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Integrated assessment of water footprint in nonirrigated vineyards

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The topic of sustainable water management has become of paramount importance at a global level, especially when considering the high-amount of water used in agriculture, which is a threat to water resource balance. Focused on 38 inventories of nonirrigated vineyard management in the Franciacorta wine-growing region in Italy, this study aims to understand how agronomic practices impact water resources. The integrated statistical approach, based on generalized linear models, reveals how context variables influence different water footprint indicators, such as water scarcity, acidification and freshwater ecotoxicity. Plant density and the presence of hillside vineyards are the primary influencing factors, while others, such as variety susceptibility, vineyard age and soil type may influence the shortage of water. The outcomes help to better understand the impact of management, thereby raising awareness in the wine sector about aspects often overlooked in traditional investigations. These findings offer specific insights for viticulturists, emphasizing the importance of a tailored management approach to minimize water footprint in viticultural practices and contribute to environmental sustainability.

The topic and critical issues related to sustainable water management have become central within the global debate across various areas: industry, economy, politics and society[1]. Sustainable water management entails the responsible and efficient use, conservation and protection of water resources to meet present and future needs without jeopardizing water availability for future generations[2]. In this context, multiple indicators have been developed over time to assess the impact of production on water resources, starting with the water footprint. The concept of water footprint was first introduced in 2011 by Hoekstra and was realized through the Water Footprint Assessment (WFA) method. The water footprint of a product or a process encompasses the direct and indirect volume of water used throughout various stages of the production chain and the resulting pollution[3]. Subsequently, a new water footprint framework for was proposed by the Water Use in Life Cycle Assessment research group, leading to the development of a method for the midpoint of water scarcity for use in Life Cycle Assessment (LCA). This LCA-based water footprint incorporates the quantification of water impacts related to freshwater use in terms of water availability footprint, water scarcity footprint and water quality in terms of ecotoxicity, eutrophication and acidification[4]. In 2014, the ISO 14046 standard defined the specifications for calculating the water footprint, incorporating the use of the LCA methodology[5]. Among the various sectors of application of the ISO 14046, the agro-industrial sector remains one of the most relevant as high water consumption in food production poses a threat to the balance of water resources in many basins[6]. As an example, the agricultural phase associated to food production contributes to eutrophication by releasing phosphorus into terrestrial runoff, which can account for between 25 and 75% of the total annual phosphorus loads in the waters of the European Union[7]. Many sectors of agro-industry have been studied in terms of water footprint using the LCA-based approach[8]. However, the wine industry, also due to its economic importance, is recognized as a relevant sector in relation to environmental sustainability issues[9,10]. Wine ranks high among plant-based products in terms of its contribution to the environmental impact of EU food consumption, mainly concerning freshwater ecotoxicity, water use and water consumption[11]. Wine producers recognize the importance of preserving natural resources and minimizing the ecological footprint of their production[12]. Actually, the use of water during the winemaking process and vineyard management has a significant impact on water scarcity, especially in high water stress areas[13], even though grapevines may be considered drought-resistant plants that do not necessarily require irrigation[12]. Considering vineyard management, the environmental impact on water resources remains relevant and is influenced by various factors that affect the entire vineyard management process. The decisions taken during the initial planting phase, including such choices as variety selection, as well as agronomic practices such as fertilization and pest control entail implications for water use and its potential environmental impact.

