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Water and carbon footprints in irrigated vineyards: an on-farm assessment

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Abstract

This research aims to contribute to improving water and carbon efficiency in irrigated grapevine production in the dry Mediterranean climate of southern Europe. In regions with water scarcity, irrigation has become a relevant input in viticulture, essential to increase productivity and achieve profits. The joint estimation of the water footprint (WF) and the carbon footprint (CF) can help to comprehensively assess the environmental implications and sustainability associated with water-intensive grapevine cultivation. In this study, the WF and CF, of the farming stage of grapes production, were calculated for three years, in three vineyards located in southern Portugal. Data used for the calculation included meteorological data, irrigation requirements, energy use, fertilizers, and pesticide inputs. The total WF mean value for the study period was 223 m^3 ton^{-1}, lower than values found for similar conditions, but the blue component, related to irrigation, was predominant, with a higher proportion (75%) occurring during the driest year. The mean total CF was 98 kg CO_2e ton^{-1}; the major contributors were fuel use, fertilizer greenhouse gas emissions, and energy for irrigation. The factor analysis revealed relationships between footprint components, yielding latent variables participated by irrigation water and energy use, pollution loads and agrichemicals use. The examination of trade-offs and/or advantageous relations between footprints and yields showed that seasonal climate conditions play an important role via their effect on the farming practices and the inputs most influential on these indicators, namely: crop water requirement; irrigation volumes; energy for irrigation; fuel consumption; nitrogen and phosphorus fertilization rates.

Introduction

In 2020, global agrifood systems emissions were 16 billion tons of carbon dioxide equivalents (CO_2e), approximately one-third of total anthropogenic greenhouse gas (GHG) emissions, with the farm gate stage representing nearly half of total agrifood systems emissions (FAO 2022). Although agriculture is a significant contributor to climate change, it is also one of the economic sectors most at risk from it, as climate change is already affecting food security through increasing temperatures, changing precipitation patterns, and greater frequency of extreme events (Mbow et al. 2019; Tubiello et al. 2021).

Water scarcity is one of the most important environmental issues facing the wine industry, and climate change may have a substantial impact on temperatures and precipitation during the growing season, resulting in increasingly severe water deficits that affect fruit yield and composition (Fraga et al. 2012; Gao and Giorgi 2008; IPCC 2018).

In several Mediterranean wine-growing regions, annual precipitation levels are below those required for economically viable grapevine cultivation (Medrano et al. 2015). While most vineyards in Europe are currently rainfed, irrigation is an option for growing sustainable yields in more arid conditions. However, the associated effects on water resources use and GHG emissions in the environment must be considered (Daccache et al. 2014; Silva and Silva 2022; van Leeuwen et al. 2019).

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Portugal is one of the main grapevine producers in Europe, with 953 thousand tons produced over an area of about 171 thousand ha in 2021; the southern Portuguese region of Alentejo contributes to 28% of production over an area of around 20% of the national territory. The introduction of irrigation in most vineyards in Alentejo has contributed to an increase in regional and national production (INE 2022). Although irrigation contributes to higher and steady crop yields, its effects on the environment, specifically those associated with water resources depletion and GHG emissions, are still unclear (Balafoutis et al. 2017; Zhang et al. 2018). Evaluating how resources are used in irrigated viticulture may help to outline sustainable management strategies to adjust to the new conditions and reduce the environmental impacts (Koushki et al. 2023; Raza et al. 2019).

A “family” of footprint indicators for the evaluation of the environmental performance of different production systems has been developed over recent decades for measuring and monitoring sustainability (Galli et al. 2012). The water footprint (WF) and the carbon footprint (CF) are among the most known environmental footprint indicators (Čuček et al. 2015). The WF is a tool to calculate the water virtually embedded in commodities, representative of the volume of water needed to produce goods and services (Hoekstra 2003; Hoekstra et al. 2011). The WF of a crop can be a quantifiable indicator for measuring the water applied by irrigation, the water stored in the soil, fractions consumed by the crop, and the potentially contaminated water as a result of the adopted agronomical practices (Mekonnen and Hoekstra 2011). The carbon footprint (CF) is a measure of the amount of GHG resulting from a particular activity, product, or service (Wiedmann and Minx 2008). In the context of crop production, CF corresponds to the total amount of GHG per unit yield that results from various activities involved in producing a crop, such as land preparation, planting, harvesting, transportation, and processing (PAS 2050a, b, 2012). Other than mobile farm operations that require fuel use, the main components of energy use in irrigated agriculture are primarily related to processes required to apply water to crops in the field by lifting, conveying, and/or pressurizing it (Rothausen and Conway 2011). Despite that the water and energy consumption associated with irrigation should increase the water incorporated in the crop products and the GHG emissions per unit area resulting from farming, irrigation normally enhances yields, which is a crucial consideration in the calculation of WF and CF (Zhang et al. 2018). Additionally, the adoption of low-input agronomic options, like reduced or water-saving irrigation strategies, conservation tillage, and/or soil and residues management that increase soil carbon sequestration, have the potential to retain water and mitigate GHG emissions (Gan et al. 2014; Litskas et al. 2017; Sapkota et al. 2020). Regardless of these relationships between irrigation and energy use, WF and CF are indicators with different scope and extent: while local GHG emissions contribute to the global stock of CO_2 irrespective of their origin, the evaporation of water has a more localized effect, impacting the basin where evaporation takes place (Fereres et al. 2017; Perry 2014).

Expanding WF and CF estimates from on-field measurements in different agri-environmental conditions can portray better the variability present at the farm level estimates and contribute to the decision-making process in selecting sustainable management practices (Herath et al. 2013; Lal 2004), as well as for delineating strategic policies regarding agricultural production, and more specifically, the wine-making sector in water-scarce regions (Ene et al. 2013; Lamastra et al. 2014).

Based on the research data obtained from an on-farm study in vineyards located in Southern Portugal, the aims of the current study were: (i) to estimate WF and CF; (ii) to explore the relationships between the WF and CF components; (iii) to analyze the trade-off between WF and CF footprints and yield, relating them to the agricultural inputs and management practices of irrigated grapevines under Mediterranean conditions.

Materials and methods

Study area

The study was carried out over three years (2018 to 2020) in three irrigated vineyards (V1 (37°52′22″N; 07°30′37″W), V2 (37°58′13″N; 07°33′18″W), and V3 (37°60′28″N; 07°32′21″W)) (Table 1).

The vineyards were in South Portugal, specifically in the hydro-agricultural area of Brinches-Enxoé, part of the Alqueva irrigation plan, presently covering approximately 120,000 ha. The climate in the region is temperate with hot and dry summers (Mediterranean), with annual precipitation and average mean monthly temperature of, respectively, 558 mm and 16.9 °C (long-term means for the 1981–2010 period, (IPMA 2023)). During the three years of study (2018, 2019 and 2020), data from an automatic meteorological station located near the study area (Latitude: 37° 58′06″N; Longitude: 07° 33′03″W; Altitude: 190 m), showed that the annual precipitation was 603 mm, 343 mm, and 615 mm, respectively. The mean temperature was 16.7 °C, 17.3 °C, and 17.8 °C, respectively, in 2018, 2019, and 2020 (COTR 2022a).

