional agriculture followed in the rating, and a small extent declared biodynamic protocols. 42 out of 342 farmers (12.3% of interviewed) declared to use more than one agricultural system ("Mix" in the table), depending on the vineyard, mainly organic and biodynamic farming (33.3% of this category) and integrated and organic farming (26.2%).

Table 4. Profile of survey participants**.**

	%
Gender	
Man	71.7
Female	21.4
No reply	6.9
Age	
< 30	4.7
30 – 45	32.7
46 – 60	46.2
> 60	16.5
Wine growing Zone (WGZ)	
ZONE CI	6.9
ZONE CII	76.6
ZONE CIII	16.5
Typology	%
winegrowers	18.7
winery producers	6.0
both	75.3

Figure 1. Map of Italian Wine Growing Zones (WGZ) as for European Union Reg. No 1308/2013, Appendix I; the number within each region corresponds to the number of responses received from that region.

Table 5 Profile of grapevine farms that participated in the survey.

	%
Vineyard extension	
< 1 ha	1.8
1 – 5 ha	25.7
6 – 10 ha	21.9
11 – 25 ha	26.9
> 25ha	23.1
Type of viticulture	
Conventional	17.5
Integrated	36.8
Organic	32.7
Biodynamic	0.6
Mix	12.3

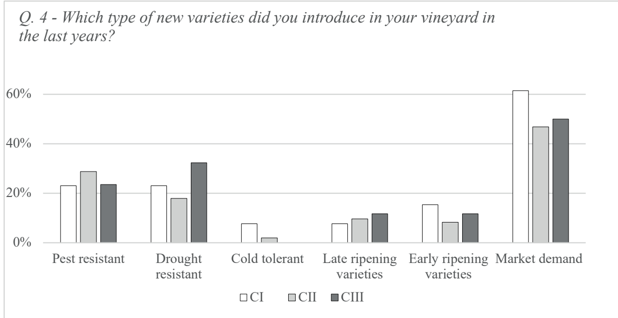

Figure 3. Percentage of new type of varieties introduced by winegrowers in the last years; frequency of answers among WGZs was analysed using Chi-squared test; significant differences were found.

3.1.1 Varietal change (questions 3 and 4)

Winegrowers were questioned about if they had introduced new varieties in the last years, and, if positive, which criteria was followed to drive the choice. In all zones, more than half of the farmers introduced new varieties, or plan to do it soon, without significant differences between the three WGZs (p-value = 0.6826) (Fig. 2).

Chi square test did not show significant differences (p-value = 0.9089) also in the type of new varieties introduced in the different WGZs (Fig. 3). The main criteria guiding the choice of new varieties for all zones was the market demand (61.5%, 46.8% and 50.0% for CI, CII and CIII, respectively). Data collected clearly indicated a prevalence in the choice of drought-resistant varieties in the southern areas, with 32.4% of winegrowers in CIII zone opting for this choice. A considerable percentage of farmers in zone CII (28.8%), gave preference to pest-resistant varieties, fewer in zones CIII (23.5%) and CI (23.1 %). As expected, late ripening varieties were preferred in the southern areas (11.8% in CIII), while early ripening varieties were the main choice in the northern areas (15.4% in CI).

3.1.2 Access to water and irrigation (questions 5 to 8)

This part of the survey was dedicated to collect information on water use in the field; growers were asked if they had access to any water resources near or in the perimeter of their vineyards and, in case of positive answer, whether irrigation was in place or not. They were also asked if they had considered having, implementing, or modifying the irrigation system in the future.

Almost 65% of participants declared a full or partial access to water resources. Chi-square test showed significant differences (p < 0.0001) between CI and the other

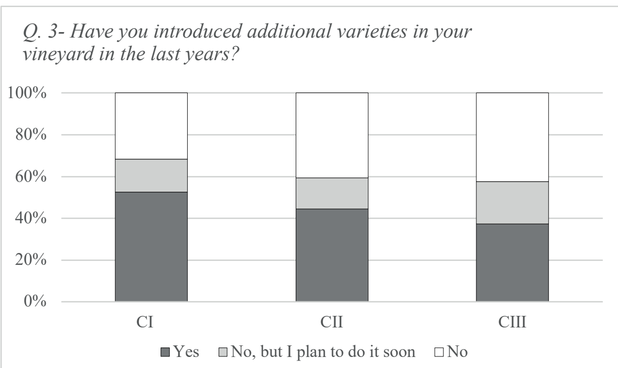

Figure 2. Percentage of winegrowers who introduced additional varieties; the frequency of answers among WGZs was 228 analysed using Chi-squared test; no significant differences were found.

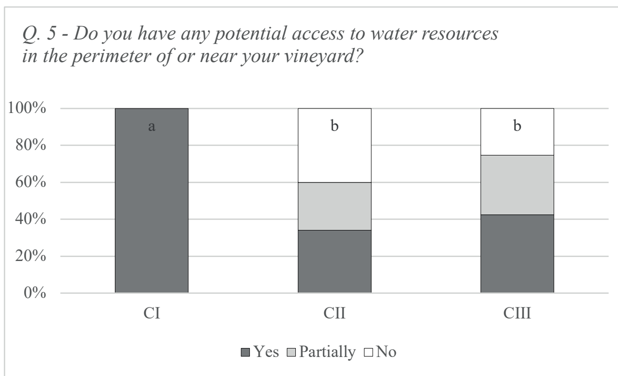

Figure 4. Percentages of farmers with access to water resources; frequency of answers among WGZs was analysed using Chi-squared test followed by pair Chi-squared (CI vs CII; CI vs CIII; CII vs CIII); significant differences are indicated by different letters.

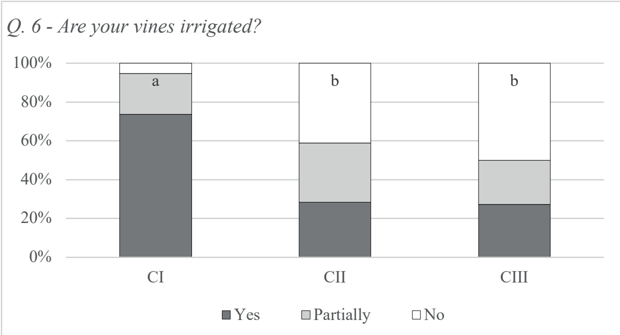

Figure 5. Percentages of farmers who irrigate among those who have water access; frequency of answers among WGZs was analysed using Chi-squared test followed by pair Chi-squared (CI vs CII; CI vs CIII; CII vs CIII); significant differences are indicated by different letters.

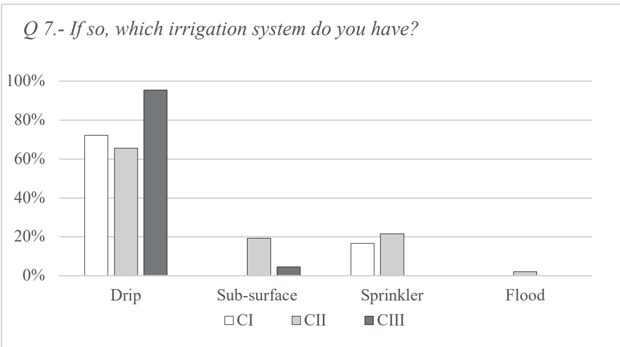

Figure 6. Irrigation systems used by winegrowers; frequency of answers among WGZs was analysed using Chi-squared test; no significant differences were found.

two WGZs, both for water access and use of irrigation (Fig. 4 and 5). In CI, all interviewed farmers confirmed having total access to water and 94.8% of them had an irrigation facility in place. In CII and CIII zones 60% and 74.6% of interviewees, respectively, had water access and about half of them, 59% and 50%, respectively, used water to irrigate.

However, no significant difference (p-value = 0.09038) concerning the irrigation systems emerged between WGZs (Fig. 6). Drip irrigation was recorded as the most widespread method in all WGZs, with a very reduced occurrence of sub-surface irrigation. Drip irrigation was the only method adopted in CIII and present in 84% of vineyards in CII zone. In CI and CII zones, a percentage of sprinkler irrigation is persisting (16.7% and 21.5%, respectively), while flood irrigation facilities are negligible (2.2%).

Even in the case of availability of water, only 39% of the winegrowers considered the option to have, implement or modify (even partially) the irrigation system in the future (question 8), without significant difference between WGZs (p = 0.4249).

3.1.3 Pests and diseases (question 9)

Winegrowers were asked to rate each of the most common pests and diseases for grapevine in the Mediterranean on a scale 1-5. The results evidence that damages caused by vine pests and diseases are currently low, never reaching level 3. However, the Kruskal-Wallis H test showed significant differences (p <0.0001) for some pathogens (Fig. 7).

Powdery mildew (*Erysiphe necator*) was the most recurring pest, followed by Downy mildew (*Plasmopara viticola*) without significant difference between zones. Conversely, grapevine trunk diseases were considered more harmful in CI and CII zones with respect to CIII. Flavescence dorée (*Candidatus Phytoplasma vitis*) was found to be a harmful pest in CII zone, while almost no damage was ascribed in CIII. Significant differences in the damage rate between the zones emerged also for grey mould (*Botrytis cinerea)*, brown marmorated stink bug (*Halyomorpha halys*) and *Metcalfa pruinosa*, even if with a very low damage level.

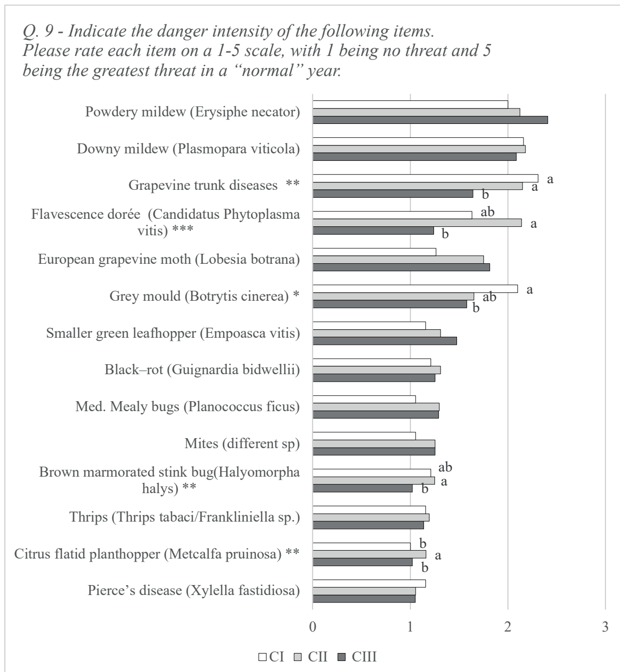

Figure 7. Levels of damage caused by vine pests and diseases (1-5 scale, 5 greatest threat). Statistical differences among WGZ were determined according to Kruskal-Wallis H test followed by Wilcoxon rank sum test; values followed by different letters are significantly different. Signif. codes: p < 0.0001 '***'; p < 0.001 '**'; p < 0.01 '*'; p < 0.05 '.'.

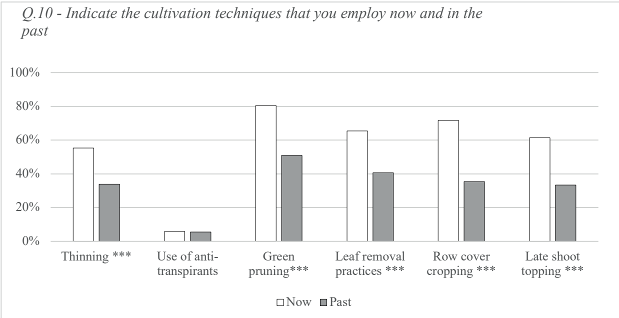

Figure 8. Cultural practices adopted by Italian farmers now and in the past; frequency of answers was analysed using Chi-squared test; significant differences between now and the past are indicated by significance codes: p < 0.0001 '***'; p < 0.001 '**'; p < 0.05 '*'.

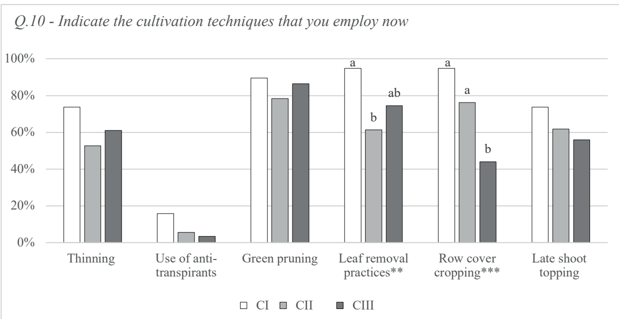

Figure 9. Percentages of cultural practices currently adopted by winegrowers by WGZs. Frequency of all answers was analysed using Chi-squared test; significant differences among WGZs are indicated by different letters. Signif. codes: p < 0.0001 '***'; p < 0.001 309 '**'; p < 0.05 '*'.

3.1.4 Cultivation techniques (question 10)

Winegrowers were asked to indicate, among a list of cultural practices, those currently applied versus those applied in the past.

With the only exception of the use of anti-transpirants, unaltered in the years, an overall significant increase in the adoption of the listed cultivation techniques by Italian winegrowers emerged. Between the listed practices, green pruning and row cover cropping were the most popular, with an increase of 29% and 37%, respectively. More than half of the winegrowers who responded to the survey currently use leaf removal practices (+ 24% respect to the past), late shoot topping (+ 28%) and thinning (+ 21%) (Fig 8).

All practices, except anti-transpirants spraying, are widespread in all three WGZs (Fig 9), often exceeding 50% of users. CI is the zone where practices are more popular, differing from CII for a larger adoption of leaf removal and from CIII for the use of row cover cropping. No other significant differences were found in the current application of the techniques among the WGZs.

3.1.5 Insurance (questions 11 to 13)

The survey asked winegrowers to indicate if they have now (question 11) and if they had in the past (question 12) any insurance policies and, in such case, for which damage (to be chosen from a list).

Although a significant increase in insurance coverage was recorded with respect to the past (p < 0.001), more than half of the interviewees (52%) do not currently adopt any form of insurance.

Considering single hazard agents one by one, Italian farmers have significantly increased their takeout of policies against wind (+ 8%) and flood damages (+ 5%), while those against hail, late frost, drought and wild animals did not change significantly. However, a relevant

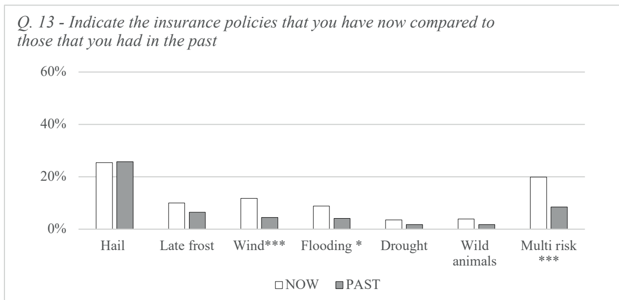

Figure 10. Type of insurance policies take out by Italian farmers now and in the past; frequency of all answers was analysed using Chi-squared test; significant differences between now and past are indicated by significance codes: p < 0.0001 '***'; p < 0.001 '**'; p < 0.05 '*'.

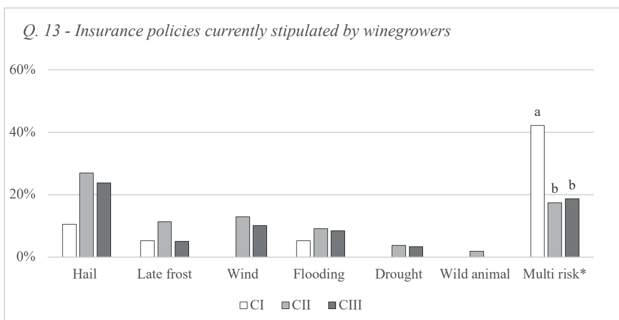

Figure 11. Type of insurance policies currently take out by winegrowers by WGZs. Frequency of all answers was analysed using Chi-squared test; significant differences among WGZs are indicated by different letters. Signif. codes: p < 0.0001 '***'; p < 0.001 '**'; p < 0.05 '*'.

increase was recorded in multi-risk 319 policies (+ 12%), encompassing, case by case, some of the aforementioned agents (Fig. 10).

When comparing the WGZs (Fig. 11), significant differences in the current insurance policies in use emerged only for the multi risk ones, more common in CI (42 %) than in CII (17 %) and CIII (19%).

Among the single-agent policies, that for hail damage alone is the most common among farmers in CII 327 (27%) and CIII (24%) zones, while only 11% of winegrowers adopts this policy in CI. Insurance against late frost is used by 11% of farmers in CII and by 5% in CI and CIII; while mono-risk wind damage insurance is exploited only by farmers in zones CII and CIII, similarly to drought damage insurance. Fewer than 10% of respondents to the survey reported flood damage policies.