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Practices such as plant protection treatments and fertilization can lead to pollution of nearby water bodies and aquifers. Specifically, wastewater in vineyards primarily originates from these agricultural operations, generating runoff that is often laden with nutrients, chemicals, and organic residues, which can contaminate adjacent water resources. The use of chemicals for vineyard protection is the largest contributor to water contamination in the viticulture sector[4]. Non-synthetic plant protection products can reduce risks related to ecotoxicity of active ingredients while potentially increasing plant protection treatments and thus fuel consumption, especially in rainy years due to their washable nature[14]. The use of nitrogen and phosphorous fertilizers contributes to eutrophication and acidification impact categories[15]. The use of nitrogen fertilizer can also result in water acidification due to ammonia emissions[16] as nitrogen fertilizers are the major contributors to acidification in viticulture[17]. Fuel consumption from machinery use and pesticide production significantly contributes to freshwater acidification[18]. This issue is compounded by soil erosion from agricultural fields, which leads to sedimentation in streams, thereby reducing water quality and compromising aquatic habitats[17]. Furthermore, the conversion of natural landscapes into farmland exacerbates these problems by resulting in the loss of wetlands and biodiversity, which further negatively impacts aquatic ecosystems[19]. In addition to management, context variables such as vineyard characteristics, structure, pathogen pressure and vine susceptibility also play a significant role. Soil moisture content and structural characteristics can influence field surface conditions and, consequently, fuel consumption[20]. The planting density could also have a significant impact on pesticide use and soil tillage[21]. Vineyard slope can impact spatial variability of disease incidence and levels of susceptibility to fungal pathogens, thereby affecting necessary phytosanitary treatments[22]. Considering and managing these factors effectively is crucial for sustainable water management in viticulture, thereby minimizing potential negative environmental impacts on water resources. To the best of our knowledge, there are currently no studies that comprehensively address the impacts on water resources in the viticultural context, considering management and context variables. Therefore, it is essential to evaluate the effect of viticultural management on water resources by integrating the impact of these context variables into the assessment. This will enhance the awareness of viticulturists, guiding them towards the adoption of more flexible and context-adaptive strategies. This case study began by analyzing 38 vineyard management inventories from 12 nonirrigated wineries in Franciacorta, north-eastern Italy, using an integrated approach to explore the interactions between agronomic and context variables and their influence on water resources. The study employed the LCA approach to calculate the water footprint, involving nonirrigated vineyards, with the aim of exploring the impact of other management practices on water resources in greater detail.

Materials and methods

Contextualization and years of the study

The case study encompasses 12 wineries located in Franciacorta, a prominent wine-producing region in northern Italy renowned for its sparkling wine production (Fig. 1). The collected data pertain to the timeframe spanning from 2009 to 2020.

A case study includes all the data collected in one year from one winery. Table 1 displays the years, grape production and the overall vineyard area managed by each winery, as applicable to the number of case studies.

Climatic description and agrometeorological characterization

Franciacorta region falls under the Cfa classification according to the Köppen climate system (temperate climate, no dry season, hot summers). Referring to data from the Corte Franca weather station (45.633, 10.021, 220), the region recorded an average annual temperature of 14.7 °C between 1997 and 2023. Annual precipitation amounts to 1140 mm, with 646 mm occurring during the vine growing season (GS), from April to September. Figure 2 shows a graph of cumulative precipitation during the GS for the period under consideration. The graph also displays the average GS trend from 1997 to 2023, along with deviations of one and two times above and below the standard deviation for the period. The GS in 2010 and 2015 indicate, respectively, a high-rainfall year and a drought year compared to the average.

Assessment framework and system boundaries

The assessment framework for the water footprint linked to grape production encompassed all viticultural activities within the system boundaries depicted in Fig. 3. By using a cradle-to-gate approach, this study included all major annual agronomic inputs that are essential for wine grape production. In agreement with other researches, the nursery stage and co-products related to grape production were not included within the system boundaries[23,24]. As a result of data unavailability, information about machinery, infrastructure (including vineyard establishment) and vehicles was excluded. Information on energy consumption was excluded, not being relevant in the context of the vineyard, given that, with no irrigation, there is no significant consumption from the system. The impact on waste management was excluded as it is deemed negligible in grape production[25]. The production area provides irrigation only in emergencies; therefore, the wineries in this study did not practice irrigation in their vineyards. The direct use of water was limited to plant protection treatments, emergency irrigation operations, and young vineyards. Alongside the system boundaries, the assessment framework (Fig. 3) also includes such context variables as management, localization, planting and year, which were analyzed in relation to their influence on water resource impacts.