The duration of the grapevines cycle varied between 154 days in V2-2019 and 189 days in V3-2020, with an overall average duration of 170 days (Table 2). Maximum daily temperatures were higher in 2020 (average of 29.9 °C), the warmest year, while the lowest precipitation values occurred in 2019 (average of 76 mm), the driest

Table 1 General characterization of the vineyards assessed in the study

Vineyard (Irrigation hydrant coordinates)	Grapevine Variety	Area (ha)	Plantation year	Predominant soil types [a]	Predominant texture	SOC (g kg^{-1}) [b]	pH	Plant density	Training system	Type of pruning	Irrigation method	Supply of pressure for irrigation	Soil management in the Interrow	Weeding in the row	Type of harvest
V1	'Antão Vaz'[c]	4.5	2007	Chromic Vertisols	Clay loam	15.7	8.34	2.8 × 1.2	Double Cordon Royat	Manual	Drip	From pump (75 kW)	Permanent resident vegetation	Chemical	Mechanical (contracted)
V2	'Aragonez'[d]	9.0	2001	Calcaric Cambisols; Chromic Vertisols	Silty clay	10.7	8.39	2.8 × 1.0	Double Cordon Royat	Mechanical pre-pruning and manual pruning	Drip	From pressurized conveyance network	Sown cover crop (mixture grass + leguminous)	Chemical	Mechanical (contracted)
V3	'Antão Vaz'	1.5	2017	Chromic Luvisols; Calcaric Cambisols	Sandy clay	12.8	8.46	2.7 × 1.1	Double Guyot	Mechanical pre-pruning and manual pruning	Drip	From pump (15 kW)	Permanent resident vegetation	Mechanical (from 2019)	Mechanical (contracted)

SOC Soil organic carbon

[a] *RSG* Reference Soil Group and principal qualifiers, when applicable (IUSS Working Group WRB 2015; Tomaz et al. 2020)

[b] Value in the 0–20 cm layer obtained from a composite sample at the beginning of the study (April-2018)

[c] Traditional white Portuguese variety

[d] Red variety (*syn.* 'Tempranillo')

Table 2 Duration of the vineyards cycle per year

Year	Vineyard	Beginning of cycle (dd/mm)	Harvest (dd/mm)
2018	V1	15/03	31/08
	V2	02/04	24/09
	V3	15/03	23/08
2019	V1	10/03	22/08
	V2	25/03	26/08
	V3	10/03	10/09
2020	V1	05/03	26/08
	V2	18/03	24/08
	V3	05/03	10/09

year. In 2018 and 2019, average seasonal precipitation was 147 mm and 207 mm, respectively.

Management practices data were provided by the farmers and are described in Table 3 and 4. The fertilizers used were primarily formulations of nitrogen (NO_3^-, NH_4^+, urea), phosphorus (P_2O_5), and potassium (K_2O). Water-soluble and liquid fertilizers, applied over the crops' cycle through irrigation water, were mostly nitrogen fertilizers but also included other fertilizers containing formulations of iron (Fe chelates), calcium (CaO), or sulfur (SO_3). Foliar applications, containing boron (B) and/or manganese (Mn), were also employed. The pesticides used were mainly herbicides and fungicides, and some insecticides. In vineyards V1 and V2, 100 Hp tractors were used, while in V3, the tractor used had 110 Hp power.

The vineyards were drip irrigated, with 50 cm spacing between drippers with flow rates of 2.2 L h^{-1} in V1 and V2, and 2.3 L h^{-1} in V3. The irrigation dose and schedule were established by the farmers based on recommendations of the Irrigation Management Model for the Alentejo region (MOGRA—Modelo de Gestão da Rega para o Alentejo (COTR 2022b). The MOGRA model performs a daily soil water balance, based on the FAO-56 single crop coefficient method for computing crop water requirements (Allen et al. 1998), using meteorological data and crop-specific information. The actual crop evapotranspiration (ETa) corresponds to an adjusted crop evapotranspiration

Table 3 Summary of crop management data per vineyard per year

Year	Vineyard	1st irrigation (dd/mm)	Last irrigation (dd/mm)	Irrigation volume (m^3 ha^{-1})	Mineral N, P, K (kg ha^{-1})	Organic N (kg ha^{-1})	Pesticides F, I, H (kg ha^{-1})	Total diesel (L ha^{-1}) *	Yield (kg ha^{-1})
2018	V1	28/06	30/10	3952	50, 50, 56	11	13.8, 0.4, 4.2	202	22,147
	V2	04/06	08/10	2600	96, 102, 179	23	31.5, 0.4, 4.2	203	16,500
	V3	15/05	15/10	3000	66, 21, 51	na	12.4, 1.9, 4.6	115	15,000
2019	V1	15/05	31/10	3111	58, 72, 100	11	8.2, 0.4, 5.2	190	19,400
	V2	15/06	29/09	3050	85, 61, 58	na	36.0, 0.3, 6.3	150	7400
	V3	27/05	12/09	1500	7, 3, 13	na	7.6, 0.3, 0.0	107	10,476
2020	V1	21/05	16/10	3054	34, 61, 50	11	22.3, 0.5, 4.7	235	12,417
	V2	21/07	16/09	1540	87, 25, 32	na	15.7, 0.9, 3.0	157	11,100
	V3	06/06	30/09	2000	1, 0.2, 0.3	na	13.8, 0.0, 0.0	112	10,476

*Number of mechanical operations are described in Table 4

N applied N; *P* applied P_2O_5; *K* applied K_2O; *F* applied fungicides; *I* applied insecticides; *H* applied herbicides, *na* not applied

Table 4 Average workdays, type and number of mechanical operations per vineyard per year

Mechanical operations	Average Workdays			2018			2019			2020		
	V1	V2	V3	V1	V2	V3	V1	V2	V3	V1	V2	V3
Pre-pruning	1	2	0.5	1	1	1	1	1	1	1	1	1
Organic fertilizer spreading	1	2	0.5	1	1	0	1	0	1	1	0	0
Mineral fertilizer spreading	1	2	0.5	1	1	1	1	1	1	1	1	1
Fungicide spraying	1	2	0.5	8	7	4	7	5	3	10	6	6
Insecticide spraying	1	2	0.5	1	1	3	1	1	1	2	2	0
Herbicide spraying	1	2	0.5	3	3	2	3	2	0	3	1	0
Pruning shredding + cover crop cutting	1	2	0.5	1	1	1	1	1	1	1	1	1
Mechanical weeding	0	0	0.5	0	0	0	0	0	1	0	0	1

value (ETc_{adj}) obtained from the multiplication of the reference evapotranspiration (ET_0, computed with the Penman–Monteith equation), by the single crop coefficients (Kc) through the cycle of grapevine for wine production, and by a stress coefficient (Ks) of approximately 0.5, compatible with a sustained deficit irrigation strategy, which is the common strategy followed by the winegrowers of the Alentejo region. The MOGRA model also provided the values of effective precipitation (P_{ef}), and irrigation requirements (IR), while effective irrigation (I_{ef}) data were provided by the farmers.

Water footprint calculations

Each of the WF components (expressed in $m^3\ t^{-1}$) was calculated following the tier 1 approach of the Water Footprint Network (Hoekstra et al. 2011) and described in Tomaz et al. (2021), using the following equations:

Green Water Footprint (WF_G):

$$WF_G = \frac{ET_G}{Y}, \tag{1}$$

where ET_G corresponds to the green component in crop water use ($m^3\ ha^{-1}$), obtained as the minimum between P_{ef} and ET_a (Hoekstra et al. 2011), and Y is the crop yield (ton ha^{-1}).

Blue Water Footprint (WF_B):

$$WF_B = \frac{ET_B}{Y}, \tag{2}$$

where ET_B is the amount of irrigation water available for plants ($m^3\ ha^{-1}$), defined as the minimum between IR and I_{ef} (Aldaya et al. 2010). In case P_{ef} is equal to or higher than the crop water requirements (CWR), IR equals 0, otherwise, it corresponds to the difference between CWR and P_{ef}.

Grey Water Footprint (WF_{Gr}):

$$WF_{Grey} = \frac{\frac{Appl \times \alpha}{c_{max} - c_{nat}}}{Y} \times 1000, \tag{3}$$

where *Appl* is the chemical application rate, in this case, the N and P application rate, α is the leaching-runoff fraction, i.e., the fraction of applied N or P that reaches the freshwater bodies, c_{max} is the maximum acceptable concentration of the contaminant in the aquatic environment ($kg\ m^{-3}$), and c_{nat} is the natural background concentration of contaminant in the aquatic environment ($kg\ m^{-3}$).