3.2 Wine makers

Table 6 summarizes the profile of the wineries in the survey sample (questions 14 and 15). A large 337 majority of them were single-member owned; about one in eight represented the cooperative reality. Most wineries had an annual wine production in the two middle classes (100-1000 and 1000-10000 hl/year, respectively), and almost 29% of respondents were represented by smaller or bigger production classes.

3.2.1 Wine quality (questions 16 to 18)

Table 7 reports the results collected from wineries about the assessed changes so far in some wine 344 characteristics (increase of pH and alcoholic content and changes in the aromatic profile).

Chi-square test did not evidence significant differences in the increase of pH between the WGZs. On the contrary, significant differences emerged among the three WGZs both for alcoholic content and changes in wine aroma profiles. CI and CII resulted, in fact, characterised by a higher increase in the wine alcoholic content (64.7% and 67.5% respectively) with respect to CIII (31.3%), while zone CII is the most affected by changes in the wine aromatic profile (46.8%).

Table 6. Profiles of wineries that participated in the survey.

	%
Winery type	
single-member property	79.7
cooperative	12.0
non-cooperative	6.8
Wine production	
less than 100 hl/year	15.5
100 – 1000 hl/year	42.6
1000 – 10000 hl/year	28.7
over 10000 hl/year	13.2

Table 7. Assessment of changes in wine characteristics by WGZs. Data are in percentages. Frequency of answers among WGZs 351 was analysed using Chi-squared test followed by pair Chi-squared (CI vs CII; CI vs CIII; CII vs CIII); significant differences are 352 indicated by different letters.

Wine quality	WGZ	No	Yes	Not known
Q.16- Have you noticed an increment in pH levels in the past 5 years?	CI	41.2	52.9	5.9
	CII	40.3	44.2	15.6
	CIII	56.3	27.1	16.7
		p-value = 0.1007		
Q.17- Have you noticed an increased alcoholic content in your wines compared to the past?	CI a	23.5%	64.7%	11.8%
	CII b	30.7%	67.5%	1.7%
	CIII c	68.8%	31.3%	0.0%
		p-value = $6.995e^{-07}$		
Q.18- Have you noticed any change in the aroma profile?	CI a	76.5	23.5	0.0
	CII b	45.5	46.8	7.8
	CIII ab	62.5	31.3	6.3
		p-value = 0.03953		

3.2.2 Mitigation strategies in the winery (question 19 to 29)

An open interrogative is understanding how much wine makers are aware of the need to reduce the CC impact of their production activities and whether they are already doing so. About this, specific questions were posed to check if they had recently performed an analysis of cost, energy and water consumption 357 in the winery, and, if not, if they intended to have one in the near future.

Only less than 50% of participants stated that they had carried out such analysis (question 19), with no significant differences between WGZs (41% in CI, 44% in CII and CIII).

Between those who had not yet done this (Fig. 12), 40% in the CI and CII zones were planning to comply in the future, while this percentage significantly rises in CIII (67%).

Wine makers were also asked whether they had recently invested in equipment or infrastructure to optimise winery energy and water consumption and, eventually, whether they invested in renewable energy, and in which ones.

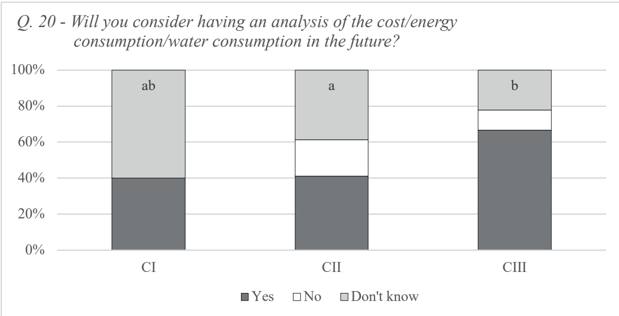

Figure 12. Percentages of winery owners who were considering having an energy and water consumption analysis in the future among those who did not have it yet; frequency of answers among WGZs was analysed using Chi-squared test followed by pair Chi-squared (CI vs CII; CI vs CIII; CII vs CIII); significant differences are indicated by different letters.

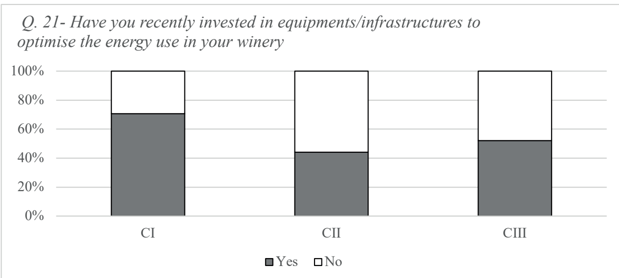

Figure 13. Percentages of winery owners who invested in equipment or infrastructures to optimise energy use in the winery; frequency of answers among WGZs was analysed using Chi-squared test; no significant differences were found.

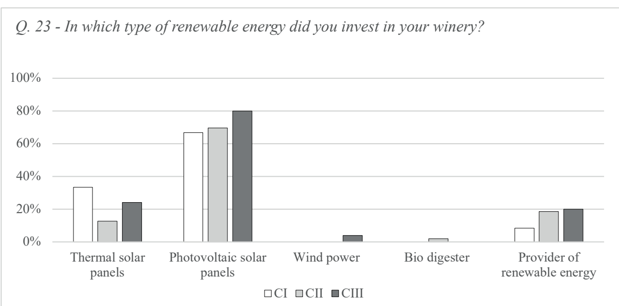

Figure 14. Type of renewable energy systems adopted by winery owners; frequency of answers among WGZs was analysed using Chi-squared test; no significant differences were found.

No significant difference (p-value =0.08023) emerged among the WGZs in such investments, even if CI zone resulted to be the one with the largest investments (71%), followed by CIII (52%) and CII (44%) (Fig. 13). Among the winery owners who answered positively to the question, almost all (92%, 82% and 96% for CI, CII and CIII, respectively) invested in renewable energy (question 22). No significant differences (p-value = 0.4026) were found among WGZs in the kind of renewable energy chosen (Fig. 14); photovoltaic panels were the most popular facility adopted by winery owners in all the WGZs; around 20% of wineries use energy provided by renewable energy suppliers and solar panels. Among the owners who have not yet invested to reduce energy consumption in the winery (Fig. 15), more than 50% are planning to do it, without significant differences between zones (p-value = 0.159).

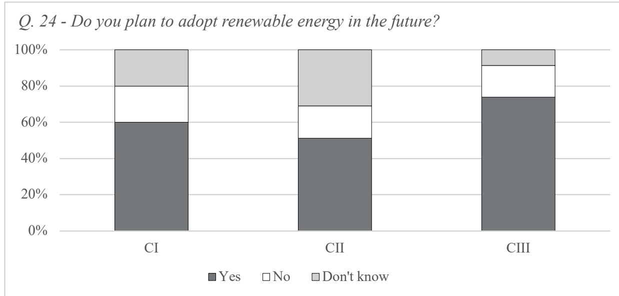

Figure 15. Percentages of winery owners who plan to adopt renewable energy in the future among those who have not done it yet; frequency of answers among WGZs was analysed using Chi-squared test; no significant differences were found.

When compared to the investments for the optimisation of energy consumption, those aimed at reducing water use (question 25) were in lower amount, especially in the CI and CII zones, where only 29% and 32% of the respondents respectively declared an active investment. Zone CIII turned out to be the one with the largest percentage of water-saving actions (48%). Interestingly, even though C1 is, to date, characterized by the lowest investment actions, it shows the highest percentage of win-

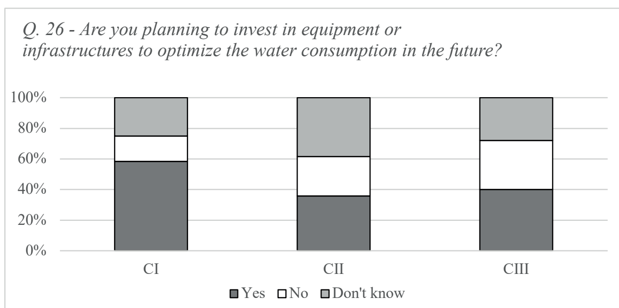

Figure 16. Percentages of winery owners who plan to invest in equipment or infrastructures to optimize water consumption in the winery in the future, among those who have not done it yet; frequency of answers among WGZs has been analysed using Chi-squared test and no significant differences were found.

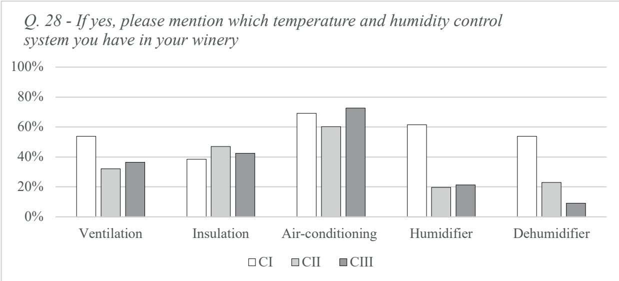

Figure 17. Type of environmental control systems adopted by winery owners; frequency of answers among WGZs was analysed using Chi-squared test; no significant differences were found.

ery owners who declared the higher willingness to plan investment in the future (58%), followed by 40% in CIII zone and 36 % in CII (Fig. 16).

Finally, wine makers were asked about the presence in the winery of any environmental system to control temperature and humidity (question 27), and its specification.

Most of them (76%, 66% and 69%, respectively for CI, CII and CIII) stated to adopt temperature and humidity control systems, with no significant differences between the WGZs (p-value = 0.6659). Similarly, no significant differences (p-value = 0.1849) were detected among WGZs about the type of environmental control systems use in the winery: air-conditioning turned out the preferred way to monitor temperature in all the regions without significant difference, while almost 40% of winery buildings are already insulated (Fig. 17). From the survey, all the WGZs showed an overall limited interest (less than 30%) in investing in climate control systems in the future (question 29).

3.3 Main future concerns (question 30)

A list of potential problems related to the professional activity was posed both to winegrowers and wine producers, who were asked to rate each of them on a Linker scale 1-5.

The average values obtained for the whole Italy are shown in Table 8. Climate change, unpredictable weather, economic crisis and reduction of profitability of productions were found to be the significantly greater concerns for the national wine sector. Conversely, the increasing barrier to export and the reduction of quality and loss of typicity were found, among those proposed, the least worrisome concerns for the future.

When separately analysing the values per WGZs, no significant differences emerged, except for the concern linked to the difficulty in finding skilled labour, stronger in zone CIII than in CI and CII (Fig. 18).

Table 8. Average values for future concerns (1-5 scale, 5 greatest concern). Statistical differences among future concerns were determined according to Kruskal-Wallis H test (p<0.0001) followed by Wilcoxon rank sum test; values followed by different letters are significantly different.

Q. 30 – Which are your main concerns for your professional activity in the long term?	Average value
Climate change	3.70 a
Unpredictable weather	3.66 a
Economic crisis and decrease in the wine demand	3.57 a
Reduction of profitability of grape and wine production	3.24 a
Reduction of public aid and increased regulation	3.19 bc
Increased pests and diseases	3.15 bc
Water stress	3.12 bc
Difficulty finding skilled labour	3.05 bc
Increased barriers to export	2.94 c
Reduction of quality and loss of typicity	2.34 d

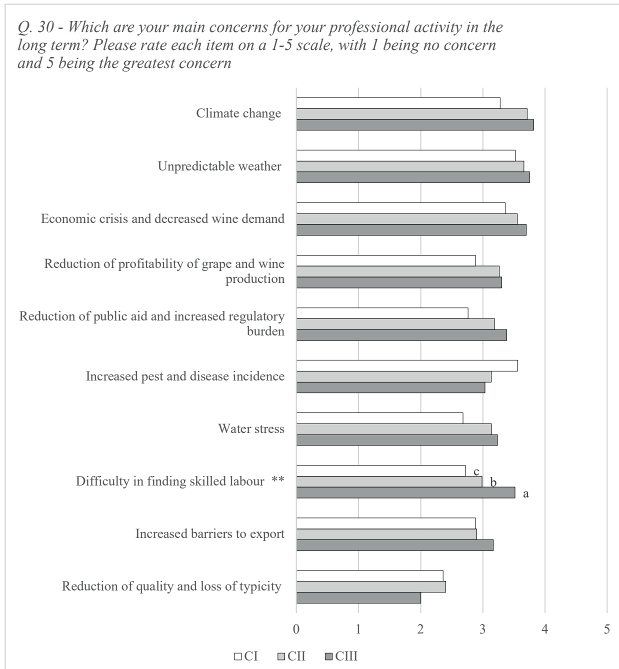

Figure 18. Levels of future concerns expressed by respondents for WGZ (1-5 scale, 1 no concerns 5 greatest concern). Statistical differences among WGZ were determined according to Kruskal-Wallis H test followed by Wilcoxon rank sum test; values followed by different letters are significantly different. Signif. codes: $p < 0.0001$ '***'; $p < 0.001$ '**'; $p < 0.01$ '*'; $p < 0.05$ '.'.

3.4 Climate change effects (question 31 and 32)

Respondents to the survey were finally asked to express their opinion about the current effects of CC on their activity, and on those expected in the future.

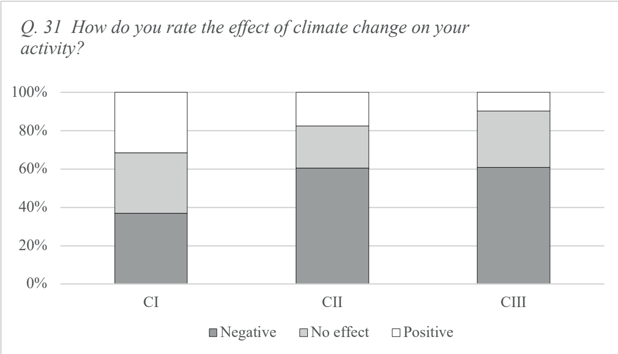

Figure 19. Respondents' evaluation of CC effects in the short-term; frequency of answers among WGZs was analysed 448 using Chi-squared test; no significant differences were found.

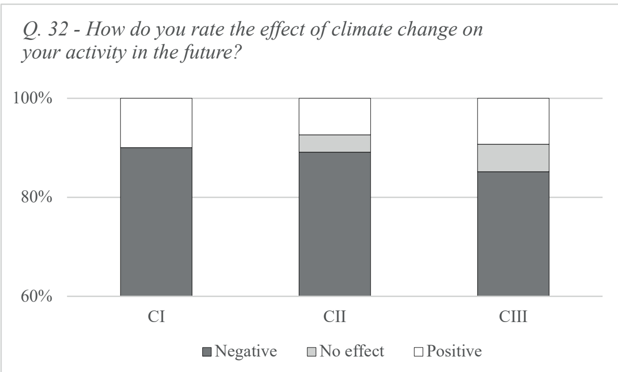

Figure 20. Respondents' evaluation of CC effect in the long-term; frequency of answers among WGZs was analysed using Chi-squared test; no significant differences were found.

The Chi-squared test showed no significant differences among the WGZs in the perceived effects of CC both at short (p-value = 0.1282) and long term (p-value = 0.7921).

At the short-term (Fig. 19), a negative evaluation of the effect of CCs between the actors of the wine value chain is prevalent, and more pronounced in CII and CIII (61%) than in CI zone (37%). However, a high percentage of respondents claims that CC is not currently affecting their production (about 30% in all zones). 32% of respondents located in CI positively rated the effect of current climate on production, while this percentage reduced to only 18% and 10% for CII and CIII, respectively.

In the longer term (Fig. 20), the percentage of respondents believing that climate change will have no impact or will have a positive impact on winery activities drastically drops, thus producing a substantial increase of those believing that climate change will have a negative effect (90%, 89% and 85% for CI, CII and CIII, respectively).

4. DISCUSSION

The sample of respondents to our survey can be considered reliable to roughly represent the wine production pool for the three Italian wine regions, especially for CI and CII. Zone CIII was mostly represented by islands, as few responses were received from the other three regions. In our survey, the percentage of farms which declared to follow organic growing protocol (32.7%) is higher compared to the national percentage of organic wine farming, standing at around 16% in 2019 (Varia et al., 2021).

The following discussion highlights some aspects of the results obtained, aggregated by topic.

Varietal change

The introduction of well-adapted genotypes is recognized as a strategic tool for both adaptation and mitigation, as it leads to minimizing chemical and agronomic inputs and water use (Van Leeuwen and Destrac-Irvine, 2017; Venios et al., 2020). The national rate of farms which introduced new varieties is already high, and likely increasing, according to the declared intentions (more than 50% as national average). Nevertheless, at the moment, the choice of new varieties is still driven by market preferences, as in line with the declared concerns and fears related to economic crisis and reduced profitability of production for the future. Introduction of drought-resistant varieties, however, highlights a potentially growing relevance of this approach, in agreement with Fraga et al., 2016.