Data acquisition: inventories and context variables

For each case study, inventory data were collected to calculate the water footprint. These data included annual grape production (kg), the type and quantity of fertilizers, pesticides and herbicides used, the volume of water employed for phytosanitary treatments, the water supplied to young plants and the fuel consumption from vehicles owned by the winer or rented from agricultural subcontractors. Additionally, the data encompassed the

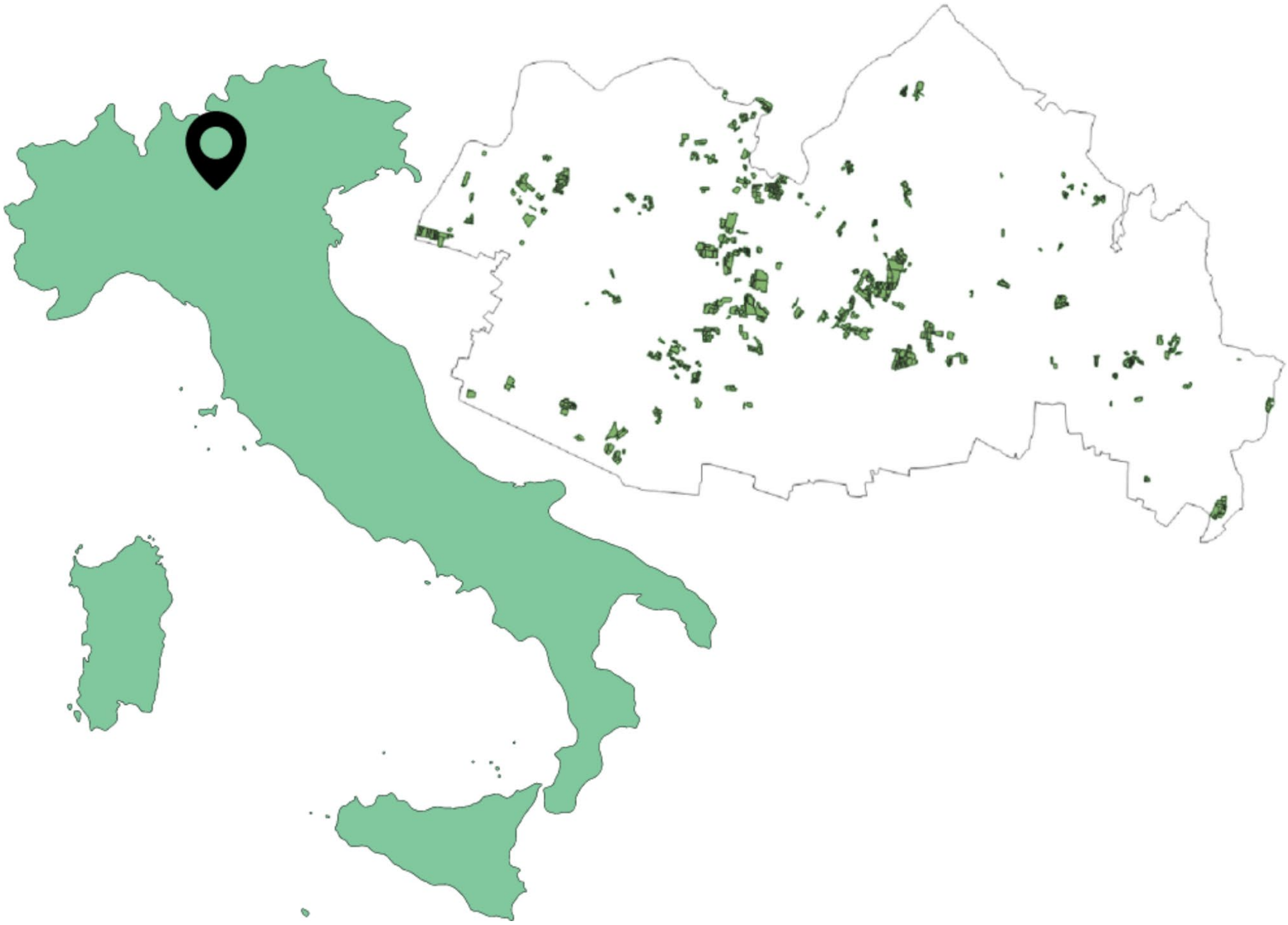

Fig. 1. Winegrowing area of Franciacorta DOCG (Designation of Controlled and Guaranteed Origin) and georeferencing of the vineyards where inventory data were collected.