In a large number of published studies about water footprints, nitrogen is considered the only contaminant in WF_{Gr} calculation but, according to the tier 1 approach described in Franke et al. (2013), when assessing the WF_{Gr}, the value for each contaminant of concern must be calculated separately and the overall WF_{Gr} will be equal to the largest value found (Franke et al. 2013). Notwithstanding the importance of pesticides' impact on soil and water resources, given the lack of consistent standards concerning diffuse sources of water pollution in Portuguese agricultural systems, in this study, we considered N and P as the major contaminants of concern. We used a value of $\alpha = 10\%$ for nitrogen fertilizers and $\alpha = 3\%$ for phosphorus fertilizers (Franke et al. 2013). For the ambient water quality standard, c_{max}, we used 50 mg $N\text{-}NO_3\ L^{-1}$ and 5 mg $P_2O_5\ L^{-1}$, the maximum allowable values, respectively, for nitrogen and phosphorus, concerning the protection of waters against pollution from agricultural sources according to Portuguese legislation (Diário da República, 1ª SÉRIE 1998). In the case of c_{nat}, many previous studies assumed the value 0 which could lead to underestimates. We used the values 0.1 mg $N\text{-}NO_3\ L^{-1}$ and 0.01 mg $P_2O_5\ L^{-1}$, respectively, for N and P (Franke et al. 2013). Another assumption that must be considered in WF_{GR} calculation is that, in these vineyards, irrigation does not contribute to the leaching of nitrogen and phosphorus, since drip irrigation systems are characterized by low losses due to percolation or runoff. Furthermore, the applied irrigation volumes correspond to deficit irrigation. Thereby, the leaching of N and P should be mainly due to precipitation immediately before or throughout the grapevine's cycle (Saraiva et al. 2020).

The total water footprint (WF) of the grapevines' crop corresponds to the sum:

$$WF = WF_G + WF_B + WF_{Gr} \tag{4}$$

Carbon footprint calculations

Irrigation powered by electricity, fertilizers and pesticides manufacturing and application, and mechanical field operations were the stages considered within the system boundary, that is, a "cradle to gate" assessment was performed (Marras et al. 2015; Nemecek et al. 2015; Novara et al. 2019; PAS 2050a, b, 2011) (Fig. 1).

Therefore, our scope was the total GHG emissions at the vineyard stage, and the functional unit considered was 1 ha of area in the studied vineyards. The GHG emission rates were estimated using an emission factor approach which, combined with the agricultural input, generates an emission for a given period (IPCC 2006, 2019; PAS 2050a, b, 2011):

$$Emission = AgriculturalInput \times EmissionFactor, \tag{5}$$

where *Emission* is the GHG emission, expressed in kg GHG ha^{-1}, the *Agricultural Input* is expressed in unit ha^{-1}, and the *Emission Factor* in kg $unit^{-1}$. The emission factors used in the study are described in Table 5.

The GHG emissions and CF calculations considered in the study were made according to the tier 1 approach of

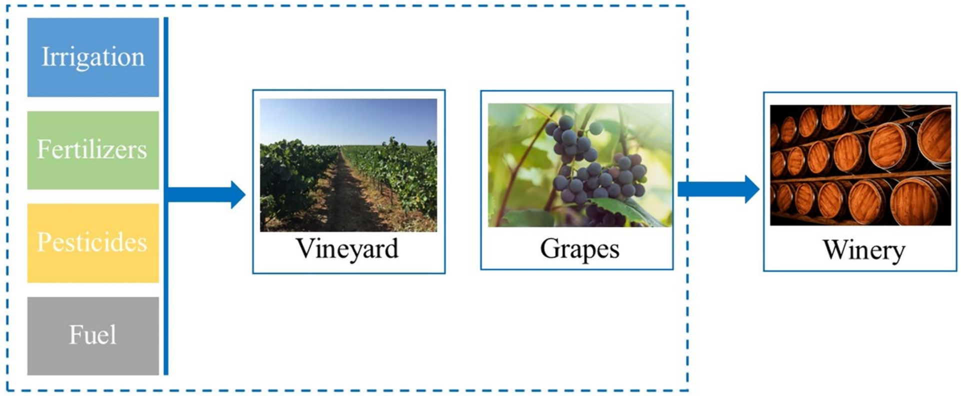


Fig. 1 System boundary and agricultural inputs considered in carbon footprint estimations

Table 5 GHG emission factors for the vineyard stage used in carbon footprint calculations

Emission source	Unit	GHG emissions/unit	Reference
Fuel	kg CO_2e L^{-1}	3.12	(Cool Farm Alliance 2023)
Electricity for irrigation	kg CO_2e kWh^{-1}	0.34	(APA 2023)
N_2O direct emissions [a]	kg N_2O–N (kg N)$^{-1}$	0.01	(IPCC 2006; Marras et al. 2015; Hefler and Kissinger 2023)
N_2O indirect emissions [a]	kg N_2O–N (kg N)$^{-1}$	0.01	(IPCC 2006; Marras et al. 2015; Hefler and Kissinger 2023)
CO_2 emissions from urea fertilization	kg CO_2–C (kg Urea)$^{-1}$	0.20	(IPCC 2006; Hefler and Kissinger 2023)
N fertilizer [b]	kg CO_2e kg^{-1}	2.78	(Cool Farm Alliance 2023)
P_2O_5 fertilizer [b]	kg CO_2e kg^{-1}	0.12	(Cool Farm Alliance 2023)
K_2O fertilizer [b]	kg CO_2e kg^{-1}	0.41	(Cool Farm Alliance 2023)
Herbicides [c]	kg CO_2e kg^{-1}	4.70	(West and Marland 2002; Cheng et al. 2011, 2015)
Fungicides [c]	kg CO_2e kg^{-1}	5.18	(West and Marland 2002; Cheng et al. 2011, 2015)
Insecticides [c]	kg CO_2e kg^{-1}	4.93	(West and Marland 2002; Cheng et al. 2011, 2015)

[a]Default value for dry cropland in the Tier 1 approach of IPCC

[b]Default value for the European region

[c]Aggregated value for production and post-production of each pesticide type

the IPCC, also described in Litskas et al. (2017) and Cool Farm Alliance (2023), following the IPCC guidelines (IPCC 2006, 2019):

Diesel fuel carbon emissions (CE_D):

$$CE_D = V_D \times EF_D, \tag{6}$$

where V_D is the volume of diesel consumed due to vineyard operations (data provided by the farmers; L ha^{-1}), and EF_D is the emission factor for diesel fuel (kg CO_2e L^{-1}).

Irrigation carbon emissions (CE_I):

$$CE_I = E_I \times EF_I, \tag{7}$$

where E_I is the energy associated with irrigation (kWh ha^{-1}) and EF_I is the emission factor of electricity for irrigation (kg CO_2e kWh^{-1}). The E_I was estimated using:

$$E_I = D_I \times E_{I;M}, \tag{8}$$

where D_I is the irrigation depth (mm) and $E_{I;M}$ is the energy requirements, dependent on the irrigation method (kWh mm^{-1} ha^{-1}), for which we used the value 2.0 for drip irrigation (Cool Farm Alliance 2023).

Nitrogen fertilizer direct ($NE_{N\text{-}Direct}$) and indirect ($NE_{N\text{-}Indirect}$) emissions:

The $NE_{N\text{-}Direct}$ are the equivalent carbon emissions related to nitrous oxide gas (N_2O) produced during nitrification and denitrification processes. The N_2O is a gaseous intermediate in denitrification and a by-product of nitrification. One of the main controlling factors in these processes is the availability of inorganic N in the soil, derived from human-induced net N additions to soils and/or management practices that mineralize soil organic N (IPCC 2006, 2019). We used the following for the calculation of the direct fertilizer-induce emissions approach (Cool Farm Alliance 2023):

$$NE_{N-Direct} = \frac{44}{28} \times (F_{MN} + F_{ON}) \times EF_F, \quad (9)$$

where F_{MN} is the annual amount of mineral N fertilizer applied (kg N), F_{ON} is the annual amount of organic N fertilizer applied (kg N), EF_F is the emission factor for N_2O emissions from N inputs, and 44/28 is the conversion factor of N_2O-N to N_2O.