Grapevine is highly sensitive to climatic conditions, and its growing and ripening are going to be negatively affected by increased temperatures. Traditionally, in the northern hemisphere, the ideal time for ripening is between early September and early October, when temperature start to decrease (Van Leeuwen and Destrac-Irvine, 2017). Introduction of late varieties to delay ripeness can greatly contribute to overcome any negative effect of CC (Van Leeuwen and Destrac-Irvine, 2017). Despite this, the survey did not reveal a significant inclination of farmers toward this adaptation strategy.

Water availability and use

Water scarcity is one of the greatest risks for crops due to CC, especially for the southern areas (Fraga, 2016). In viticulture, water deficit generally positively impacts berry sugar promoting wine quality, so, traditionally, vineyards are not irrigated; but, if the water deficit is severe, berry sugar content can decrease due to reduced plant photosynthesis (Van Leeuwen and Destrac-Irvine, 2017). Easy access to water and its efficient use are, therefore, key factors in managing new variable climatic conditions. As expected, the highest rate of water availability characterizes the coolest mountainous areas; such highwater availability resulted in a larger diffusion of irrigation practice among winegrowers. On the contrary, in the Mediterranean part of the peninsula (CII and CIII zones), the limited access to the water resource leads to the reduction of irrigation in the vineyards. However, even among winegrowers with potential access to water, less of 60 % (and even less for CIII) claims their willingness of establishing an irrigation facility on site. Consequently, it may be deducted that the need for irrigation is not felt as an urgency yet, and this hypothesis is also supported by the results emerged from the question about major future concerns, where water stress occupies the fourth-to-last position in the ranking, also in the South.

At the same time, the high investment costs of irrigation systems (Van Leeuwen and Destrac-Irvine, 2017) may also be contributing factors in limiting their adoption, and this even more markedly in the Southern areas, where drought events are more probable and the stabilization of production will become ever more important.

Data on the adopted irrigation systems confirm that, regardless of wine growing zones, farmers prefer systems that optimise water use (drip and sub-surface irrigation), showing a responsible attitude, especially in the South, with a 100% of farmers.

Pests

This section of the survey displayed some minor differences between the three zones. Although CC is potentially involved in a modification of the distribution and severity of pests and diseases (Mira de Orduña R., 2010; Bois et al., 2017), current pest-related damages on grapevines are not rated high in Italy. Current pathogen containment strategies seem to be still adequate, and farmers expressed only a moderate concern about the increase of pathogens in the long term.

Cultivation techniques

With respect to the past, an evident implementation of cultural practices recognized as environmentally friendly and climate-smart emerged as an important sign of adaptation. Row cover cropping is now the most widely implemented practice with respect to the past, although much more applied in northern than in southern areas, probably due to the commitment in avoiding water deficit caused by competition with the grass cover (Celette et al., 2009). It is however already demonstrated that grass cover generally has a smaller impact on vines' water status because of their deeper root systems, enabling them to access deeper water reserves (Van Leeuwen and Destrac-Irvine, 2017).

The many benefits deriving from green pruning on cluster ripening and shoots development make it the most commonly used practice both today and in the past. Late shoot topping and leaf removal practices resulted also highly exploited by farmers in this survey. The attention of vine growers towards the latter two last techniques is higher than in the past, since they are now more carefully modulated, allowing a slower ripening, with lower sugar levels and a more marked acidity (Petrie et al., 2003). Anti-transpirants are mainly adopted in coolest zones even if they could be particularly effective in the dry areas. In fact, they reduce transpiration by forming films that reduce moisture losses and are also effective in reducing sugar accumulation without significantly affecting phenolic compounds accumulation (Paliotti et al., 2013)

The general increase of application of adaptation techniques witnesses, on one hand, the necessity of facing more challenging conditions during the growing season, showing, on the other hand, a good preparedness of farmers who answered the poll to cope with more challenging climate conditions.

Insurances

The adoption of insurance policies is highly recommended by EU Common Agricultural Policies (CAP), as they are considered a valuable tool for fostering agricultural resilience and adaptation to CC (Iglesias and Garrote, 2015; Jørgensen et al., 2020). Targeted insurance policies have, in fact, the potential to stabilise farm income, and this is even more marked in the case of high-value crop as winegrapes (Čop et al., 2020). With respect to the past, a significant increase of specific weather risk policies and multi-peril crop insurance was recorded. Among mono-risk, the insurance that dominates both today and in the past is that against hail damage. This evidence confirms the high concern against this meteorological phenomenon, considered to be potentially more hazardous today than in the past, as according to supported some time series analysis (Eccel et al., 2012; Sanchez et al., 2017). The increased adherence to multi-risk insurance emerged from the survey is in line with the policies adopted since 2000, aimed at encouraging the transition from mono-risk to pluri-risk contracts (Santeramo, 2018).

Nevertheless, an alarming observation emerged from the survey: more than half of the interviewed winegrowers are not currently adopting any form of insurance policies. This may be in part explained since the adoption of an insurance implies an increase of bureaucracy for farmers and additional costs (Santeramo, 2018). Although there is a long tradition of farm subsidies to cover part of the insurance costs in Europe (Martinez Salgueiro, 2019), individual farmers' participation in crop insurance is still difficult due to scarce knowledge, non-uniform information and lack of experience (Chiappori and Salanie, 2013; Santeramo, 2018) and public intervention alone is clearly not enough to ensure an adequate insurance coverage for the sector.

Impacts on wine quality

The increase of the adoption of management practices able to contribute to the reduction of sugar accumulation (such as late shoot topping and leaf removal practices) reflects the wine producers' assessment of a modification in wine characteristics. The survey evidenced impacts on wine quality as measured by three parameters (pH, alcohol content, aroma profile), with some differences among the zones. A lower impact resulted in the Southern Mediterranean (CIII), where producers reported, compared to the past, the least variations for all three quality parameters. This difference can be partly explained by the fact that warmer regions have been longer faced with the need to correct grape quality parameters, and consequently have consolidated technologies and solutions for adapting to such urgencies. Short-term climate change adaptation strategies such as irrigation, adaption of sunscreens or soil management (van Leeuwen et al, 2019; Santos et al., 2020) and oenological practices for pH and ethanol management (Dequin et al., 2017) are effective strategies to mitigate the undesirable effects of CC on wine quality.

Mitigation strategies in wineries

Analysis of costs and of energy and water consumption can greatly contribute to rationalise and optimise management, saving money, at the same time decreasing the environmental impact of the winery. The analysis revealed the most critical points in the production chain and the most expensive steps in terms of energy and water consumption; such consideration reinforces the need to introduce tailored strategies to mitigate consumptions and costs, making use of environmental control systems and less impactful energy sources. Although less than half of the owners have not carried out this type of analysis yet, they showed some interest, and especially in the southern area 67 % expressed interest in doing so in the future.

Even if there are still not many winery owners who have invested in infrastructures to optimise energy, a large percentage is intending to do so in the future, especially relying on renewable energy, and especially in the South (74%). The choice of the technology to adopt has to be seriously considered, as different control systems for temperature and humidity parameters have different emission impacts. Air conditioning, found to be the most common temperature control system in wineries, is also the most environmentally impactful; fortunately, cellar insulation, which is less impactful and highly encouraged by community policies, has also turned out to be well spread.

The contribution of wine to global anthropogenic greenhouse gas emissions has been estimated approximately 0.3% of annual global GHG emissions, increasing at 0,6% in countries with a high wine consumption per capita (e.g. Ponstein et al., 2019). Although wine making processes account for a small portion of the emissions attributable to the wine sector (Rugani et al., 2013), adopting measures to limit the energetic footprint in the winery such as the use of renewable energy and insulation systems is a viable mitigation strategy.

Another key issue in the strategy of reduction of resource consumption is water. In line with previous findings regarding the lower use of irrigation and the high propensity in saving water in the field, southern regions turned out the ones with the largest percentage of investments to optimise water consumption in winery (48%).

5. CONCLUSIONS

Many of the results of the survey point out the concern for climate change and the needs for adaptation and the importance of addressing climate-linked issues in the whole value chain. A proper awareness of climate urgencies might in fact enhance appropriate adaptation actions, given the higher openness, in this category of farmers, towards the implementation of long-run strategies (Merloni et al., 2018). However, climate change concerns were found to be currently at the same level as the economic ones for the wine sector and slightly higher than all of the proposed threat categories, rated around a medium level of concern. It is not to be overlooked the contingency of the period when the survey was proposed to firms: in 2020 the great uncertainty brought by the pandemic crisis was potentially able to bias the general feeling about the most stringent urgencies for a sector tightly connected with HoReCa. With these premises, direct consequences of climate change, such as potential increases in pest and diseases and water stress were not perceived as major threats, resulting in medium concerns, with negligible differences among climate zones.

An interesting result is the clear strong increase of the concern about climate impacts in the future with respect to the present time; the majority of respondents claimed some effects, with a generalised pessimistic outlook, and the percentage of farmers and wine makers who considered climate change as potentially positive until now (reaching 32% in CI zone) decreases to negligible values for the future scenarios.

In agreement with Jørgensen et al. (2020), signals emerged in this study about the fact that farmers are already partially adapting to climate change and are aware of future challenges due to unpredictable weather: a significant percentage of farmers has already switched from traditional to more climateadaptable varieties, such as the pest- and drought-resistant ones, although the choice of marketable varieties prevailed. Likewise, the prevalence of water-saving irrigation methods, such as drip irrigation or sub-surface irrigation, is indicative of the farmers' commitment in water use efficiency. An evident implementation of cultural practices recognized as environmentally friendly and climate-smart, as row cover cropping, late shoot topping, and a better defoliation management, also emerged as an important sign of adaptation. Conversely, the risk associated with a scarce use of insurance as a tool for fostering adaptation to climate change, as revealed by the survey, should not be overlooked.

The strong link of European viticulture with traditional practices is likely to be complemented by more marked-oriented adaptation capacities, enabling farmers and wine producers to successfully cope with a wide range of climate change-induced threats. In addition, administrators and policy makers are called to seriously address the issues brought to their attention by the supply chain.

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Effects of sowing date on bolting and frost damage to autumn-sown sugar beet (*Beta vulgaris* L.) in temperate regions

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Abstract. Sugar beet is mostly cultivated in relatively cool regions of the temperate zones by sowing in spring, but in some Mediterranean areas with mild winters, the crop is sown in autumn. Due to global warming, autumn cultivation of sugar beet is gradually extending towards new areas that are still characterized by relatively cold winters. Seedling loss and bolting are two factors limiting the adoption of autumn sugar beet cultivation in new areas. The objectives of this study were to determine the effects of sowing date on (i) duration and rate of field emergence, (ii) phenological stages of sugar beet during early growth, (iii) quantitative traits of seedlings and (iv) bolting occurrence as well as frost killing of autumn-sown sugar beet. Field experiments were conducted in a randomized complete block design to determine the appropriate sowing date for autumn-sown sugar beet in 2017/18 and 2018/19 in the Karaj and Mashhad regions of Iran, which are both characterized by relatively cold winters. The experiment was conducted with a bolting-resistant cultivar and six sowing date treatments. The results showed that to reach plant growth stages of cotyledon, 2, 4, 6, 8, 10, 12, 14 and 16 leaves, 163, 200, 321, 418, 500, 600, 639, 700 and 757 growing degree days (GDD), respectively, were required. The average duration and speed of seedling emergence increased and decreased, respectively, with delay in sowing. The results suggest adjusting the sowing date of winter sugar beet so that when temperatures effective for bolting (6-8 °C) occur, the plant has already received about 300 to 400 GDD. At this time, the growth stage and the largest root diameter of sugar beet are approximately 4-6 leaves and 0.11-0.27 cm, respectively. After 14- to 16-leaf stage (≥700-750 GDD), the percentage of killed plants due to low temperatures were negligible. Although, the risk for frost losses is higher at 4- to 6-leaf stage (300-400 GDD), accepting higher losses is justified by a lower probability of bolting.

Keywords: bolting, growing degree days, killed plants, sowing date.

HIGLIGHTS:

- Autumn sugar beet growth up to the 16-leavestage is modeled using growing degree days.

- Delayed autumn seeding delayed emergence but increased the rate of emergence.
- The age of the plants affected bolting more than the number of days with effective temperatures on bolting.
- Linear regression model can predict the frost damage at different growing degree days.
- Proper sowing date allows for successful cultivation of autumn sugar beet in relatively cold areas.

INTRODUCTION

Sugar beet (*Beta vulgaris* L.) and sugarcane (*Saccharum officinarum* L.) are the two sources of sucrose in the world (Mohammadian and Baghani, 2020). Sugar beet is mostly cultivated as spring crop in temperate zones of the world, but in some Mediterranean regions (such as southwestern Spain, northern Egypt and Morocco) sugar beet is sown in autumn (Jaggard and Qi, 2006). Up to the 1960ies, sugar beet has also been sown in autumn and harvested in mid-spring the next year in the Khuzestan province of Iran (located in the southwest of Iran, latitude: 30-33°, Max altitude: 143 m above sea level).

The important advantage of autumn-sown sugar beet is the use of the rainfall in autumn and winter, implying lower water consumption for irrigation than in spring-sown sugar beet (Mohammadian and Baghani, 2020; Jaggard and Qi, 2006). For example, in the Khuzestan province of Iran, the water consumption for the irrigation of autumn-sown sugar beet is about 400 mm, while for spring-sown sugar beet in provinces at higher latitudes the consumption is approximately 900 mm (Mohammadian and Baghani, 2020). It has been found that water use efficiency for sucrose production of autumn-sown sugar beet is higher than that of spring-sown sugar beet (Rinaldi and Vonella, 2006). In view of global warming and depletion of water resources in recent decades, there is growing interest for the possibility of autumn cultivation of sugar beet in areas of higher latitudes (more than 33° N), but due to environmental limitations and lack of information, autumn cultivation of sugar beet is currently adopted only in a few areas.

One of the major limitations for autumn-sown sugar beet is bolting. The sugar beet is a biennial plant and the cold weather in winter and subsequent long-day conditions in spring cause bolting (Milford et al., 2010). In autumn cultivation conditions, cold weather followed by long days may cause bolting in the first year. It has been reported that maximum daily temperatures effective for sugar beet vernalization are in the range 1-12 °C with an optimum range of 6-8 °C (Milford et al., 2010). The occurrence of bolting in the first year significantly reduces root and sugar yield, and causes problems in processing sugar beet roots due to the hardening and fibrosis of roots (Hoffmann and Klug-Severin, 2011), making them unsuitable for sugar factories. Consequently, for autumn cultivation of sugar beet in areas with cold winters, cultivars with very high resistance to bolting, as recently introduced by some companies, are needed (Bosemark, 2006).

Sowing date is a key agronomic factor affecting the occurrence of bolting and early sowing of sugar beet is expected increase the probability of bolting (Al-Jbawi et al., 2015). On the other hand, sowing date also determines the length of the growth period (thermal time), and is therefore one of the most important factors affecting the sugar yield of sugar beet (Hoffmann, 2019). Especially in years with suitable weather conditions a large increase in yield from timely cultivation was found (Esmaeili et al., 2022). Moreover, there is a positive correlation between-root yield and light energy intercepted during sowing and harvest period (Jaggard and Qi, 2006). Therefore, increasing the length of the plant growth period by earlier sowing date causes more radiation absorption by leaves resulting in greater yield of sugar beet.

Many problems have been reported for the survival of young autumn-sown sugar beet seedlings during frost periods (Albuquerque and Carvalho, 2003; Kockelmann and Meyer, 2006). Under Central European climates, there is a 10 to 35 percent risk of freezing stress in autumn-sown sugar beet (Reinsdorf and Koch, 2013). In view of the low resistance of young sugar beet seedlings to cold weather and frost (Deihimfard et al., 2019), autumn cultivation of sugar beet in colder northern regions to escape the summer heat may not be a favorable strategy even if the presence of a snow cover can partially protect plants from frost (Sokratov and Barry, 2002). Furthermore, results of field trials for autumn-sown sugar beet in Germany showed that the survival rate depends more on the growth stage reached before frost than on the impact of weather conditions during winter (Loel and Hoffmann, 2014). The importance of reaching a minimum growth stage with respect to cold weather resistance underlines once more the importance of the sowing date for the success of autumn cultivation of sugar beet (Jaggard and Qi, 2006).