		Grape production (kg)		Vineyard surface area (ha)	
Years	**Number of case studies**	**Mean**	**[min; max]**	**Mean**	**[min; max]**
2009	3	613,571	[101,100; 1,353,731]	71.19	[23; 149.24]
2010	10	220,233	[44,150; 501,292]	43.29	[9.22; 149.24]
2011	6	661,205	[161,065; 1,528,257]	62.69	[15.58; 150.25]
2012	3	706,418	[245,900; 1,107,823]	86.96	[25.44; 150.78]
2013	3	767,849	[240,872; 1,194,264]	88.86	[25.44; 156.5]
2014	3	812,374	[247,357; 1,495,097]	90.36	[25.44; 160.98]
2015	2	1,167,957	[656,305; 1,679,610]	133.58	[84.65; 182.51]
2016	3	742,439	[161,111; 1,643,564]	96.44	[24.03; 180.63]
2017	1	229,814	[229,814; 229,814]	84.56	[84.56; 84.56]
2018	1	1,014,176	[1,014,176; 1,014,176]	84.56	[84.56; 84.56]
2019	2	445,736	[152,273; 739,200]	54.545	[24.53; 84.56]
2020	1	956,463	[956,463; 956,463]	84.57	[84.57; 84.57]

Table 1. Number of case studies included in the study, years of data collection, grape production and vineyard surface area.

total managed area (ha), planting years, cultivars, and vine pruning systems for each vineyard managed by the winery in the study year. All companies managed the inter-row space of the vineyard using permanent cover cropping. All primary inventory data are available in Supplementary File S1, while Table 2 reports the minimum, maximum, and average values for each variable.