Emissions of N_2O also take place through two indirect pathways, namely, (i) the volatilization of N as NH_3 and oxides of N (NO_x), and the deposition of these gases and their products NH_4^+ and NO_3^-, and (ii) the leaching and run-off from the land of N from synthetic and organic fertilizer additions, which can be negligible in dry climates (IPCC 2006, 2019). Thereby:

$$NE_{N-Indirect} = \frac{44}{28} \times (F_{MN} \times a + F_{ON} \times b) \times EF_F, \quad (10)$$

where a and b are, respectively, the fraction of mineral and organic N fertilizer that volatilize as NH_3 and NO_x. The default values for a and b are 10% and 20%, respectively (IPCC 2006, 2019).

In the absence of differentiated EF for all types of fertilizers used in the studied vineyards, we used the default values for dry cropland in the IPCC tier 1 approach, both in Eq. 9 and Eq. 10. For the calculation of total nitrogen fertilizer carbon equivalent emissions (CE_N), it should be noted that each GHG makes a different contribution to global warming. According to the IPCC 5th Assessment Report (IPCC 2014), N_2O has a global warming potential (GWP) of 265, that is, compared to CO_2, it is 265 times higher in terms of the 100-year global warming potential, therefore:

$$CE_N = (NE_{N-Direct} + NE_{N-Indirect}) \times 265 \quad (11)$$

Urea fertilizer carbon emissions (CE_U):

Adding urea ($CO(NH_2)_2$) to soils leads to a loss of CO_2 that was fixed in the industrial production process. To estimate the amount of CO_2 emission that results from the addition of this type of fertilizer, Eq. (11) was used:

$$CE_U = \frac{44}{12} \times F_U \times EF_U, \quad (12)$$

where F_U is the annual amount of Urea fertilizer applied (kg Urea), EF_U is the emission factor for CO_2 emissions from Urea inputs, and 44/12 is the conversion factor of CO_2-C to CO_2.

Fertilizer production carbon emissions (CE_{PF}):

The fertilizer production and transport related carbon emissions were calculated separately for N, P_2O_5, and K_2O using:

$$CE_{PF} = F \times EF_{PF}, \quad (13)$$

where F is the amount of fertilizer applied (kg N, kg P_2O_5, or kg K_2O) and EF_{PF} is the default emission factor for the European region of N, P_2O_5, or K_2O fertilizer production (includes raw material extraction, energy supply, the manufacturing process to the product storage at the production site) (Cool Farm Alliance 2023).

Pesticides production carbon emissions (CE_{PP}):

The pesticide production related carbon emissions were calculated separately for herbicides, fungicides, and insecticides using:

$$CE_{PF} = P \times EF_{PP}, \quad (14)$$

where P is the amount of pesticide applied (kg herbicide, kg fungicide, or kg insecticide) and EF_{PP} is the correspondent emission factor of herbicides, fungicides, or insecticides production and post-production (West and Marland 2002).

Carbon footprint (CF):

The GWP per unit grain production is the CF, expressed in kg CO_2e ton^{-1}. The CF components, CF_i, were obtained by the ratio between the input-related carbon equivalent emissions, CE_i and yield (ton ha^{-1}):

$$CF_i = \frac{CE_i}{Y}, \quad (15)$$

Where i corresponds to the type of emission from Eq. 6 to Eq. 14, and $CE_i = CE_D$, CE_I, CE_N, CE_U, CE_{PF}, CE_{PP}. The total CE, $\sum CE_i$, represents the total GWP per unit area, within the system boundary on each year, that is, the absolute value for GHG emission.

Statistical analyses

Data were analyzed using Statistica 7 (StatSoft, Inc. 2004). Factor Analyses (FA) were conducted to examine latent (unobserved) common characteristics of the water and carbon footprints and explore relationships between footprint components. The factors were extracted using the Principal Components Analysis (PCA) method and the matrix of factor loadings was submitted to varimax rotation to yield a factor structure simpler to interpret (Jagadamma et al. 2008; Tomaz et al. 2021). Factors were retained when presenting eigenvalues > 1 and a contribution for the proportion of variance > 10%. Footprint components with large absolute value factor loadings are more likely to represent a common factor, thereby, they were considered highly correlated whenever factor loadings were > 0.60 and moderately correlated when loadings were between 0.40 and 0.60 (Jagadamma et al. 2008; Lee et al. 2005; Tomaz et al. 2021).

The total WF and CF were plotted on yield, separately, on a Cartesian plane to distinguish the effects of vineyard management practices and to reveal de relationships between the estimated footprints and yield, following the methodology described by Zhang et al. (2018). These plots facilitate visualization of the relationships between WF and CF and above-average yield (*Win–Win* and *Lose-Win*) and below-average yield (*Win-Lose* and *Lose-Lose*), identifying groups of vineyards/year in each quadrant (Fig. 2). The inputs and outputs for each group of vineyards/year were summarized, through the calculation of the mean and standard error (SE) values.

Results and discussion

Water and carbon footprints

The total WF mean value for the three vineyards, over the study period 2018–2020, was 223 m^3 ton^{-1}, varying from 491 m^3 ton^{-1} in 2018 to 773 m^3 ton^{-1} in 2019. (Fig. 3). Therefore, values presented considerable variability that can be explained with different meteorological conditions over the three years. The WF_B was, on every year and vineyard, the most important component, with the higher proportion occurring in 2019 (75%), which is explained by the dry climatic conditions of the year, leading to higher crop water requirements. The WF_B/WF_G ratio was consistently > 1, varying from 1.2 (V2-2020) to 4.4 (V2-2019).

More than the WF_B absolute values, these ratios show the dependence on irrigation for the crops to attain sustainable yields in the dry Mediterranean conditions of South Portugal. Another important observation is that the WF values found were lower than the benchmark of 609 m^3 t^{-1} for grapevines worldwide (Mekonnen and Hoekstra 2011) or generally lower than 300 m^3 t^{-1}, found by Steenwerth et al. (2015) for irrigated grapevines in California.

The CF components estimated are presented in Fig. 4. The average total CF was 98 kg CO_2e ton^{-1}. Average values each year were 86 kg CO_2e ton^{-1} in 2018, 111 kg CO_2e ton^{-1} in 2019, and 97 kg CO_2e ton^{-1} in 2020. The major components were CF_D (35%-47%), followed by CF_{Fe} (18%-26%) and CF_I (14%-15%).

Average CF_D increased in 2020 when favorable conditions for the development of pests and diseases in the Spring led to more insecticide and fungicide spraying operations. The use of nitrogen fertilizer is an important source of CO_2 and nitrous oxide gas (N_2O) emissions. To reduce direct and indirect N_2O emissions, it is important to improve N use efficiency, by minimizing losses caused by erosion, leaching and/or volatilization and identifying alternate sources including nitrogen fixation and carbon sequestration by