Due to the limited water resources and climate change, the prospect for continuing sugar beet cultivation in arid and semi-arid regions, such as Iran, is related to the possibility of developing autumn cultivation. Owing to the lack of knowledge in this regard, this study was conducted to evaluate the effects of phenological stages of autumn-sown sugar beet on cold and both frost tolerance as well as bolting. The specific objectives of this study were to determine the effects of sowing date on: (i) duration and rate of field emergence ; (ii) phenological stages of sugar beet in early growth; (iii) quantitative traits of seedlings just before starting winter; and, (iv) bolting occurrence as well as frost killing on autumn-sown sugar beet.

Table 1. Historical weather data of Karaj and Mashhad 2002-2016.

Location	Temperature °C					Rain mm
	Min	Max	Mean of Min	Max of Min	Mean	
Karaj	-17	42	9	22	16	239.0
Mashhad	-24	43	10	23	16	219.8

MATERIALS AND METHODS

Site characteristics

The experiments were conducted during the autumns of 2017 and 2018 in Iran, in the two regions of Karaj, Alborz province (latitude: 35°59′N and longitude: 51°6′E, altitude: 1320m above sea level) and Mashhad, Khorasan-Razavi province (latitude: 36°13′N and longitude: 59°40′E, altitude: 1050m above sea level). Climatic characteristics of the two experimental sites inferred from meteorological data for 2002-2016 are shown in Table 1. Although the average temperature at the two sites was similar, there were differences in terms of absolute minimum and maximum temperatures, average minimum and the maximum of minimum temperatures. The minimum temperature observed in Mashhad was 7 °C lower than that in Karaj. However, the average minimum temperature in Mashhad was 1 °C higher than in Karaj. The data suggest that winter in Mashhad was somewhat warmer than Karaj.

Table 2 illustrates the climatic characteristics during the sugar beet growth period in two experimental years. In the first year of the trial, the amount of rainfall in Mashhad was higher than in Karaj. However, in the second year, there was no significant difference between the two locations in term of rainfall. The absolute minimum

Table 2. Climatic characteristics during the sugar beet growth periods addressed by this study.

Year	Month	Karaj					Mashhad				
		Temperature (°C)				Rain (mm)	Temperature (°C)				Rain (mm)
		Min	Max	Mean of Min	Mean		Min	Max	Mean of Min	Mean	
2017	9	9.7	31.0	13.4	21.0	0.0	5.8	31.0	11.6	19.2	0.1
	10	4.0	29.0	10.6	17.0	4.8	3.6	31.0	8.9	16.9	0.0
	11	-3.5	24.0	6.3	11.5	0.6	-1.7	31.0	5.2	12.1	14.5
	12	-3.4	22.0	1.4	6.7	4.7	-6.5	24.0	-0.9	5.9	0.4
2018	1	-11.7	16.0	-0.1	4.1	8.6	-11.9	21.0	-1.7	4.8	0.9
	2	-8.5	15.0	1.7	6.5	16.6	-7.7	22.0	1.8	7.7	41.8
	3	0.2	30.0	8.1	14.7	14.1	4.2	33.0	9.0	14.8	37.8
	4	-0.3	26.0	7.8	13.6	26.8	1.0	32.0	8.9	14.4	33.5
	5	6.2	32.0	12.1	18.4	57.1	9.1	36.0	13.7	20.6	56.8
	6	13.0	35.0	16.2	24.2	7.2	17.3	40.0	19.5	26.6	2.1
2018	9	13.4	31.0	15.7	21.7	0.0	10.9	29.0	13.0	21.0	0.0
	10	5.9	30.0	11.2	16.6	29.1	2.6	31.0	8.0	15.0	41.9
	11	0.0	16.0	5.4	9.1	65.9	-1.3	22.0	4.0	9.0	18.8
	12	-0.8	18.0	4.0	11.0	33.8	-1.4	22.0	1.0	7.0	0.3
2019	1	-5.5	16.0	0.4	4.5	50.5	-4.9	22.0	0.0	7.0	12.8
	2	-3.6	14.0	0.8	5.3	12.2	-5.0	17.0	0.0	6.0	52.2
	3	-2.4	18.0	3.3	8.1	70.7	-0.4	24.0	5.0	10.0	62.7
	4	-1.1	24.0	6.6	12.5	41.9	3.4	25.0	9.0	14.0	77.1
	5	5.8	32.0	12.8	20.5	12.0	8.6	34.0	14.0	21.0	47.7
	6	16.2	37.0	18.0	26.4	0.0	13.4	36.0	17.0	25.0	10.0

temperature recorded in each of the two years of the trial was not different between the two locations (about -12 and -5 °Cin the first and second years, respectively). Although, the mean temperature recorded in the winter season in Mashhad was higher than Karaj (about 1 °C). In summary, Mashhad had slightly warmer winters compared with Karaj.

Experimental design

The experiments were arranged as randomized complete block design in five replications with six sowing dates from mid-September to mid-November (except for the first year of the experiment in Karaj, where the sixth treatment was in the second half of December). They were conducted with a bolting-tolerant cultivar called "Jerra". Sowing dates are shown in Table 3. The dates were set based on 15-year meteorological statistics to generate different sugar beet growth stages before the onset of winter. Each experimental plot consisted of 6 eight-meters long rows, with 50 cm row spacing.

Agricultural operations

Urea, triple superphosphate and potassium sulfate were used as fertilizers. They were applied in accordance with the soil test results. Seeds were sown with a seeder with an in-row spacing of about 4.8 cm and 50 cm row distance. Furrow irrigation was applied immediately after sowing at intervals of about 4 days for safeguarding germination and emergence. Plants were thinned to about 5 plants per meter of row at the 4-6 leaf stage. Because of the weather conditions, further irrigation was not required until the end of the experiment (late April).

Table 3. Sowing date treatments in Karaj and Mashhad in 2017 and 2018.

Treatment sowing date	Karaj		Mashhad	
	2017	2018	2017	2018
1	19-Sep.	24-Sep.	23-Sep.	23-Sep.
2	3- Oct.	2- Oct.	2- Oct.	1- Oct.
3	10-Oct.	10-Oct.	9-Oct.	10-Oct.
4	19-Oct.	20-Oct.	21-Oct.	20-Oct.
5	2-Nov.	3-Nov.	1-Nov.	5-Nov.
6	18-Dec.	19-Nov.	21-Nov.	26-Nov.

Determination of duration and speed of seedling emergence

The number of emerging seedlings in a 0.5 m^2 area on each plot was counted at the two experimental sites in the second year and after the first irrigation. Counting was continued until reaching a maximum number of seedlings emerged, after which no new ones were observed. In each plot, there were 42 seeds sown per each meter of row length. Equations 1 and 2 (Ellis and Roberts (1980) for seed germination were used to calculate the mean time of emergence, $\bar{D}$, and the average daily emergence rate, $\bar{R}$, respectively:

$$\bar{D} = \frac{\sum D\, n}{\sum n} \quad (1)$$

$$\bar{R} = \frac{1}{\bar{D}} \quad (2)$$

where D is the number of days after the first irrigation date and is the number of seedlings appearing on day$D$.

Phenological evaluation in the early growth stage

At both sites and for each treatment, plant phenological stages up the 16-leaf stage were recorded. A phenological stage was considered as achieved when about 50% of the plants were in this stage. Corresponding cumulated growing degree-days, GDD (°C d) were evaluated based on equation (3):

$$GDD = \sum T_{eff} \quad (3)$$

where the effective temperature is given by:

$$T_{eff} = \begin{cases} \frac{T_{min} + T_{max}}{2} - T_{base} & if\ T_{min} > 3°C\ \&\ T_{max} < 40°C \\ 0 & otherwise \end{cases} \quad (4)$$

In this equation, T_{max} and T_{min} are the maximum and minimum daily temperatures in °C, respectively, and T_{base} is the sugar beet base temperature, considered to be 3 °C.

Different regression models were fitted to express the relation between growth stages and thermal time for Karaj and Mashhad, separately, and for the average of the two regions. In all circumstances, the quadratic model had a higher coefficient of determination (R^2) compared to the linear, logarithmic, inverse, compound, power, s, growth, exponential, logistic and cubic models.

Determination of seedling morphological traits

In the first and second year at the Karaj site, morphological traits of the seedlings, including the largest root diameter, and root, leaf and petiole dry weights, were measured in late November for the first four levels of seeding dates treatment. The amount of plan growth for the last two levels of the seeding dates treatment were very negligible in late November and so it could not be measured.

Plants in 2 m^2 area on each plot were harvested and counted. In the laboratory, after measuring the largest diameter of each root, the leaves, petioles, and roots of each plant were separated. The samples were placed in an oven for 48 hours at 75 °C, and then the dry matter of the samples was measured. Data for each trait were averaged according to the number of plants in each sample and evaluated on a single-plant basis. Next, regression models were fitted to express the size of the largest root diameter during the growing season as a function of thermal time. Among the models, the quadratic and cubic models had a higher coefficient of determination (R^2) compared to the linear, logarithmic, inverse, compound, power, s, growth, exponential and logistic models, and the quadratic model was, therefore, retained for predicting the root diameter.

Bolting percentage assessment

In mid-spring, bolting percentage for each treatment was calculated by counting the total number of plants and the number of the bolted plants in a 4 m^2 area on each plot. Thereafter, we determined the number of days in which plants were exposed to temperatures effective for bolting, which we calculated as the number of days for which T_{max} was between 0 and 12 °C, and 6 and 8 °C (Milford et al. 2010). Next, we assessed the correlation between the percentage of bolting and the number of days with temperatures effective for bolting and the age of the plants (based on GDD) at the onset of bolting. Various regression models on bolting percentage of treatments over thermal time at the onset of bolting were fitted. Quadratic and cubic models exhibited the best fit (higher R^2), and the quadratic model was retained.

Cold and frost damage assessment

The number of plants was counted in a 1 m^2 area on each plot at the beginning of winter (January 1) and also at the beginning of spring (early April), so that the percentage of plants lost due to cold climate and frost during the cold season could be calculated. Regression models were subsequently fitted to express the percentage of frost damage as a function of thermal time after January 1st. Since linear and logarithmic regression models had a higher coefficient of determinations compared to other models, the linear model was retained to predict the percentage of killed plants at different seedling ages during the winter.

Statistical analysis

We carried out an analysis of variance (ANOVA) with respect to the duration and speed of field emergence as well as quantitative traits of sugar beet seedlings using the SAS software (version 9.1). The comparison of the means was conducted by the least significant difference test ($P \leq 0.05$).

The statistical software SPSS (version 16) was used to fit Pearson correlations and regression models for phenological stages, root diameter, bolting percentage and killed plants percent over GDD.

Significant differences between regression models established separately for the two sites and the model inferred from the combined data sets were evaluated by the F-test (Motulsky,1999). The following formula was used:

$$F = \frac{(SS_{combined} - SS_{separate})/(DF_{combined} - DF_{separate})}{SS_{separate}/DF_{separate}} \quad (5)$$

Where *SS* denotes the total sum of squares and *DF* the total degrees of freedom for each of the settings (combined versus separated). As the results indicated that the F-tests were non-significant ($P > 0.05$), only the combined models were used (Mohammadian et al., 2014; Traversa, 2003).

RESULTS

Duration and rate of field emergence

The analysis of variance showed that the effect of sowing date on the mean duration and rate of field emergence was significant ($P < 0.01$). Overall, delay in sowing date, due to decreasing air temperature at the time of germination, caused the duration to increase and the rate of field emergence to decrease (Table 4).

Phenological stages

Figure 1 shows the model that predicts the stages of sugar beet growth up to the 16-leaf stage as a function

Table 4. The effect of sowing date on duration and rate of field emergence of autumn sown sugar beet in 2018. DAS: days after seeding, $\overline{D}$: mean emergence time; $\overline{R}$: average rate of emergence. Lowercase letters next to numbers in each column indicate differences in significance based on the least significant difference test (P ≤ 0.0 5).

Treatment	DAS	Karaj			DAS	Mashhad		
		%Emergence	$\overline{D}$ (Day)	$\overline{R}$ (n. seed/ day)		%Emergence	Day	$\overline{R}$ (n. seed/ day)
1	12	80.9	5.54e	0.18a	13	55.9	8.52d	0.12a
2	12	71.4	7.06d	0.14b	16	35.7	9.51d	0.11a
3	13	78.6	9.17c	0.11c	21	54.7	14.32c	0.07b
4	11	66.7	9.38c	0.11c	23	39.3	16.16bc	0.06b
5	25	51.2	15.07b	0.07d	32	67.3	17.88b	0.06b
6	33	42.3	22.37a	0.04d	54	47.6	29.30a	0.03c

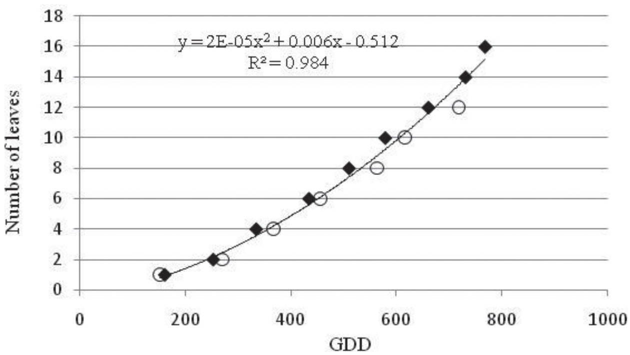

Figure 1. Relationship between GDD and number of leaves (1: Cotyledon leaf stage, 2-16: Leaf stage) in the early growth stage of autumn sugar beet. Each dot represents the mean of five replications, 6 sowing dates and two years. The symbols ○ and ◆ represent results for Mashhad and Karaj, respectively.

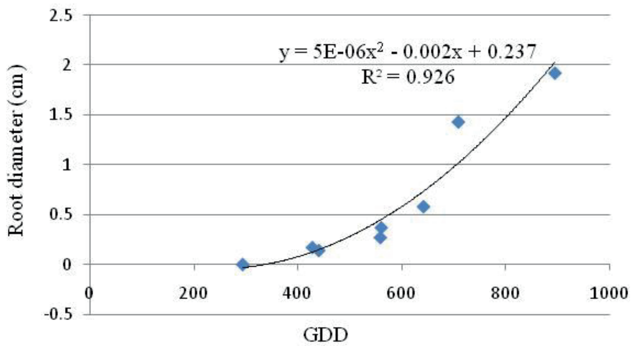

Figure 2. The relationship between GDD and the size of largest root diameter of autumn sugar beet in late November. Each dot represents the mean of five replication.

of thermal time. According to the model, 163 GDD are required for cotyledon leaves to appear above the surface of the soil, while to reach stages 2, 4, 6, 8, 10, 12, 14 and 16 true leaves, 200, 321, 418, 500, 600, 639, 700 and 757 GDD are required, respectively.

The effect of sowing date on quantitative traits of sugar beet seedlings

The effect of sowing date on leaf, shoot (leaf+ petiole) and root weight and root diameter of sugar beet plants was significant (P < 0.01) (Table 5). The comparison of means showed the greatest root diameter, root, leaf and shoot weight in 2017/18 and 2018/19 with 894 and 708 GDD, respectively; such values were achieved by the first

Table 5. The effect of sowing date on autumn sown sugar beet in 2017/18 and 2018/19 in Karaj. Lowercase letters next to numbers in each column indicate differences in significance based on the least significant difference test (P ≤ 0.05).

Treatment	GDD	Root diameter (cm)	2017/18			GDD	Root diameter (cm)	2018/19		
			Root weight	Leaf weight	Shoot(leaf+ petiole) weight			Root weight	Leaf weight	Shoot(leaf+ petiole) weight
			(g/plant)					(g/plant)		
1	894.2	1.92a	5.73a	7.11a	8.13a	708.8	1.43a	2.88a	4.36a	6.56a
2	642.0	0.58b	0.24b	0.97b	1.15b	559.1	0.27b	1.20b	1.73b	2.83b
3	560.9	0.37cb	0.08b	0.62b	0.70b	428.9	0.17c	0.67c	1.25c	1.92c
4	441.1	0.14c	0.02b	0.08b	0.10b	295.1	0.001d	0.18d	0.49d	0.49d

Table 6. Percentage of bolting, number of days with T_{max} between 0 and 12 °C, and 6 and 8 °C, respectively, and GDD on the first day these temperatures occurred.

Location	Year	Treatment	$0< T_{max} \leq 12$°C		$6\leq T_{max} \leq 8$°C		Date of counting	Number of plants (m^{-2})	Bolting (%)
			Number of days	GDD	Number of days	GDD			
Karaj	2017/18	1	62	894	13	894	6-May	12	81
		2	62	642	13	642	26-May	12	29
		3	62	561	13	561	26-May	7	0
		4	62	441	13	441	26-May	2	0
		5	62	230	13	230	26-May	1	0
		6	41	58	9	58	26-May	3	0
	2018/19	1	96	595	18	817	14-May	9	79
		2	96	445	18	667	19-May	9	78
		3	96	315	18	537	9-June	9	30
		4	96	181	18	403	9-June	9	0
		5	96	27	18	249	9-June	2	0
		6	89	37	18	158	9-June	0	0
Mashhad	2017/18	1	55	773	17	773	3-July	10	45
		2	55	627	17	627	3-July	10	7
		3	55	550	17	550	3-July	9	1
		4	55	376	17	376	3-July	9	0
		5	55	213	17	213	3-July	7	0
		6	55	25	17	25	3-July	2	0
	2018/19	1	73	252	9	713	23-June	10	79
		2	73	112	9	573	23-June	9	34
		3	72	230	9	454	23-June	9	1
		4	72	131	9	355	23-June	10	0
		5	64	59	9	201	23-June	8	0
		6	58	18	9	67	23-June	7	0

Table 7. Pearson correlation coefficients between the percentage of bolting and the number of days (N days) with the temperatures effective on bolting and GDD on the first day these temperatures occurred for the treatments of sowing date in autumn sugar beet.*, **and ns: significant differences at P = 0.05 and 0.01, and non-significant, respectively.

	$0< T_{max} \leq 12$°C		$6\leq T_{max} \leq 8$ °C	
	N days	GDD	N. days	GDD
Bolting%	0.332ns	0.524**	0.071ns	0.769**

sowing date. Figure 2 shows the regression model of root diameter as a function of thermal time. According to this model, the root diameter reaches 0.11, 0.27, 0.49, 0.84, 1.00, 1.29 and 1.59 cm at cumulated GDDs of 321, 418, 500, 600, 639, 700 and 757°C d, respectively.

Evaluating the effect of sowing date on bolting

Table 6 shows the number of days with T_{max} between 0 and 12 °C, and 6 and 8 °C, respectively. In this table,

Table 8. Summary of the regression models for predicting bolting percentage as a function of GDD at the beginning of the effective temperature and killed plants as a function of GDD cumulated from January 1st.

Independent variable	T_{max} (C°)	Equation	Model Summary					Parameter Estimates		
			R Square	F	df1	df2	Sig.	Constant	b1	b2
% bolting	$0< T_{max} \leq 12$ °C	Quadratic	0.285	4.176	2	21	0.030	3.762	0.022	4.935E-5
% bolting	$6\leq T_{max} \leq 8$ °C	Quadratic	0.756	31.056	2	20	0.000	6.522	-0.094	0.000
% killed plants	-	Linear	0.302	6.928	1	16	0.018	58.246	-0.071	-

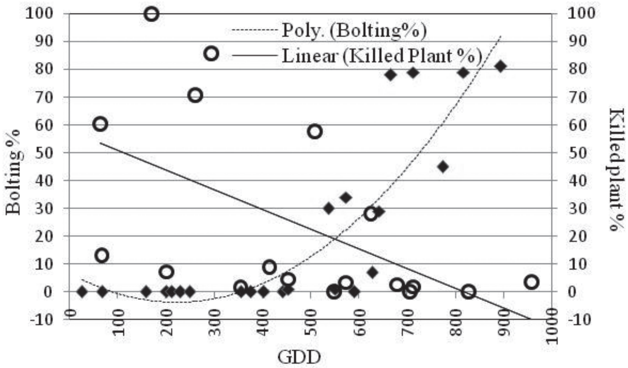

Figure 3. Relationships between GDD at the beginning of winter and percentage of killed plants (R^2= 0.302) and between GDD at the beginning of the period with T_{max} between 6 and 8 °C and percentage of bolting (R^2 = 0.756). Details of regression models are presented in Table 8. Each dot represents the mean of five replication. Bolting%= ◆, Killed plant%= ○.

GDD is the cumulated sum attained on the first day on which the above conditions were satisfied. In general, the percentage of bolting in Karaj was greater than that in Mashhad in both years. Also, compared with Mashhad, the number of days with T_{max} between 0 and 12 °C in Karaj was greater in both years. The minimum and maximum number of days with T_{max} between 0 and 12 °C were recorded in Mashhad in 2017/18 and in Karaj in 2018/19. However, the recorded number of days with T_{max} between 6 and 8 °C was different each year, and it was higher in the first year in Mashhad but in the second year in Karaj, respectively.

The correlation between the percentage of bolting and GDD, on the one side, and the correlation between the number of days with T_{max} between 0 and 12 °C, and 6 and 8 °C, respectively, and GDD, on the other side, were both positive (Table 7), but only the correlation between the percentage of bolting and GDD was significant ($P < 0.01$).

Table 8 shows regression models for predicting bolting percentage as a function of GDD. The coefficient of determination (R^2) is considerably higher with respect to the beginning of the period with T_{max} between 6 and 8 °C (R^2= 0.756) than with respect to the period with T_{max} between 0 and 12 °C (R^2 = 0.285).

The effect of cold and frost stress on sugar beet seedlings

In the present experiment, the lowest daily temperature in 2017/18 and 2018/19 in Karaj and in 2018/19 in Mashhad was about -12 °C (Table 2). Table 8 shows the model for the prediction of plant losses during the winter as a function of GDD. The results indicate a negative relationship between the percentage of plant loss during winter and plant age at the beginning of winter (Figure 3).

DISCUSSION

Duration and rate of field emergence

The average duration of field emergence increased from about 7 to 26 days from the first sowing date (second half of September) to the sixth sowing date (second half of November). Conversely, the emergence rate decreased from 0.15 to 0.03 seeds per day. If soil moisture and structure are optimal, the field emergence of sugar beet largely depends on temperature (Esmaeili et al. 2022, Hoffmann et al., 2020). Germination increases with increasing temperature and reaches a maximum at 22-25°C (Campbell and Enz, 1991). The minimum temperature for sugar beet growth is 3 °C (Milford et al., 1985a, 1985b), but growth decreases at temperatures below 10 °C, so the critical growth period for seedlings is longer than estimated based alone on a critical threshold of 3 °C. Delay in autumn sowing of sugar beet leads to germination at temperatures below the desired level, increases the average duration, and decreases the emergence rate. Hongyong et al. (2007) reporter that wheat typically germinates in 7 days, but requires about 13 days in case of delayed sowing. In our experiment, the maximum delay in autumn cultivation of sugar beet (about two months) increased the time to reach emergence by about 31days (this value is the average for Mashhad and Karaj of the differences in DAS between treatment 6 and 1 in Table 4).

If the seeds are in the ground at temperatures below the desired level, the germination process proceeds very slowly and the germinating seeds and the seedlings remain vulnerable to soil-borne pests and diseases for a long time (Jaggard and Qi, 2006). Thus, in such conditions there is a high possibility of poor establishment in the field.

Phenological stages

It has been reported that the basal temperatures for leaf emergence and leaf expansion are 1°C and 3°C, respectively (Milford et al., 1985a). As the leaf area increases, so does the number of leaves (Milford et al., 1985b). On average, each of the growth stages until the 16-leaf stage required about 70 GDD. The highest partial GDD sum was required to reach the cotyledon stage. The time of onset of vegetative and reproductive stages and the number of the organs depend on temperature and length of the day, but the subsequent survival and size of these organs depend on the availability of nutrients (Slafer, 2007). Our study evaluated sugar beet phenology up to the 16-leaf stage at two sites in Iran separated by 1 degree of latitude. As the relationship between number of leaves and GDD did not differ significantly between sites, we conclude that the growth stages were not affected by latitude. This is consistent with the finding reported by Krüger et al. (2012), that phenology stages of strawberry were independent from latitude.

The effect of sowing date on quantitative traits of sugar beet seedlings

Quantitative traits of sugar beet seedlings, including leaf, shoot and root weight and maximum root diameter, were significantly reduced by delayed sowing dates. Hence, it is possible to have different levels of sugar beet growth stages before the onset of cold weather by adjusting the sowing date. It has been reported that in spring cultivation and in the presence of water stress in the early stages of growth, the genotypes that produce higher root and total dry weight early in the growing season, usually produce higher root and sugar yield at the end of the growing season (Mohammadian et al., 2005). It has also been found that the production of sugar beet leaves and roots in autumn until winter has a strong relationship with sowing date, and that more yield is obtained with earlier sowing dates (Hoffmann and Kluge-Severin, 2011). In addition, the yield of sugar beet directly depends on the amount of radiation received by the leaves from sowing to harvest. Therefore, management of sowing and harvesting dates plays an important role in determining the yield (Lee et al., 1987).

Evaluating the effect of sowing date on bolting

In general, the differences of bolting percentage for locations, seasons, and sowing dates are related to the number of cold days after sowing (Hoffmann et al., 2020). We found a higher percentage of bolting in Karaj than in Mashhad, which is explained by the greater number of cold days (T_{max} in the range 0 to 12 °C) at the former location. However, in each year and location, the bolting percentages differs depending on the sowing dates. The percentage of bolting was higher for early than late sowing dates (Table 6).

Moreover, our results showed that the age of the plants at the beginning of the period with temperatures effective for bolting had a larger impact on bolting percentage than the number of days with the suitable temperatures for bolting (Table 7). According to the coefficient of determination (R^2) of the regression models predicting the percentage of bolting as a function of GDD, the temperatures 6 to 8 °C were found to be more effective than the temperatures 0 to 12 °C on the percentage of bolting (Table 8).

Figure 3 indicated that in order to minimize bolting percentage, it is necessary to adjust the sowing date so sugar beet is already at stage 4-6 leaves (300 to 400 GDD) at the time of occurrence of temperatures effective for bolting. At this time, the largest root diameter of sugar beet was 0.11 to 0.27 cm.

Effect of cold and frost stress on sugar beet seedlings

It has been shown that sugar beet roots are damaged by at temperatures below -6 °C (Reinsdorf and Koch, 2013). In addition, autumn sugar beet sowing in colder regions carries the risk of frost and freezing of the cell membrane and leakage of intracellular solutes (Baker and Rosenquist, 2004). In particular, Nezami et al. (2015) reports that, under controlled conditions, electrolyte leakage start to be effective when temperature drops below -7 °C.

Our findings indicate that there is a reverse relation between the degree of growth of sugar beet at the end of fall and cold tolerance and survival rate in winter (Fig. 3). In our experiment, we observed the least number of killed plants when the growth stage of sugar beet was beyond 16 leaves (more than 850 GDD). According to the equation presented in Figure 2, the largest diameter of the sugar beet root at 850 GDD is about 2cm. This is in line with the finding of a highest capacity to withstand temperatures below -7°C and maximum survival of sugar beet plants at 600-900 GDD after sowing (Loel and Hoffmann, 2014). Moreover, it has also been reported that the highest tolerance to sugar beet frost is when the root diameter reaches 1 to 2.5cm (Reinsdorf and Koch, 2013).

According to the results presented in Table 2 and Figure 3, we recommend for the region of Iran, in which our study took place, that sowing date for autumn cultivation are chosen so that the plants are able to reach the 14-16 leaf stage (700-750 GDD from sowing) before January. We expect that in these conditions, sugar beet plants will be able to tolerate cold temperatures which eventually will limit the percentage of killed plant to below 7%.

CONCLUSION

Climate change has made it possible to grow sugar beet in the autumn in areas, where in the past only spring sowing was possible. However, unlike in warmer regions, in these areas autumn and early winter temperatures below the base temperature (3 °C) can delay growth, implying higher risk of frost damages. The results of our study showed that delayed sowing date led to an increase in the average duration of the early development phases, a decrease in the speed of field emergence, and reduced growth of sugar beet seedlings before the onset of winter in cold regions. This was associated with higher frost killing compared with earlier sowing dates.

The number of days with T_{max} in the range 6 to 8°C was more relevant for bolting than the number of days with T_{max} in the range 1 to 12°C. In our study, the bolting percentage depended on the growth stage achieved at the onset of the time period with temperatures effective for bolting (6 to 8°C). Assessing the effect of sowing date on bolting percentage is therefore of paramount importance for the success of autumn cultivation of sugar beet, even for cultivars with relatively high bolting tolerance. As a rule, sowing should be planned to allow sugar beet to accumulate 300 to 400 GDD at the time temperatures drop at levels effective for inducing bolting. In addition, 700 to 750 GDD at the time temperatures drops below 0°C are necessary to minimize the risk of frost killings. Considering 15 years of weather data allows obtaining a first-order estimate of the optimum time window for sowing. Finally, we would like to point out that in autumn cultivation of sugar beet it is better to sow the seed at higher densities than typically recommended for spring cultivation, because thinning can be performed after once the plants are successfully established.

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Estimation of daily global solar radiation based on different whitening applications using temperature in Mediterranean type greenhouses

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Abstract. The study aimed to estimate the daily global solar radiation (R_s) in Mediterranean-type greenhouses. Five different temperature-based R_s estimation models developed for open-field conditions were calibrated and validated in Mediterranean-type greenhouses in Almeria, Spain and Antalya, Türkiye, between August 26, 2013, and January 1, 2023, and between October 1, 2018, and 1 January 2023, respectively. Whitening applications were categorized according to greenhouse light transmissivity and classified as follows: without whitening or light-whitening, medium-whitening, and severe-whitening. Additionally, the best-performing model were compared with greenhouse plastic light transmissivity method. The estimation performance of the models was evaluated using the statistical indicators of the p-value of the slope, determination coefficient (R^2), Nash–Sutcliffe model efficiency coefficient (NSE), root mean square error (RMSE), mean absolute error (MAE), relative error (RE), and Willmott Index (d). Compared with the other models, the Bristow and Campbell model showed a slightly higher performance in all whitening applications. Although the light transmissivity coefficient method performed slightly better than the temperature-based R_s estimation model, there was no statistical difference in the performances of the estimation models. Temperature-based estimation models offer a highly viable alternative for individuals who rely on the light transmittance approach to estimate R_s in greenhouses. This method can prove particularly useful in areas where measuring R_s outside the greenhouse is not possible or where partial time measurements cannot be taken owing to equipment malfunctions. All calibrated models can be used to estimate solar radiation using temperature data from various Mediterranean countries with similar climates and greenhouse cultivation.

Keywords: calcium carbonate suspension, extraterrestrial radiation, modelling, short wave radiation, shadow powder.

HIGHLIGHTS

- R_s estimation models had high agreement and accuracy with measured R_s values of Mediterranean-type greenhouses.
- There was no statistical difference between the R_s estimation model and light transmission coefficient method.
- Calibrated models are good alternatives if R_s outside the greenhouse is unmeasured or malfunctioning.

1. INTRODUCTION

Greenhouse cultivation has become a widespread practice, with an area of 5.6 Mha worldwide, owing to its ability to reduce dependence on climate and increase income per unit area (Hickman, 2020). Recently, greenhouse cultivation has grown significantly, particularly in regions such as the Mediterranean Basin, where mild winter temperatures permit low-cost vegetable crop production (Pardossi et al., 2004; Baudoin et al., 2013). In such areas, greenhouse cultivation is generally carried out in low-cost greenhouses without heating and ventilation systems. Baudoin et al. (2013) reported that polyethylene plastic is widely used (90%) as a cover material in these greenhouses. Additionally, Büyüktaş et al. (2019) noted that farmers in the region tend to favor the use of polyethylene ultraviolet (UV) + infrared ray barrier (IR) + diffuser (DIF) + ethylene vinyl acetate (EVA)-added plastic cover material with a service life of 36 months. This material is typically replaced after three years of use. In greenhouse cultivation, light is a crucial and a limiting factor for most cultivated species, along with other factors such as temperature and relative humidity (Stanghellini and Heuvelink, 2007; Colantoni et al., 2018). Global solar radiation (R_s) is a fundamental driving variable for many plant physiological processes including evapotranspiration, photosynthesis, carbohydrate partitioning, and dry matter production (Woli and Paz, 2012). Previous studies demonstrated that R_s was correlated with various plant growth parameters such as leaf area index (Bergamaschi et al., 2010), yield (Palencia et al., 2013), fatty acid profile (Gauthier et al., 2017), CO_2 assimilation rate (Francesconi et al., 1997), stomatal conductance (Marini and Sowers, 2019), chlorophyll content (Mielke et al., 2010) and root oxygen uptake (Nieuwenhuizen, 1983).

R_s is crucial for plant metabolism, growth, and development as it directly affects the greenhouse climate. Inadequate levels of radiation can lead to reduced photosynthesis, premature senescence, and ultimately decreased yield. Conversely, excessive solar radiation can inhibit photosynthesis through a process called photoinhibition, resulting in permanent yield reduction (López-Martínez et al., 2019). Therefore, growers apply whitening techniques (calcium carbonate ($CaCO_3$) suspension) to prevent photoinhibition, ensure that plants receive optimal light conditions, and maintain a controlled greenhouse climate (de los Ángeles Moreno-Teruel et al., 2020).