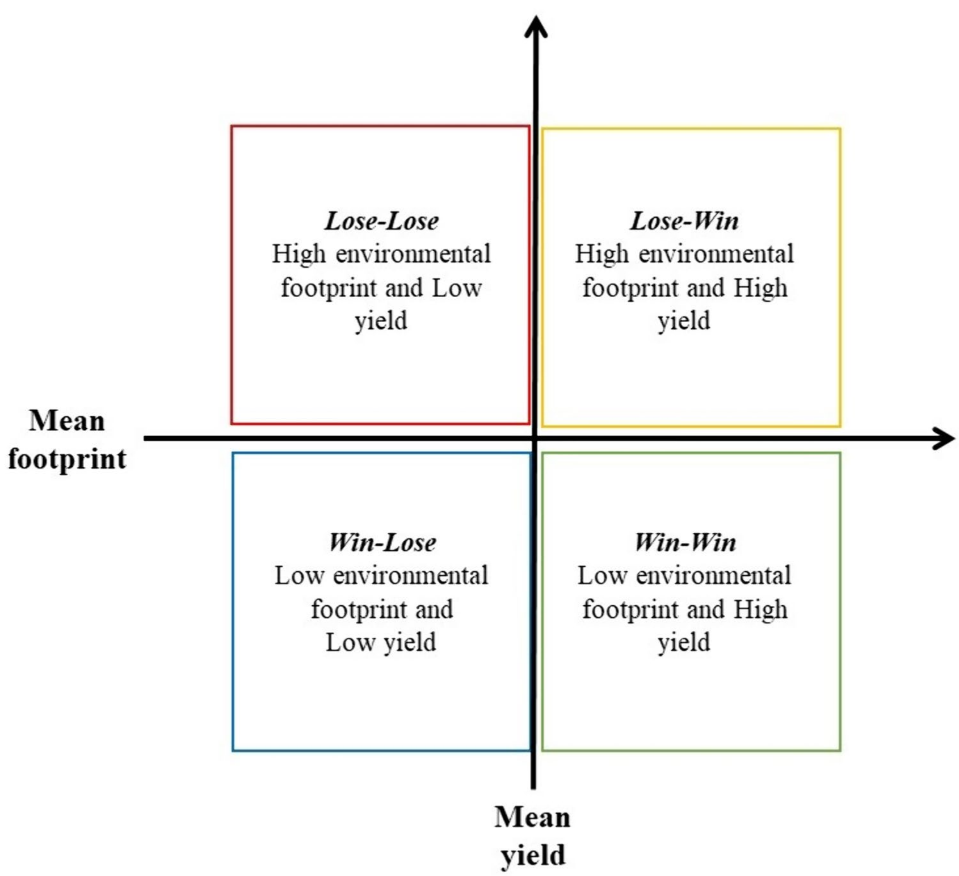


Fig. 2 Plot to visualize the relationships between environmental footprints and yield (methodology adopted from Zhang et al. (2018))

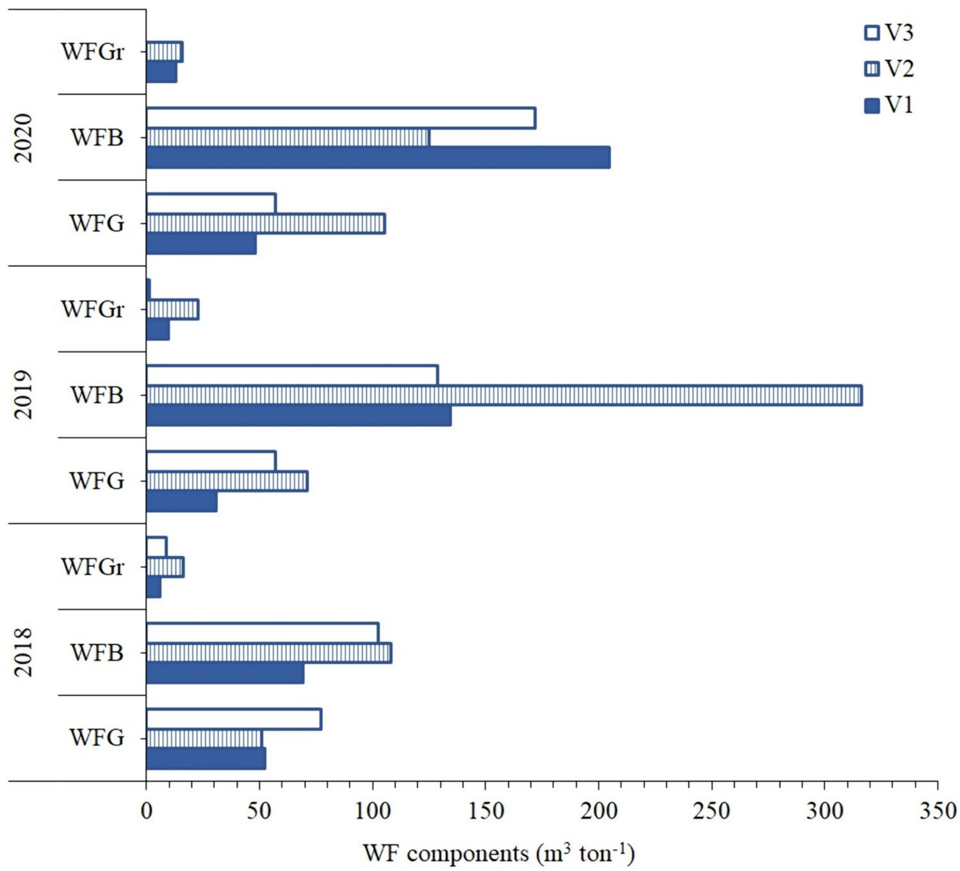


Fig. 3 WF components in the studied vineyards from 2018 to 2020. *WFG* green water footprint, *WFB* blue water footprint, *WFGr* grey water footprint

cover crops in the row, alternative fertilizer sources, and recycling nutrients contained in crop residue (Barão et al. 2019; Cataldo et al. 2020; Freibauer et al. 2004; Lal 2004; Novara et al. 2019, 2020; Pacheco et al. 2023).

As expected, a higher proportion of CF_I occurred in 2019, the driest year, when an average emission of 16 kg CO_2e ton^{-1} was due to irrigation. The absolute maximum value of CF_I was observed in V2 in 2019 (28 kg CO_2e ton^{-1}), but the highest proportion of CF_I to total CF occurred in V3 (on average, 20%).

Overall, the estimated CF is lower than the findings in previous studies with irrigated grapevines: 87–584 kg CO_2e ton^{-1} (Steenwerth et al. 2015); 280–850 kg CO_2e ton^{-1} (Litskas et al. 2017); 317–346 kg CO_2e ton^{-1} (Hefler and Kissinger 2023).

The relationships observed among footprint components were explored through factor analysis and translated into a three-factor model which explained 91.7% of the total variance (Table 6). Factor 1 explained 63.5% of the variance and presented high positive loadings (> 0.60) of WF_B (0.97), CF_D (0.83), CF_I (0.90), CF_{Hb} (0.69), and CF_{Fg} (0.85). Thereby, given the high weights (> 0.90) of the blue components of footprints, WF_B, and CF_I, this factor can be described as an "Irrigation latent variable". Factor 2 was responsible for explaining 16.9% of the total variance and it was mainly influenced by WF_G (0.94), CF_{Is} (0.87), and CF_{Nf} (0.47). Lastly, Factor 3 accounted for 11.4% of the total variance and presented high correlations with WF_{Gr} (0.84), CF_{Fe} (0.80), CF_{Nf} (0.72), CF_{Pf} (0.84), and CF_{Kf} (0.96), therefore, it can be denoted as a "Grey latent variable". The structure of the three-factor model showed how the WF and CF components indicators correlate and interact (Galli et al. 2012). Safeguarding differences in scope, this allows for a joint interpretation and the exploratory analysis of multivariate relationships in further agricultural plot- or farm-level studies.

Trade-off and win–win relationships

The analysis of the trade-off and win–win relationships between yield and WF showed that vineyards/years were grouped in the *Win–Win* quadrant mostly due to a "year effect" (Fig. 5a). In fact, all vineyards in 2018 were present in this group, indicating how the higher annual and Spring rain and ensuing lower irrigation requirements during the 2018 season, led to decreased total WF, WF_B, and higher yields (Fig. 5b and Table 7).