In addition to other climatic parameters, R_s is considered a crucial input required by most crop models to effectively simulate crop response. This is because plant growth is dependent on several complex physiological processes that involve the utilization of R_s. Furthermore, R_s is an important input for estimating crop evapotranspiration (ET_c) (Allen et al., 1998).

In recent years, the number of outdoor climate stations has increased; however, their application in greenhouse environments remains limited. Moreover, measurement of R_s is limited, particularly in developing countries (Yıldırım et al., 2018). This inadequacy hinders the estimation of greenhouse climate using various empirical methods. Greenhouse cultivation activities in regions with a Mediterranean climate are generally carried out in low-technology greenhouses with the aim of achieving high production with minimal input costs (Pardossi et al., 2004; Baudoin et al., 2013). Consequently, growers in these regions often do not collect climate data beyond temperature and humidity, which are both easy and inexpensive to measure. When evaluating the sensor cost, the global solar radiation (R_s) sensor is among the most expensive sensors and has a short economic lifespan that is dependent on quality. Additionally, expertise is required to collect and evaluate the data generated by this sensor. When the R_s value outside the greenhouse is known, the R_s value inside the greenhouse can be estimated by using the plastic cover transmissivity coefficient (Valdés-Gómez et al., 2009; Chen et al., 2020). However, several researchers have reported that this coefficient is not fixed. Fernández et al. (2010) stated that the transmissivity of the cover in a Mediterranean type greenhouse varied between 48.1% and 60.8% during the period of whitening application, while this value was 60.9% on average during the period without whitening application. Valdés-Gómez et al. (2009) also stated that this value is 62% on average. Fernández et al. (2001) reported that whitening with calcium carbonate caused a decrease in light transmissivity with varying percentages depending on the amount applied (e.g., 10% reduction for 175 g/l, 30% reduction for 250 g/l, 60% reduction for 400 g/l, 90% reduction for 1000 g/l). Due to the fact that whitening is typically applied using simple equipment, such as spraying the greenhouse, the application is often not uniform. Jimenez et al. (2010) noted that the greenhouse's light transmittance coefficient, after whitening was applied, was not uniform across the entire spectrum and varies based on the time of day. In general, the density of an application can varies based on the experience of the individual performing the application. Consequently, different intensities of whitening are applied to regulate R_s within the greenhouse to the desired level, based on the specific crop variety and phenological conditions. Similarly, prior whitening applications may be partially or entirely removed to augment the transmissivity of light into the greenhouse. For this reason, Gallardo et al. (2014) categorized the application of whitening into three levels: light, moderate, and severe, to aid farmers in utilizing the light transmissivity coefficient. In countries with low technology, Mediterranean-type greenhouses, where global solar radiation values are generally not measured, it is crucial to estimate R_s using parameters that are easily measured.

Greenhouse air temperature is correlated with R_s, with little or no time lag (Nieuwenhuizen, 1983). Numerous studies have attempted to estimate global solar radiation (R_s) using temperature values in outdoor conditions (Bristow and Campbell, 1984; Hargreaves and Samani, 1985, 1982; Donatelli and Campbell, 1998; Goodin et al., 1999; Chen et al., 2004). Hargreaves and Samani (1982) reported that R_s is related to extraterrestrial radiation (R_a) and relative sunshine duration (n/N) and that R_s can be estimated using these parameters. Hargreaves (1981) and Hargreaves and Samani (1982) established a correlation between daily temperature range (ΔT_1) and relative sunshine duration. Moreover, they proposed an empirical coefficient fitted to R_s/R_a versus temperature data, which served as the initial basis for other R_s estimation models (Hargreaves and Samani, 1985). Bristow and Campbell (1984) modified the definition of daily temperature range to account for the potential influence of large-scale hot or cold air masses that may move through the study area, because the maximum temperature may rise due to the hot air mass on the day of measurement. Because this phenomenon occurs after the measurement of the minimum temperature value, it causes the maximum and minimum air temperature differences to be high. Therefore, it is considered that the prediction models overestimate the value of R_s (Bristow and Campbell 1984). The opposite situation occurs in the case of a cold air mass, and underestimation of the incoming radiation would result in these conditions. Thus, Bristow and Campbell (1984) used the difference between the maximum air temperature and average minimum temperature values for two consecutive days to determine the daily temperature range. Donatelli and Campbell (1998) improved this model by incorporating a summer-night air temperature factor, as the ristow and Campbell model underestimated the value of R_s in the July-August period for the Northern Hemisphere and the January-February period for the Southern Hemisphere (Grillone et al., 2012). Goodin et al. (1999) added an additional R_a parameter to the Bristow and Campbell model and validated its reliability outside of the calibration region. Additionally, several researchers (Hunt et al. 1998; Chen et al. 2004) have modified these models and achieved a high level of accuracy in estimating the R_s value under outdoor conditions. However, despite the development and modification of these models for outdoor conditions, there are currently no calibrated or modified models for greenhouse conditions.

The primary aim of current study was to calibrate and validate six temperature-based models (namely, Hargreaves, Bristow and Campbell, Donatelli and Campbell, Chen, and Goodin) originally designed for outdoor conditions to estimate Rs in low-tech plastic greenhouses with a Mediterranean climate. Additionally, temperature-based prediction models were compared with the greenhouse light transmissivity coefficient method to determine the optimal approach under the prevailing conditions.

2. MATERIALS AND METHODS

2.1 Experimental sites

The study was carried out in two regions, at the University of Almeria (UAL) Experimental Farm in Almeria (SE Spain, 36°51'N latitude, 2°16'W longitude; 92 m above sea level) and Akdeniz University (AU) Experimental Farm in Antalya (TR Türkiye, 36°53'N latitude, 30°38'E longitude;12 m above sea level) in plastic greenhouses.

2.1.1 Experimental greenhouse in Almeria

The dimensions of the greenhouse in Almeria were 32 m (four tunnels of 8 m) width and 45 m length with ridge and gutter heights of 5.7 and 4.5 meters, respectively. The greenhouse was covered with a 200 µm polyethylene film featuring UV, IR, EVA, and AD additives and possessed a 36-month strength. The plastic coverings of the greenhouse were replaced three times on 08/03/2013, 09/03/2016, and 17/12/2019, respectively.

Climatic parameters, including air temperature, relative humidity (RH), and incident solar radiation were

Table 1. Crop varieties and corresponding growing periods cultivated within the research greenhouse in Almeria.

Crop Variety	Growing Period*
Cucumber	05/09/2013 - 22/11/2013
Pepper	04/03/2014 - 28/05/2014
Pepper	12/08/2014 - 29/01/2015
Pepper	19/07/2016 - 24/03/2017
Cucumber	30/03/2017 - 22/06/2017
Pepper	21/07/2017 - 20/02/2018
Cucumber	24/04/2018 - 03/07/2018
Pepper	27/02/2020 - 11/06/2020
Pepper	22/07/2020 - 28/01/2021
Melon	26/02/2021 - 08/06/2021
Pepper	16/07/2021 - 15/03/2022
Pepper	11/07/2022 - 16/03/2023

*The growth periods listed in the table include the start and end dates.

monitored inside the greenhouse at 5-minute intervals. The temperature and humidity were measured using temperature and humidity sensors (Model 43502, R.M. Young Company, Michigan, USA) and the solar radiation was measured using a pyranometer (model SKS 1110, Skye Instruments, Llandrindod Wells, Wales, United Kingdom) situated in the central area of the greenhouse at a height of 1.5 m above the ground. All monitored data were collected and stored using a data logger (model CR10X, Campbell Scientific, Inc., Utah, USA). Meteorological data outside the greenhouse were obtained from the Agricultural and Fisheries Research and Training Institute (IFAPA) meteorological station located at 36°50'N latitude and 2°24'W longitude. The distance between both sites was 10.1 km. Climate data collected both inside and outside the greenhouse were used in the study, covering the period from August 26, 2013, to January 1, 2023.

Indoor climatic data were interrupted between 18 November 2014 to 17 December 2014, between 6 June 2016 to 12 July 2016 and between 4 June 2019 to 23 February 2020, due to greenhouse maintenance activities. Table 1 shows the crops grown in the research greenhouse of Almeria, including their respective growing periods.

2.1.2 Experimental greenhouse in Antalya

The dimensions of the greenhouse in Antalya were 9.6 meters in width and 25 meters in length, with ridge and gutter heights of 6.0 and 4.0 meters, respectively. The greenhouse was covered with a 180 μm polyethylene film featuring UV, IR, EVA, and AD additives and possessed a 36-month strength. The plastic coverings of the greenhouse were replaced twice on July 11, 2018, and February 20, 2021.

Table 2. Crop varieties and corresponding growing periods cultivated within the research greenhouse in Antalya.

Crop Variety	Growing Period*
Grass	01/08/2018 - 01/01/2021
Tomato	27/02/2021 - 24/06/2021
Tomato	08/09/2021 - 24/01/2022
Tomato	24/02/2022 - 22/06/2022
Grass	15/07/2022 – 01/01/2023

*The growth periods listed in the table include the start and end dates.

The climate inside the greenhouse was monitored with a meteorology station located in the center of the greenhouse at a height of 1.5 m above the ground at 5-minute intervals. The meteorological station was equipped with various sensors, including an air temperature (PT100 1/3 Class B, Pessl Instruments, Weiz, Austria), relative humidity (Rotronic hygrometer IN-1, Pessl Instruments, Weiz, Austria), pyranometer (LI-200SZ, Pessl Instruments, Weiz, Austria) and net radiation with all its components (CNR4, Kipp&Zonen, Delft, Netherlands). Net radiation data were collected using a model CR1000X data logger (Campbell Scientific, Inc., Utah, USA), while all other recorded data were collected using an iMETOS 3.3 data logger (Pessl Instruments, Weiz, Austria). The climatic data outside the greenhouse were obtained from the station of Turkish State Meteorological Service, located at latitude 36° 53' N and longitude 30° 38' E. Distance between both sites is 0.3 km. Indoor greenhouse climate data were collected between October 1, 2018, and January 1, 2023, for a period of four years and three months. The solar radiation sensor located outside the greenhouse began collecting data on February 26, 2019, and finished on January 1, 2023. Data could not be collected outside the greenhouse between April 10, 2019 - April 22, 2019, and October 1, 2020 - October 30, 2020 due to sensor failure. Table 2 shows the crops grown in the research greenhouse of Antalya, including their respective growing periods.

2.2 Whitening application and data selection

During the research, whitening was applied at different doses and rates according to the crop species grown in both research greenhouses, the growing season, and the phenological period of the crop. Simi-

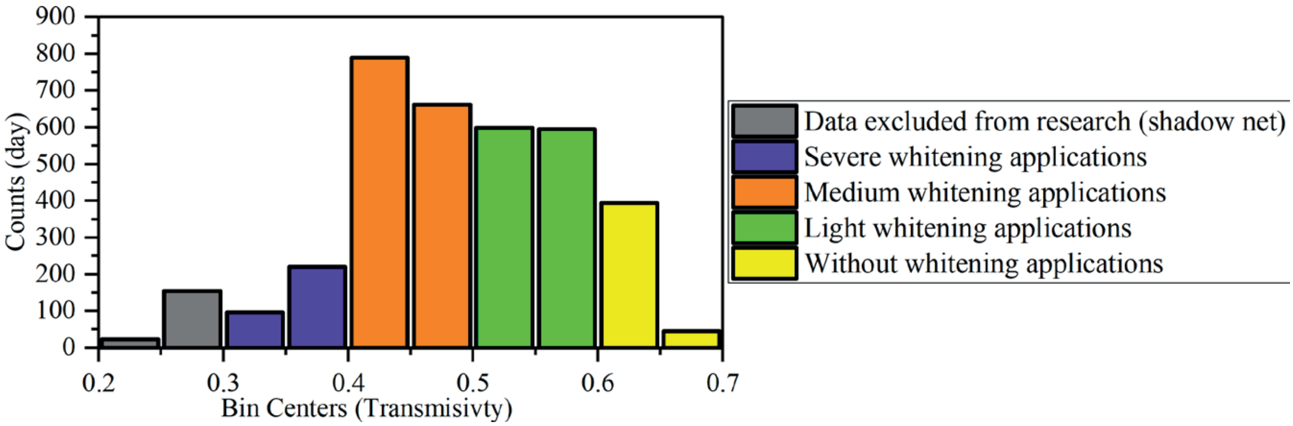

Figure 1. Histogram plot of transmissivity values in the dataset used in the experiment.

larly, the whitening density was reduced by washing to increase the intensity of the light entering the greenhouse. In addition, the whitening of the greenhouse cover was naturally washed away by precipitation. For this reason, the ratio of $R_{s\text{-indoor}}$ (solar radiation values inside the greenhouse) to $R_{s\text{-outdoor}}$ (solar radiation values outside the greenhouse) was used instead of the applied doses while selecting the data. The data between 12 August 2014 to 19 August 2014, 10 May 2016 to 17 July 2016, 13 July 2017 to 01 August 2017, and 05 May 2022 to 17 May 2022 were not included in the research conducted in the Almeria research greenhouse, as shade nets were extended during these periods. The $R_{s\text{-indoor}}/R_{s\text{-outdoor}}$ and $R_{s\text{-indoor}}/R_a$ ratios were used to eliminate erroneous data caused by sensor malfunctions during research. A histogram plot of the transmissivity values in the dataset used for the experiment was used to the classify the whitening application (Figure 1).

In the study, the classification of whitening applications was based on transmissivity values, where values between 0.6-0.7 indicated "without whitening", values between 0.5-0.6 indicated "light whitening", values between 0.4-0.5 indicated "medium whitening", and values between 0.3-0.4 indicated "severe whitening". The extraterrestrial radiation (R_a) was calculated using the method described by Allen et al. (1998).

2.3 Overview of the models

Table 3 summarizes the five different models that were calibrated and validated to estimate R_s based on temperature.

The unknown parameters (a, b, and c) for the greenhouse conditions of the models listed in Table 3 were determined using MS Excel Solver. The calibration and validation of the models for each whitening application class were conducted using data from odd and even days, respectively.

Table 3. Temperature-based solar radiation estimation models used under greenhouse conditions.

Model	Equation
HS (Hargreaves and Samani, 1985)	$R_s = a\sqrt{\Delta T_1}\, R_a$
BC (Bristow and Campbell, 1984)	$R_s = a\left(1 - exp(-b\,\Delta {T_2}^c)\right) R_a$
DC (Donatelli and Campbell, 1998)	$R_s = a\left(1 - exp\left(-b\dfrac{\Delta {T_2}^c}{\Delta T_m}\right)\right) R_a$
CH (Chen et al., 2004)	$R_s = (a\,ln\,\Delta T_1 + b)\, R_a$
GO (Goodin et al., 1999)	$R_s = a\left(1 - exp\left(-b\dfrac{\Delta {T_2}^c}{R_a}\right)\right) R_a$

Abbreviations: R_s, global solar radiation (MJ m^{-2} day^{-1}); R_a, extraterrestrial radiation (MJ m^{-2} day^{-1}); Alt, altitude (m); ΔT_1, difference between daily maximum (T_{max}) and minimum (T_{min}) air temperatures (°C); ΔT_2, the difference between the maximum air temperature and the average of the minimum temperatures for two consecutive days (°C); ΔT_m, average monthly temperature (°C), a, b and c: models coefficients.

2.4 Evaluation of the performances of the models and statistical analysis

In current study, firstly, all models were calibrated for each whitening application, and the coefficients of each model were determined for greenhouse conditions. Then, the performance of the models was evaluated using these coefficients in the validation dataset. Finally, the best temperature-based R_s model was compared with the R_s estimated using the light transmissivity coefficient method ($R_{s\text{-}Tr}$) and measured R_s values ($R_{s\text{-}measured}$). In the light transmissivity coefficient method, 0.65, 0.55, 0.45 and 0.35 coefficients were used for no whitening, light, medium and severe, respectively.

A scatter plot was generated by applying linear regression to the relationship between the estimated and measured data to visualize the distribution of the data around the 1/1 line. The estimation performance of the models was evaluated using statistical indicators using the p-value of the slope, determination coefficient (R^2) (Eq-1), Nash–Sutcliffe model efficiency coefficient (NSE) (Eq-2), root mean square error (RMSE) (Eq-3), mean absolute error (MAE) (Eq-4), relative error (RE) (Eq-5) and Willmott Index (d) (Eq-6).

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(X_i - \overline{X_i}\right)\left(Y_i - \overline{Y_i}\right)\right]^2}{\sum_{i=1}^{n}\left(X_i - \overline{X_i}\right)^2 \sum_{i=1}^{n}\left(Y_i - \overline{Y_i}\right)^2} \tag{1}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{\sum_{i=n}^{n}\left(X_i - \overline{X_i}\right)^2} \tag{2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{n}} \tag{3}$$

$$MAE = \frac{\sum_{i=1}^{n}|X_i - Y_i|}{n} \tag{4}$$

$$RE = \frac{RMSE}{\overline{Y_i}} \tag{5}$$

$$d = 1 - \frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{\sum_{i=n}^{n}\left(\left|X_i - \overline{Y_i}\right| + \left|Y_i - \overline{Y_i}\right|\right)^2} \tag{6}$$

Where n is number of observations, X_i is estimated R_s, Y_i is measured R_s and $\bar{X}_i$ is mean value of estimated R_s, $\bar{Y}_i$ is mean value of measured R_s.

R^2, NSE, and d values equal to 1, and RMSE, RE, and MBE values equal to 0 indicate the best possible regression relationship. Climatic data from Almeria and Antalya were compared using two-sample t-tests. Also, some climatic data (monthly average minimum temperature, mean temperature, maximum temperature, sunshine hours, and extraterrestrial radiation) related to the temperature-based R_s estimation models of six different greenhouse regions (Alger, Algeria; Almeria, Spain; Antalya, Türkiye; Bizerte, Tunisia; Kalamata, Greece; Siracusa, Italy) at similar latitudes were obtained from CLIMWAT 2.0 (Muñoz and Grieser, 2006). The aim of this was to determine the climatic similarities or differences between these regions using one-way ANOVA. The results of this statistical analysis are provided in the Supplementary Material (Figure S1). All statistical analyses were performed using SPSS Statistics Base v23 (SPSS Inc., Chicago, IL, USA) and figures were prepared using OriginPro v2023a (OriginLab Corporation, MA, USA).

3. RESULTS

3.1 Climatic analogies between Almeria and Antalya

The relationship between the monthly average solar radiation and sunshine duration data outside the greenhouse for Almeria and Antalya and the extraterrestrial radiation data of the two regions is shown in Figure 2.

The distribution of external solar radiation throughout the year showed great similarities between Almeria and Antalya (Figure 2). The annual average sunshine durations of Almeria and Antalya were 8.15 and 8.23 hour, respectively. Almeria had 0.08-hour shorter sunshine duration (p=0.38). The longest sunshine duration in both regions occurred in July. The annual average solar radiation of Almeria (17.7 MJ m^{-2} day^{-1}) was 0.5 MJ m^{-2} day^{-1} lower than Antalya (18.24 MJ m^{-2} day^{-1}) (p=0.65). There was a strong relationship between extraterrestrial radiation in Antalya and Almeria (R^2=0.999, RMSE=0.014, RE=0.0005).

Figure 3 showed the temperature, relative humidity, and precipitation data for Antalya and Almeria, with the significance level of the two-way test analysis of variance represented by "p".

There were no significant differences in the maximum, mean and minimum air temperatures (p=0.28, 0.33 and 0.49, respectively) between Antalya and Almeria (Figure 3a). In both regions, the air temperature showed an increasing trend between January and August, whereas it decreased in the following months. In contrast to air temperature, there was a significant difference in the monthly average relative humidity (p<0.05) and precipitation values (p<0.001) between the two regions (Figure 3b). Almeria and Antalya received a seasonal total of 200 and 1058 mm of precipitation, respectively.

3.2 Calibration of models

Table 4 shows the coefficients of the calibrated models used for estimating solar radiation values inside the greenhouse categorized under different whitening application conditions.

The scatterplot in Figure 4, which is a 1/1 plot, shows the correlation between the solar radiation within

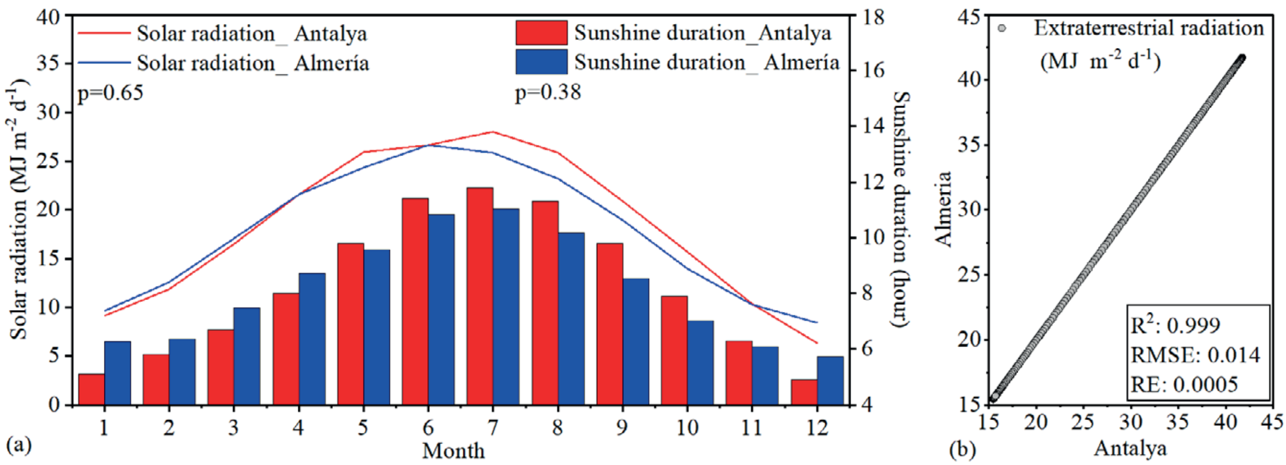

Figure 2. Monthly average solar radiation and sunshine duration data for Almeria and Antalya outside the greenhouse (a) and the relationship between the extraterrestrial radiation data of the two regions (b). *p is the significance level of the two-sample t-test;* R^2 *is the determination coefficient; RMSE is the root mean square error; RE is the relative error.*

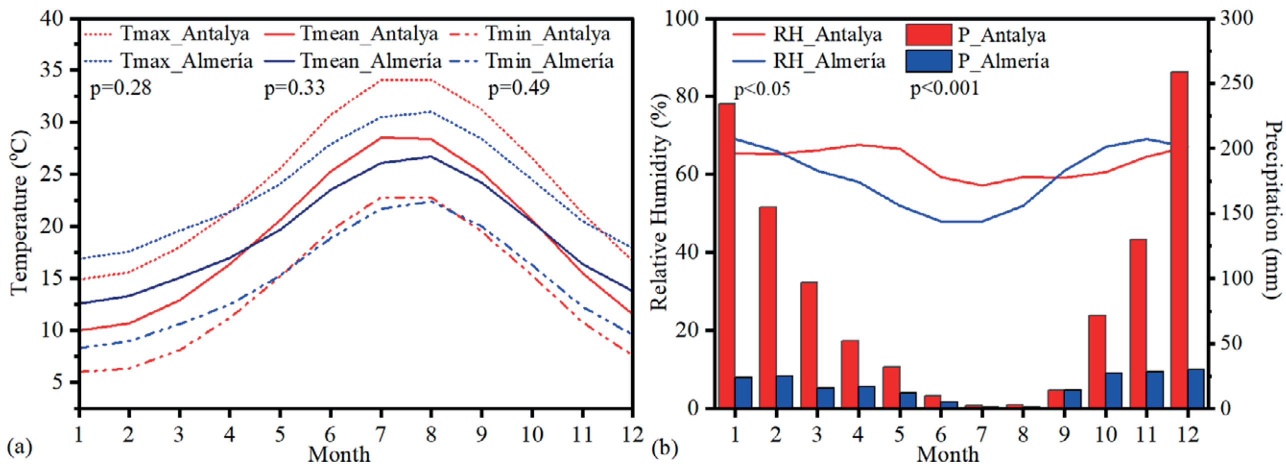

Figure 3. Maximum, mean and minimum temperature (a), relative humidity and precipitation data (b) of Antalya and Almeria. *T_{max} is the maximum temperature, T_{mean} is the mean temperature, T_{min} is the minimum temperature, RH is the relative humidity, P is precipitation and p is the significance level of the two-sample t-test.*

the greenhouse calculated using the calibrated models and the values measured by the sensors. The calibration performance of the models for the four whitening applications is listed in Table 5.

The calibration performance of the solar radiation estimation models for greenhouses was remarkably similar to one another within each whitening application. The relationship between the estimated and measured R_s values was highly significant in all calibrated models and whitening applications (p<0.001) (Figure 4). Similarly, the coefficients of determination of the relationship between the measured and estimated R_s values in each calibrated model ranged from 0.960-0.981 and were remarkably close to each other. Despite this, in certain models and whitening applications, the intensities of both the measured and estimated R_s values, as represented by the dark colors, were more closely aligned with the 1/1 line. Table 5 gave more details on these differences between calibrated models. The estimation performance of the calibrated models varied depending on the whitening application used. In all models, except for the NSE indicator of HA, the highest NSE, d, and lowest RMSE, MAE, and RE values proved that the best calibration performance was in the medium whitening application. All calibrated models had the lowest estimation performance in severe whit-

Table 4. Coefficients of models calibrated to estimate solar radiation inside the greenhouse for different whitening applications.

Whitening application	Model	Equation coefficient		
		a	b	c
Without whitening	Hargreaves (HA)	0.0866		
	Bristow and Campbell (BC)	0.4593	0.3565	0.5593
	Donatelli and Campbell (DC)	0.4163	1.2769	1.2587
	Chen (CH)	0.0803	0.1496	
	Goodin (GO)	0.3921	0.5108	2.0664
Light	Hargreaves (HA)	0.0812		
	Bristow and Campbell (BC)	0.4497	0.2023	0.7055
	Donatelli and Campbell (DC)	0.3871	0.4105	1.6478
	Chen (CH)	0.1005	0.0628	
	Goodin (GO)	0.3622	0.0148	3.3984
Medium	Hargreaves (HA)	0.0702		
	Bristow and Campbell (BC)	0.3307	0.3329	0.7002
	Donatelli and Campbell (DC)	0.3147	1.1624	1.3779
	Chen (CH)	0.0495	0.1591	
	Goodin (GO)	0.3064	2.8110	1.4448
Severe	Hargreaves (HA)	0.0577		
	Bristow and Campbell (BC)	0.2363	0.7958	0.5062
	Donatelli and Campbell (DC)	0.2305	5.3442	0.8858
	Chen (CH)	0.0210	0.1700	
	Goodin (GO)	0.2514	25.1243	0.4428

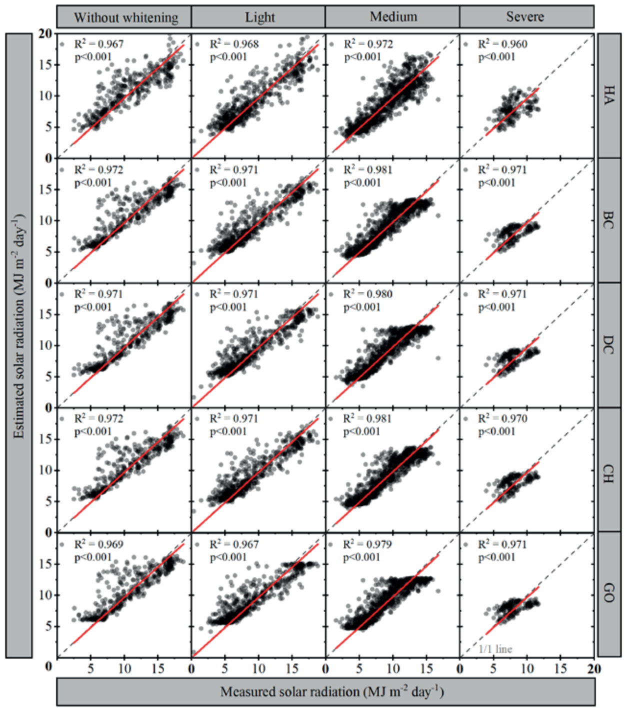

Figure 4. Relationship between estimated solar radiation from different models (HA, BC, DC, CH and GO) and measured solar radiation, at different greenhouse whitening applications for calibration data. *HA, Hargreaves; BC, Bristow and Campbell; DC, Donatelli and Campbell; CH, Chen; GO, Goodin. R^2 is the determination coefficient. p is the significance of regressions.*

ening application. Among the calibrated models without whitening application conditions, the BC model exhibited the best performance (NSE: 0.79, RMSE: 1.93, RE: 0.18), whereas the HA model had the lowest performance (NSE: 0.74, RMSE: 2.10, RE: 0.19). The calibrated BC and CH models showed the best estimation performance in the light whitening application, with the HA and GO models showing relatively weak performance. Among the models used in the medium whitening application, the BC, DC, and CH models were nearly identical in their superior estimation performance relative to the other models. The performances of all calibrated models, except for HA, were closely matched to each other in the severe whitening application, with HA exhibiting the lowest level of performance.

3.3 Validation of models

The distribution of solar radiation estimated from different models (HA, BC, DC, CH and GO) and measured solar radiation values in different greenhouse whitening applications for the validation data are shown in Figure 5, while the results of the statistical indicators for these models are given in Table 6**.**

The relationship between the measured and estimated solar radiation inside the greenhouse was significant during the validation process (p<0.001) (Figure 5). In all models and whitening applications, the determination coefficients of the relationship between the estimated and measured greenhouse solar radiation values showed good agreement (R^2>0.960). The BC model had the highest R^2 value (0.982) in the medium whitening treatment and the HA model had the lowest R^2 value (0.960) in the severe whitening treatment. The statistical indicators in Table 6 showed that the highest estimation performances in the validation stage as well as in the calibration stage were obtained with the medium whitening application in all models except for the NSE of HA. Compared with other whitening applications, all models showed higher prediction performance in light and medium whitening applications. The DC model had the highest NSE (0.78) and the lowest RMSE (1.93) in the without whitening application (Table 6). The validation performances of BC (NSE: 0.77, RMSE:1.97) and CH (NSE: 0.77, RMSE:1.96) models were remarkably close to those of the DC model. The estimation accuracies of the BC, DC and CH mod-

Table 5. Statistical indicators of calibration for greenhouse conditions of five R_s estimation models for different whitening applications.

Whitening application	Model	Statistical indicators				
		NSE	RMSE	MAE	RE	d
Without whitening	HA	0.74	2.10	1.61	0.19	0.92
	BC	0.79	1.93	1.42	0.18	0.93
	DC	0.78	1.93	1.43	0.18	0.93
	CH	0.78	1.92	1.40	0.18	0.93
	GO	0.76	1.99	1.49	0.18	0.93
Light	HA	0.81	1.78	1.36	0.20	0.94
	BC	0.83	1.69	1.25	0.18	0.95
	DC	0.83	1.70	1.25	0.18	0.94
	CH	0.83	1.69	1.25	0.18	0.95
	GO	0.81	1.78	1.30	0.19	0.94
Medium	HA	0.77	1.60	1.21	0.18	0.94
	BC	0.84	1.31	0.98	0.15	0.95
	DC	0.84	1.33	0.98	0.15	0.95
	CH	0.84	1.31	0.98	0.15	0.96
	GO	0.83	1.36	1.01	0.15	0.95
Severe	HA	0.00	1.62	1.37	0.21	0.68
	BC	0.26	1.39	1.21	0.18	0.70
	DC	0.26	1.39	1.21	0.18	0.69
	CH	0.27	1.39	1.21	0.18	0.70
	GO	0.28	1.38	1.15	0.17	0.65

Abbreviations: HA, Hargreaves; BC, Bristow and Campbell; DC, Donatelli and Campbell; CH, Chen and GO, Goodin. NSE, Nash–Sutcliffe model efficiency coefficient; RMSE, root mean square error; RE, relative error; MBE, mean bias error; d, Willmott Index.