A trade-off relationship (*Win-Lose*) was found for V3, in 2019, mostly because of low applied irrigation and low levels of phosphorous fertilization, influencing blue and grey

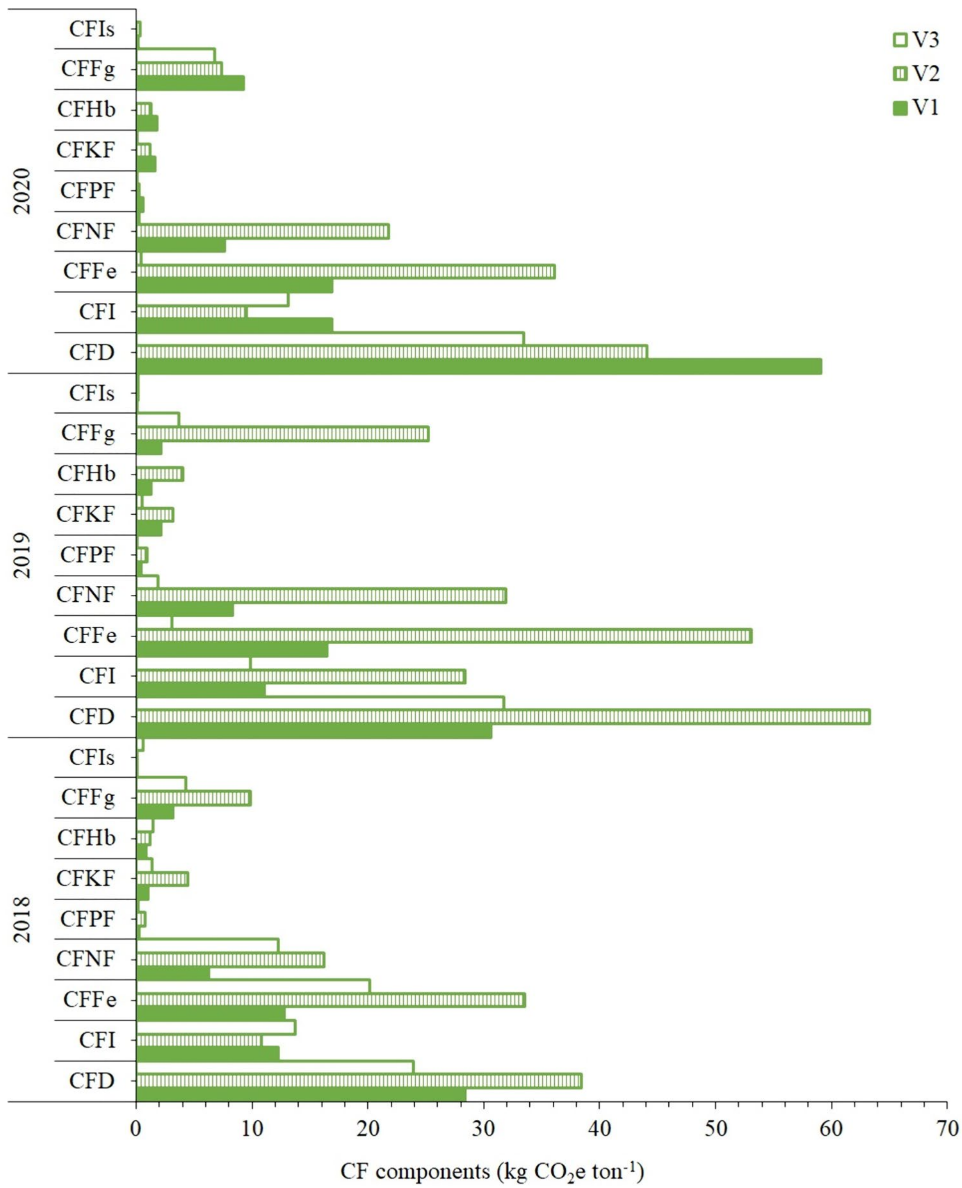


Fig. 4 CF components in the studied vineyards from 2018 to 2020. *CFD* diesel carbon footprint, *CFI* irrigation carbon footprint, *CFFe* fertilizer emissions carbon footprint, *CFNF* nitrogen fertilizer carbon footprint, *CFPF* phosphorus fertilizer carbon footprint, *CFKF* potassium fertilizer carbon footprint, *CFHb* herbicide carbon footprint, *CFFg* fungicide carbon footprint, *CFIs* insecticide carbon footprint

components of WF. In the *Lose-Lose* quadrant, we found again, a "year effect" since all vineyards in 2020, plus V2 in 2019 were grouped. In this group, neither irrigation volumes nor fertilization doses were the highest, so it was primarily the reduced yields that led to this result.

While the relationships between yield and WF were mostly "year-controlled", the same pattern did not apply to yield and CF relations. The *Win–Win* quadrant includes two vineyards (V1, V3) in 2018 but also V1 in 2019 (Fig. 6a). This group was characterized by lower CF components resulting from fuel consumption, N and P_2O_5 fertilization, as well as reduced fertilizer and pesticide use (Fig. 6b). In general, and as expected, the average values of inputs were lower than the ones found for the vineyards in the *Lose-Lose* quadrant (Table 8).

Notwithstanding these observations, it is clear that the higher average yield (18.3 ton ha^{-1}) played an important role in grouping the vineyards in the *Win–Win* quadrant. The V3 vineyard in 2019 and 2020 was located in the trade-off quadrant of lower CF *versus* lower yield (*Win-Lose*), a result that was mainly related to very low energy inputs (fuel and irrigation), as well as very reduced use of fertilizers and pesticides. The trade-off of high CF *versus* high yield (*Lose-Win*), found for V2 in 2018, relates to moderate yield (16.5 ton ha^{-1}) coupled with moderate use of fuel (203.3 L) and energy for irrigation (520 kWh), but higher fertilization rates.

Together with the latent variables found in factor analysis, relating different components of WF and CF, it is worth noting the overlapping of groups of vineyards/year from

Table 6 Factor loadings, eigenvalues, and percentage of total variance in a three-factor model for 12 variables (footprints components)

Variable	Factor 1	Factor 2	Factor 3
WF_G	0.131	**0.935**	−0.019
WF_B	**0.966**	−0.051	0.137
WF_{Gr}	0.436	0.269	**0.842**
CF_D	**0.832**	0.010	0.339
CF_I	**0.902**	0.026	0.264
CF_{Fe}	*0.427*	0.387	**0.801**
CF_{Nf}	*0.470*	*0.471*	**0.717**
CF_{Pf}	*0.505*	−0.166	**0.840**
CF_{Kf}	0.088	−0.163	**0.960**
CF_{Hb}	**0.691**	0.209	**0.625**
CF_{Fg}	**0.851**	0.097	*0.450*
CF_{Is}	−0.132	**0.865**	0.103
Eigenvalue	7.617	2.028	1.364
Proportion of variance (%)	63.48	16.90	11.37

Bold values: absolute loading > 0.60; Italic values: absolute loadings > 0.40

WF_G green water footprint, *WF_B* blue water footprint, *WF_{Gr}* grey water footprint, *CF_D* diesel carbon footprint, *CF_I* irrigation carbon footprint, *CF_{Fe}* fertilizer emissions carbon footprint, *CF_{NF}* nitrogen fertilizer carbon footprint, *CF_{PF}* phosphorus fertilizer carbon footprint, *CF_{KF}* potassium fertilizer carbon footprint, *CF_{Hb}* herbicide carbon footprint, *CF_{Fg}* fungicide carbon footprint, *CF_{Is}* insecticide carbon footprint

Figs. 5a and 6a, namely: V1-18, V1-19, and V3-18, in the *Win–Win* quadrant; V3-19, in the *Win-Lose* quadrant; V1-20 and V2-20 in the *Lose-Lose* quadrant. Thereby, we can consider that these correspondences translate (i) the relationships between the two footprint indicators, (ii) the interconnection of agricultural inputs *versus* yields in affecting the environmental impacts and production results, and (iii) the farming practices most influential on these environmental indicators in irrigated grapevines, which we identified as being:

- Irrigation volumes, and energy for pressurized irrigation systems, dependent on crop water requirements, given the annual climate conditions;
- Fuel consumption, dependent mostly, on the number of pesticides spraying operations and, indirectly, on favorable climate conditions for the development of pests and diseases;
- Nitrogen and phosphorus fertilization rates, depending on the productive potential of the vineyards, which is also, indirectly related to climatic conditions.

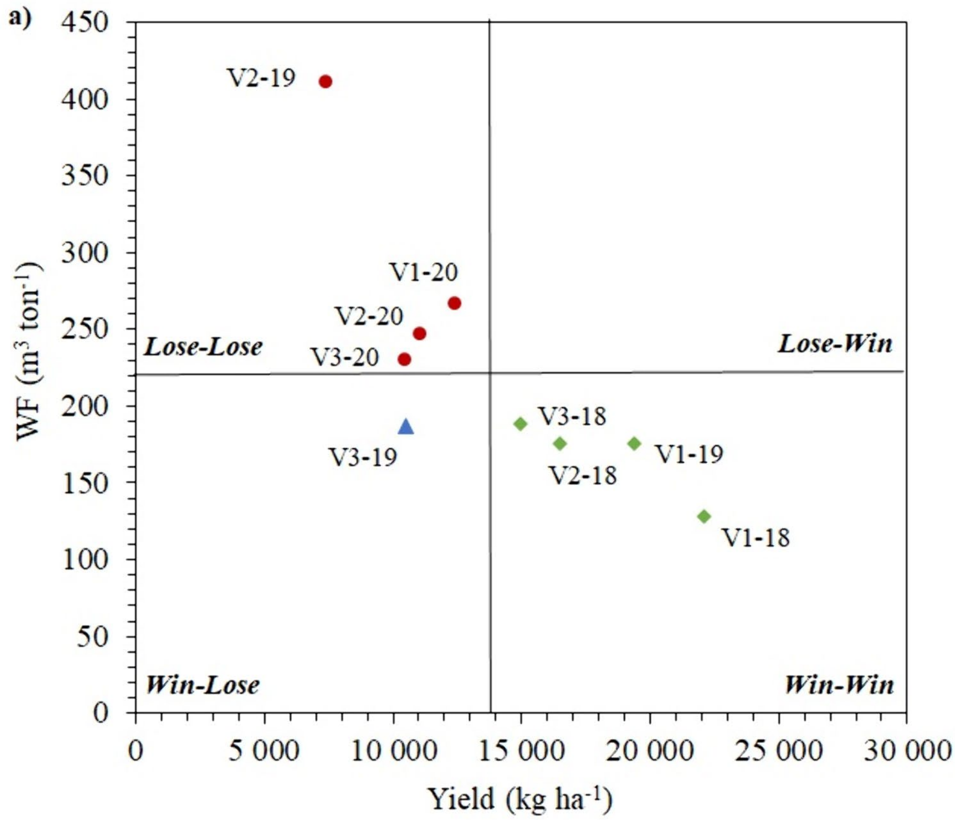
In summary, the estimates of WF and CF cannot be decoupled from grapevine yield and the role that climate conditions and adjusted agronomic options play to meet potential productivity. At the farm level, the capture of variability in the footprints indicators and components, along with the possibility of correlations with features of the cropping systems, of the adjusted technical options and of the local climatic data, makes this assessment more meaningful with a degree of detail required for an accurate assessment, in line with the conclusions by Herath et al. (2013) in their study of the water footprint of New Zealand's wines.

The carbon stock changes that could arise from the type of biomass residue management (pruning wood cutting and incorporation) and soil management practices (cover crops in the interrow) adopted by the farmers in this study, were not estimated due to lack of data. Mediterranean-type perennial crops such as grapevine exhibit biological, structural, and management features, like the incorporation of pruning debris, and the practice of cover cropping in the interrow, which have the potential to sequester important amounts of CO_2 (Vendrame et al. 2019). Examples of studies that report on these estimations are Litskas et al. (2017), Marras et al. (2015), Tezza et al. (2019) or Novara et al. (2020). Although the IPCC Guidelines for national greenhouse gas inventories (IPCC 2006; 2019) include the account of changes in carbon stocks that can result from alterations in land use, management practices (tillage), and biomass (inputs), the increase in soil carbon stocks with the adoption of various improved management practices may not be properly credited (Sanderman and Baldock 2010). Nevertheless, these potential positive effects on carbon budgets should be considered in future research projects, designed to address the problem of insufficient data and inconsistent methodological approaches.

Other inconsistencies regarding water and carbon footprints estimations have been addressed in several studies, e.g.: the variability in cumulative seasonal ET estimations influence on reliable WF assessments (Laan et al. 2019); shortcomings associated with grey water footprint accounting, like the variability of water quality standards or the account of multiple pollutants (Liu et al. 2017); the variability in emission factors from inorganic and organic fertilizer production and use, which often results in high uncertainty on the outcomes of the analyses (Walling and Vaneeckhaute 2020); the need to adjust emission factors to the particularities of the cropping systems of each region regarding water management, crop type, and fertilizer management (Cayuela et al. 2017; Minardi et al. 2022).

Recent policy initiatives, like the European Green Deal, and emerging soil carbon markets, proposed to align with the United Nations Sustainable Development Goals and accelerate management transitions, are promoting new paradigms in different economic sectors, including agriculture (European Comission 2023; United Nations 2023). These policies and regulations require rational methods to assess the impacts of

Fig. 5 Relationships between WF and yield (**a**) and between WF components and groups of vineyards (**b**). The vertical and horizontal lines in (**a**) indicate, respectively, the mean yield and mean WF for all vineyards. *Win–Win* (green diamonds)—WF win-yield win; *Win-Lose* (blue triangles)—WF win-yield lose; *Lose-Lose* (red circles)—WF lose-yield lose



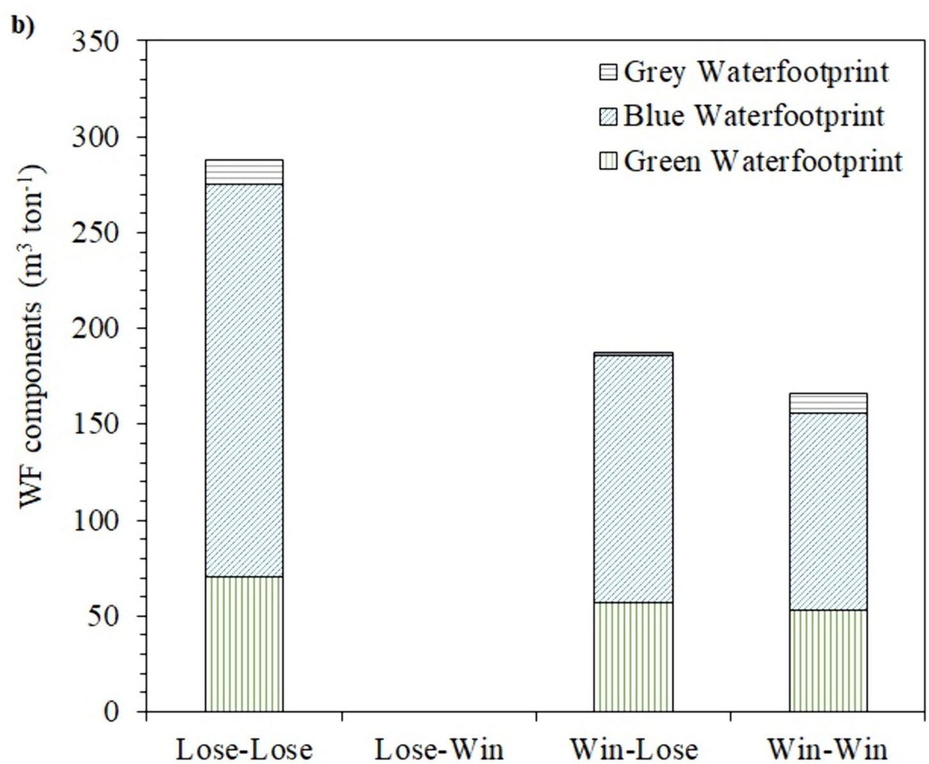


Table 7 Relevant inputs of WF and yield for four groups of vineyards/year (means ± SE)

Group (n)	Win–Win (4)	Win-Lose (1)	Lose-Win (0)	Lose-Lose (4)
Effective precipitation (mm)	93.7 ± 13.5	60	–	72.4 ± 12.9
Crop evapotranspiration (mm)	280.1 ± 13.6	279	–	293.2 ± 8.8
Applied irrigation (mm)	316.6 ± 28.4	150	–	241.2 ± 38.2
N (kg ha^{-1})	67.5 ± 10.0	7	–	51.8 ± 20.9
P_2O_5 (kg ha^{-1})	61.3 ± 17.1	3	–	36.8 ± 14.9
Yield (ton ha^{-1})	18.3 ± 1.6	10.5	–	10.3 ± 1.1

n number of elements in each group

freshwater use in agriculture and measure GHG emissions but also the sequestration of SOC and the carbon sinking potential of agroecosystems (Blasi et al. 2016; Stanley et al. 2023).