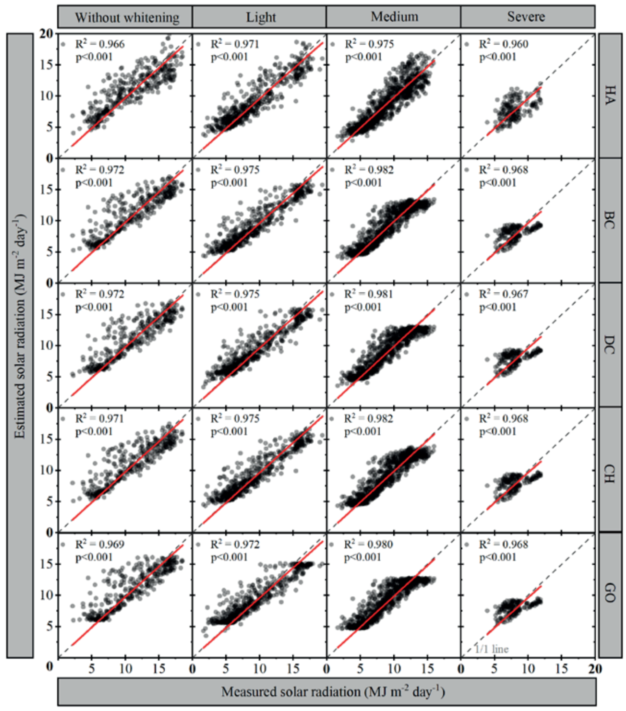

Figure 5. Relationship between estimated solar radiation from different models (HA, BC, DC, CH and GO), and measured solar radiation, at different greenhouse whitening applications for validation data. *HA, Hargreaves; BC, Bristow and Campbell; DC, Donatelli and Campbell; CH, Chen; GO, Goodin. R^2 is the determination coefficient. p is the significance of regression.*

els in light whitening applications were slightly better than those of the other models. The HA model showed low validation performance in both Medium and Severe whitening applications. In the validation stage, similar to the calibration stage, all models had lower estimation performance in the severe whitening application than in the other whitening applications. Furthermore, in the validation phase, the BC model showed better performance than the other models in the severe whitening application. All models demonstrated adequate performance in predicting in-greenhouse solar radiation, despite the slight differences observed in their validation results.

3.4 Comparison of the temperature-based method and the light transmissivity coefficient method

The relationships and distributions among the Bristow and Campbell model ($R_{s\text{-}BC}$), greenhouse light transmissivity coefficient ($R_{s\text{-}Tr}$), and measured ($R_{s\text{-}measured}$) solar radiation values, in various whitening applications are shown in Figure 6, and the statistical indicators of these relationships are listed in Table 7.

There was a significant relationship between the estimated with $R_{s\text{-}BC}$ and $R_{s\text{-}Tr}$ and $R_{s\text{-}measured}$ in all the whitening applications (p<0.001) (Figure 6). The regression analysis between the estimation methods and $R_{s\text{-}measured}$ showed that $R_{s\text{-}Tr}$ had a greater coefficient of determination than $R_{s\text{-}BC}$ for each whitening application. Nonetheless, a significant relationship was observed between the estimation methods in all whitening applications (p<0.001, R^2>0.967). The scatter plot showed that the data points in the $R_{s\text{-}Tr}$ method were distributed closer to the 1/1 line compared to the $R_{s\text{-}BC}$ model, which implied a lower error rate. Moreover, the NSE, RMSE, MAE, RE and d values of the relationship between the estimation methods ($R_{s\text{-}BC}$ and $R_{s\text{-}Tr}$) and the $R_{s\text{-}measured}$ were remarkably similar (Table 7). However, compared with $R_{s\text{-}BC}$, the $R_{s\text{-}Tr}$ method displayed superior NSE and d (higher), as well as RMSE, MAE, and RE (lower) in all whitening applications. As with all temperature-based R_s esti-

Table 6. Statistical indicators of validation for greenhouse conditions of five R_s estimation models for different whitening applications.

Whitening application	Model	Statistical indicators				
		NSE	RMSE	MAE	RE	d
Without whitening	HA	0.73	2.12	1.67	0.19	0.91
	BC	0.77	1.97	1.45	0.18	0.93
	DC	0.78	1.93	1.43	0.18	0.93
	CH	0.77	1.96	1.45	0.18	0.93
	GO	0.75	2.05	1.53	0.19	0.92
Light	HA	0.83	1.68	1.29	0.19	0.95
	BC	0.86	1.57	1.17	0.17	0.95
	DC	0.85	1.56	1.18	0.17	0.95
	CH	0.85	1.59	1.20	0.17	0.95
	GO	0.84	1.64	1.24	0.18	0.95
Medium	HA	0.80	1.47	1.14	0.17	0.95
	BC	0.86	1.25	0.96	0.14	0.96
	DC	0.85	1.27	0.96	0.14	0.96
	CH	0.85	1.25	0.96	0.14	0.96
	GO	0.84	1.31	0.99	0.15	0.95
Severe	HA	0.07	1.63	1.37	0.21	0.71
	BC	0.29	1.46	1.26	0.18	0.68
	DC	0.25	1.46	1.26	0.19	0.68
	CH	0.26	1.45	1.26	0.18	0.69
	GO	0.28	1.43	1.19	0.18	0.65

Abbreviations: HA, Hargreaves; BC, Bristow and Campbell; DC, Donatelli and Campbell; CH, Chen and GO, Goodin. NSE, Nash–Sutcliffe model efficiency coefficient; RMSE, root mean square error; RE, relative error; MBE, mean bias error; d, Willmott Index.

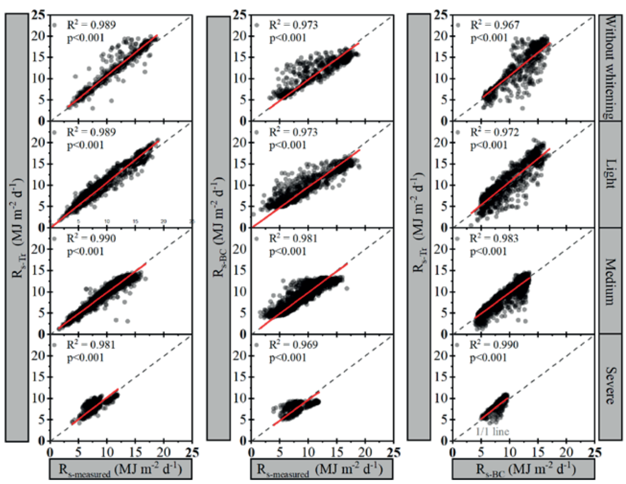

Figure 6. Relationships between the R_s values of the Bristow and Campbell model ($R_{s\text{-}BC}$) and the light transmissivity coefficient method ($R_{s\text{-}Tr}$) with the measured R_s ($R_{s\text{-}measured}$) in greenhouse under various whitening applications. *R^2 is the determination coefficient and p is the significance of the regressions.*

Table 7. Statistical indicators of the relationships between the two different R_s estimation methods for greenhouse conditions among themselves and with measured values.

Whitening application	Model	Statistical indicators				
		NSE	RMSE	MAE	RE	d
Without whitening	$R_{s\text{-}measured}$ – $R_{s\text{-}Tr}$	0.84	1.61	1.06	0.13	0.96
	$R_{s\text{-}measured}$ – $R_{s\text{-}BC}$	0.77	1.96	1.46	0.17	0.93
	$R_{s\text{-}BC}$ - $R_{s\text{-}Tr}$	0.44	2.51	1.91	0.21	0.89
Light	$R_{s\text{-}measured}$ – $R_{s\text{-}Tr}$	0.90	1.32	1.06	0.13	0.97
	$R_{s\text{-}measured}$ – $R_{s\text{-}BC}$	0.84	1.65	1.23	0.18	0.95
	$R_{s\text{-}BC}$ - $R_{s\text{-}Tr}$	0.64	2.03	1.63	0.20	0.93
Medium	$R_{s\text{-}measured}$ – $R_{s\text{-}Tr}$	0.93	0.90	0.64	0.10	0.98
	$R_{s\text{-}measured}$ – $R_{s\text{-}BC}$	0.85	1.29	0.97	0.15	0.96
	$R_{s\text{-}BC}$ - $R_{s\text{-}Tr}$	0.84	1.22	0.85	0.14	0.96
Severe	$R_{s\text{-}measured}$ – $R_{s\text{-}Tr}$	0.50	1.17	0.96	0.14	0.85
	$R_{s\text{-}measured}$ – $R_{s\text{-}BC}$	0.26	1.43	1.24	0.18	0.69
	$R_{s\text{-}BC}$ - $R_{s\text{-}Tr}$	0.32	0.92	0.76	0.11	0.86

Abbreviations: $R_{s\text{-}measured}$, measured solar radiation inside the greenhouse; $R_{s\text{-}Tr}$, greenhouse solar radiation calculated using the light transmissivity coefficient; $R_{s\text{-}BC}$, Bristow and Campbell solar radiation estimation model calibrated for greenhouse conditions; NSE, Nash–Sutcliffe model efficiency coefficient; RMSE, root mean square error; RE, relative error; MBE, mean bias error; d, Willmott Index.

mation models, the estimation performance of the $R_{s\text{-}Tr}$ method for R_s inside the greenhouse showed a slight relative decrease under severe whitening application.

4. DISCUSSION

The average annual solar radiation value of Almeria is 0.53 MJ m^{-2} day^{-1} less than that of Antalya. Specifically, from December to April, the values of solar radiation outside the greenhouse were relatively higher in Almeria than in Antalya. However, in the remaining months, the solar radiation values were slightly lower in Almeria. This trend was closely related to the clear-sky index. According to Zhang et al. (2022), the solar radiation received at different regions of the same latitude can vary owing to the presence of varying amounts of water vapor and other aerosols in the atmosphere.

Despite the similarities between the two regions in climatic parameters such as air temperature, solar radiation, and relative humidity, there was a difference in the average annual and monthly precipitation values. Antalya is located at the base of the Taurus Mountains, which can affect a city's weather patterns and create a rain shadow effect, resulting in higher precipitation levels (Atalay et al., 2014). In contrast, the precipitation levels in Almeria are constrained, largely because of the influence of the Sierra Nevada Mountains, which act as a barrier that impedes the majority of moisture from the Atlantic Ocean. Additionally, dry and hot winds originating from North African continent further exacerbate this limitation (Frot et al., 2002). The amount of precipitation that falls in Antalya between December and April accounts for 70.4% of the total annual precipitation, resulting in a slightly higher sunshine duration and external greenhouse solar radiation in Almeria during these months.

Given the proximity in latitude between Antalya and Almeria, the climatic parameters that directly influence the temperature-based estimation model for R_s (maximum temperature, minimum temperature, solar radiation, extraterrestrial radiation, and sunshine duration) show significant similarities between the two regions. Based on these similarities, it is hypothesized that the R_s estimation models calibrated in this study for greenhouse cultivation in these regions can also be applied to other Mediterranean regions with similar latitudes and climatic conditions, and greenhouse activities. Moreover, the minimum temperature, mean temperature, maximum temperature, sunshine hours, and extraterrestrial radiation parameters were statistically similar among the six greenhouse regions (Alger, Algeria; Almeria, Spain; Antalya, Türkiye; Bizerte, Tunisia; Kalamata, Greece; Siracusa, Italy) supports this hypothesis.

The amount of solar radiation that reaches greenhouse plastic cover is closely related to various atmospheric factors, such as sunshine duration, cloud cover, and weather phenomena such as precipitation and fog (Díaz-Torres et al., 2017; Matuszko, 2012; Tuononen et al., 2019). However, the amount of solar radiation that penetrates the interior of a greenhouse is influenced by a number of additional factors, including the thickness of the greenhouse cover material, any additives present in the material, and the presence of whitening, among other parameters (Cabrera et al., 2009; Fernández et al., 2010). Hence, to apply temperature-based models that are adjusted for Mediterranean-style low-tech greenhouse conditions to greenhouse regions situated at close latitudes, the characteristics of the greenhouses in this region should be similar.

During both the calibration and validation phases, all R_s estimation models showed a high level of agreement ($p<0.001$) with the measured R_s values in all whitening applications. During the assessment of the R_s estimation models, minor variations were observed in their estimation capabilities, although these were not statistically significant. These small differences were identified by analyzing various statistical indicators, including R^2, NSE, RMSE, MBE, RE, and d. The estimation models performed similarly in terms of RMSE, MAE, and RE for all whitening applications during both calibration and validation stages. However, differences were observed in the NSE and d indicators for the severe whitening application as compared to the other whitening applications owing to a slight deviation in the distribution of the points from the 1/1 line. This deviation can be attributed to the reduction in light transmissivity of the greenhouse, ranging from 30% to 40%, owing to the severe whitening application, which caused a change in the behavior of the maximum and minimum temperature differences in the greenhouse. During severe whitening application, there was a significant decrease in solar radiation reaching the greenhouse on cloudy days. However, the maximum and minimum temperature differences in the greenhouse did not decrease at the same rate, which caused a higher level of error compared to other whitening applications.

In the present study, the estimation performance of the $R_{s\text{-}BC}$ model was lower than that of the $R_{s\text{-}Tr}$ method. In addition, the data exhibited a wider and more distant distribution around the 1/1 line, indicating a higher error rate in the $R_{s\text{-}BC}$ model. The primary explanation for this is that temperature-based estimation approaches depend on the difference between the maximum and minimum temperatures, and the impact of cloud and precipitation records on the maximum and minimum temperatures varies (Dai et al., 1999; Pyrgou et al., 2019). In particular, there was a larger fluctuation in the maximum temperature values than in the minimum temperature values. Upon examining the hourly temperature data, the maximum temperature was observed to occur at noon and the minimum temperature occurred at sunrise (data not shown). Cloud density affects on the amount of energy that penetrates a greenhouse, leading to a reduction in the maximum temperature. Conversely, during the coldest hours of the day, increased cloud density results in an increase in minimum temperature values within the greenhouse (Pyrgou et al., 2019). This led to greater daily oscillations in the maximum temperature values than in the minimum temperature values.

The degree of light transmissivity in a greenhouse is strongly affected by the choice of the cover material (Tantau et al., 2012). However, in current study, it was determined that the use of greenhouse covers with similar characteristics, which are widely used in the Mediterranean region, in both regions did not have a significant effect on the results. The high estimation performance observed in the model when using pooled data indicates that the age of greenhouse cover does not have a significant impact on the predictive ability of the model. Tantau et al. (2012) had already pointed out that there was no conclusive evidence on how aging affects the light transmittance of materials.

The temperature-based models used to estimate the R_s values may not be appropriate for greenhouses with heating systems. This is because these models are dependent on temperature, and any additional energy source that alters the greenhouse temperature diminishes the accuracy of the R_s estimation. On the Mediterranean coast, producers typically do not use heating systems in their greenhouses, because the average daily temperature usually remains above 7 °C. In rare cases of extremely cold weather, producers may apply simple heating measures to sustain their production (Baytorun and Zaimoglu, 2018). Therefore, this temperature-based estimation models can be reliably employed in unheated greenhouses throughout the growing season in the Mediterranean region, with the exception of a few days.

The results revealed that all calibrated models exhibited a high level of accuracy in estimating the daily global solar radiation (R_s) using daily temperature data in a Mediterranean-type greenhouse. In terms of performance under various whitening applications, the BC, DC, and CH models displayed slightly better estimation sensitivities than the other models. Nevertheless, this finding does not necessarily indicate the unsuitability of HA and GO models for estimating R_s under greenhouse conditions. Notably, all calibrated models demonstrated high estimation performance and had similar performances, with negligible differences. For this reason, all calibrated models can be used in important greenhouse cultivation regions located between 36.5-37.5 ° N latitudes (Algeria, Greece, Italy, Spain, Türkiye, Tunisia).

The light transmissivity method is commonly used in specific regions to estimate indoor solar radiation (Fernández et al., 2010; Gallardo et al., 2016; Zhang et al., 2020). If data cannot be obtained from the solar radiation sensor for any reason, all the calibrated models can be used to estimate R_s. Indeed, in the present study, solar radiation values outside of a greenhouse could not be collected for a limited period owing to sensor failure.

5. CONCLUSIONS

The aim of current study was to calibrate and validate five different models used for estimating daily global solar radiation (R_s) under various whitening applications for Mediterranean type greenhouses. The results demonstrated that all calibrated models were effective in estimating the solar radiation inside the greenhouse. The method of estimating solar radiation (R_s) within the greenhouse using the light transmissivity coefficient showed slightly superior performance compared to the models calibrated with temperature data. Consequently, in situations where R_s data for outside the greenhouse are unavailable, any of the calibrated models can be used for R_s estimation. In this context, calibrated models serve as useful tools for regional farmers, consultants, and researchers.

SUPPLEMENTAL MATERIAL

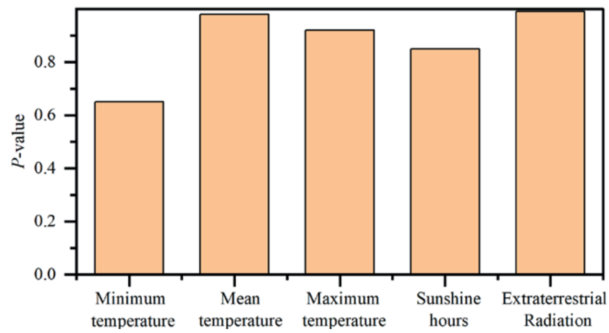

Figure S1. The *p* values of some climatic variables (minimum temperature, mean temperature, maximum temperature, sunshine hours, and extraterrestrial radiation) among the six Mediterranean greenhouse regions (Alger, Algeria; Almeria, Spain; Antalya, Türkiye; Bizerte, Tunisia; Kalamata, Greece; Siracusa, Italy).

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