Conclusions

The current study provided insights into the water and carbon footprints of irrigated Mediterranean vineyards. The results point to the relationships between different components of these footprints, namely related to energy and agrichemicals use, and interconnection between environmental conditions, agricultural practices, and yield on the footprints of irrigated agroecosystems. The adoption of practices like deficit irrigation strategies, suitable variety rootstock selection, low to no-till or the use of cover crops, can promote an increase in water use efficiency and in soil, water and biodiversity conservation, reducing farm inputs and environmental footprints. Therefore, the potential for carbon sequestration of biomass residue management and soil management practices, like cover crops in the interrow of vineyards should be properly credited in CO_2 accounting. Moving away from conventional farming to low-input systems, like integrated, organic or regenerative viticulture is a pathway that is already recognized by the International Organization of Vine and Wine (OIV) and being followed in different viticultural regions. Using environmental footprints to measure the demand for natural resources linked to farm practices can lead to some considerations about the importance of carefully considering the trade-off between productive and environmental consequences of farming practices and driving farmers toward maintaining or increasing sustainable actions. The contribution of different farming options to increase the water and carbon efficiency in grapevine production under the dry Mediterranean conditions of southern Europe is a field of study that can provide farmers, planners, and policy makers with valuable information to an effective green transition of viticulture.

Fig. 6 Relationships between CF and yield (**a**) and between CF components and groups of vineyards (**b**). The vertical and horizontal lines in (**a**) indicate, respectively, the mean yield and mean CF for all vineyards. *Win–Win* (green diamonds)—CF win-yield win; *Win-Lose* (blue triangles)—CF win-yield lose; *Lose-Win* (yellow squares)—CF lose-yield win; *Lose-Lose* (red circles)—CF lose-yield lose

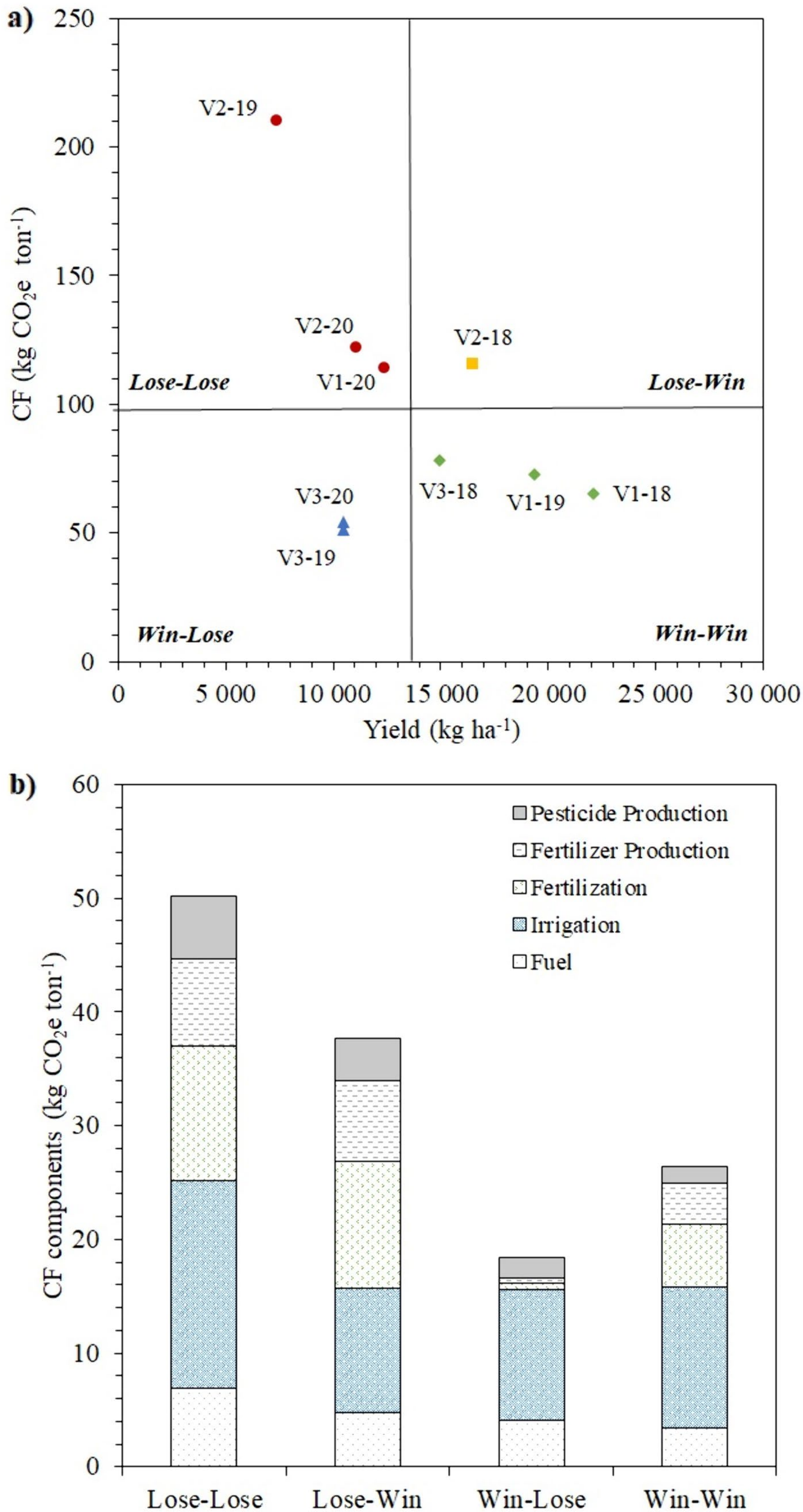


Table 8 Relevant inputs of CF and yield for four groups of vineyards/year (means ± SE)

Group (n)	Win–Win (3)	Win-Lose (2)	Lose-Win (1)	Lose-Lose (3)
Diesel fuel (L)	169.1 ± 27.1	109.4 ± 2.9	203.3	180.6 ± 27.4
Energy for irrigation (kWh)	671.4 ± 60.6	350.0 ± 50.0	520.0	509.3 ± 100.6
N (kg ha^{-1})	58.0 ± 4.6	4.0 ± 3.0	96.0	68.7 ± 17.3
P_2O_5 (kg ha^{-1})	47.7 ± 14.8	1.6 ± 1.4	102.0	49.0 ± 12.0
K_2O (kg ha^{-1})	69.0 ± 15.6	6.7 ± 6.4	179.0	46.7 ± 7.7
Fungicide (kg ha^{-1})	11.4 ± 1.7	10.7 ± 3.1	31.5	24.7 ± 6.0
Insecticide (kg ha^{-1})	0.9 ± 0.5	0.2 ± 0.2	0.4	0.5 ± 0.2
Herbicide (kg ha^{-1})	4.6 ± 0.3	0.0 ± 0.0	4.2	4.7 ± 1.0
Yield (ton ha^{-1})	18.8 ± 2.1	10.5 ± 0.0	16.5	10.3 ± 1.5

n number of elements in each group

Authors contributions Alexandra Tomaz and Patrícia Palma performed the study conception and design; Material preparation, data collection and analysis were performed by Alexandra Tomaz, José Dôres, Inês Martins, Adriana Catarino, Luís Boteta, Marta Santos, Manuel Patanita, and Patrícia Palma; The first draft of the manuscript was written by Alexandra Tomaz and all authors commented on previous versions of the manuscript; All authors read and approved the final manuscript.

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Data availability The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Conflict of interest The authors report there are no competing interests to declare.

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