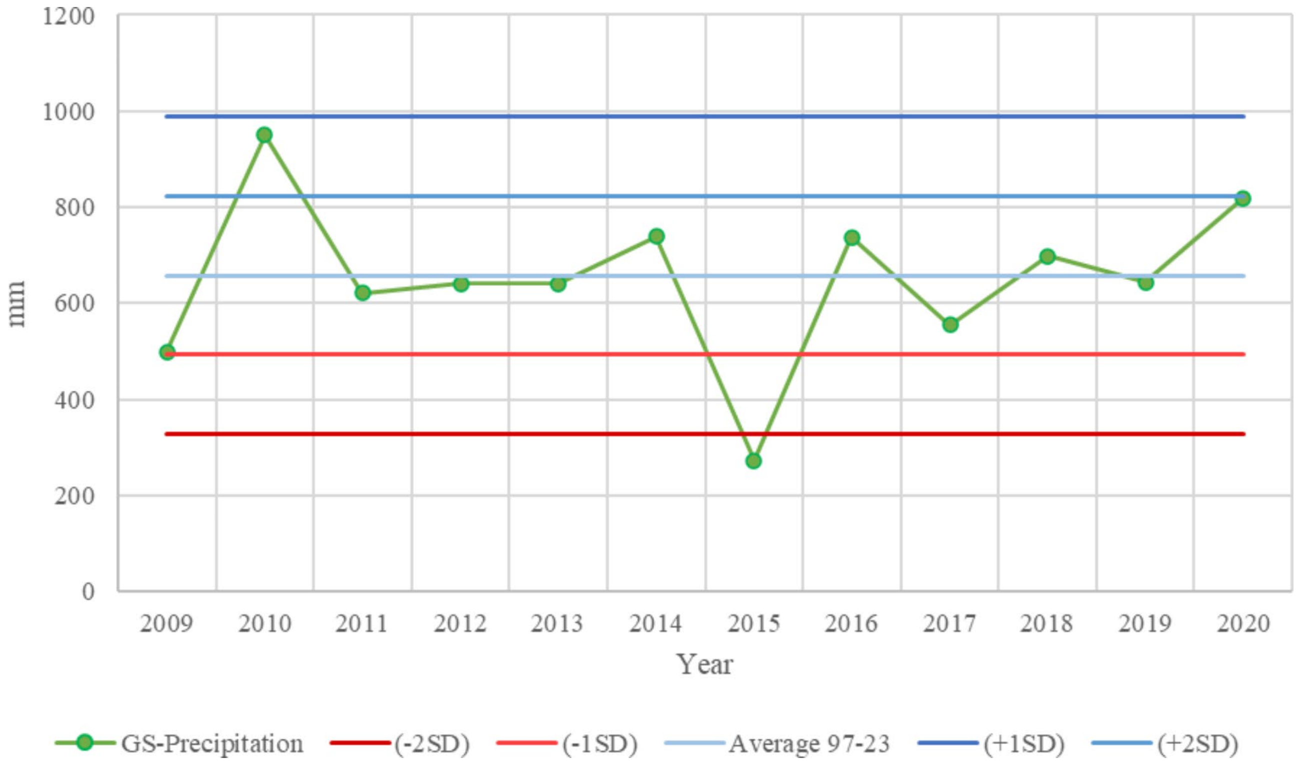

Fig. 2. Graph of cumulative precipitation during the vine growing season (GS) for the period under consideration in the Franciacorta area, including the average GS trend from 1997 to 2023 and the standard deviation from the average.

The inventory structure also includes emissions to air and soil that impact water quality[5]. Direct emissions to water, air and soil resulting from the use of plant protection products, fertilizers and fuels were determined as reported in Table 3.

The context variables for each case study were collected through three procedures: inventory data collection, the utilization of a georeferenced database of Lombardy (Northern Italy) at a scale of 1:250,000[31] and a survey conducted among the viticulturists. Context variables for each case study are shown in Table 4. These variables were collected both as continuous variables, representing the ratio over the entire surface of the vineyards managed by the winery for that study year and as dichotomous variables, by identifying two options for each variable. The variables of 'Planting' and 'Management' (Fig. 2) were obtained through the inventory data collected for each case study. In detail, in the 'Planting' category, for the dichotomous variable 'plant density', the inventories with vineyard plantings exceeding 7000 vines per hectare were classified as 'high' density, while others were categorized as 'regular' density. The continuous variables 'vines up to 3 years' and 'vines over 20 years' were determined based on the planting year and the year of the case study. For the continuous variable 'susceptible varieties', the ratio was calculated between the area planted with varieties considered more susceptible to fungal diseases[32,33] and the total managed vineyard area. In the 'Management' category, for the dichotomous variable 'sub-row management', wineries were divided into those using chemical weed control, i.e. herbicides, and those employing only mechanical methods, i.e. tillage for sub-row management. Fertilizer data allowed the categorization of dichotomous variables for 'organic fertilization' and 'synthetic fertilization'. The continuous variable 'Guyot training system' was determined as the ratio of the area managed using the Guyot system to the total managed area. In the 'Localization' category (Fig. 2), the georeferenced database of Lombardy was employed. More specifically, the continuous context variable 'sandy soil' was calculated as the ratio of the vineyard areas located on soils classified as sandy in the soil map to the total area of vineyards managed by the winery for the year of the case study. Similarly, through level curves determination, the continuous context variable 'hillside vineyards' was determined as the ratio between the areas of terraced vineyards and the total managed area. Concerning the variable 'Years', a survey was conducted among viticulturists from the participating wineries, who were asked their opinion on the susceptibility to the main fungal pathogens in grapevines, namely Downy mildew (*Plasmopara viticola*), Powdery mildew (*Erysiphe necator*) and Bunch rot (*Botrytis cinerea*) based on years. As expected, 2010, characterized by higher rainfall was classified by the viticulturists from the participating wineries as susceptible to Downy mildew. In 2015, despite the drought year, none of the wineries in the study resorted to emergency irrigation.

Water footprint impact assessment

The water footprint was assessed in accordance with the ISO 14046 standard for Water Footprint (WF)[5]. Water scarcity was assessed using the Available WAter REmaining (AWARE) method, which is designed to gauge the

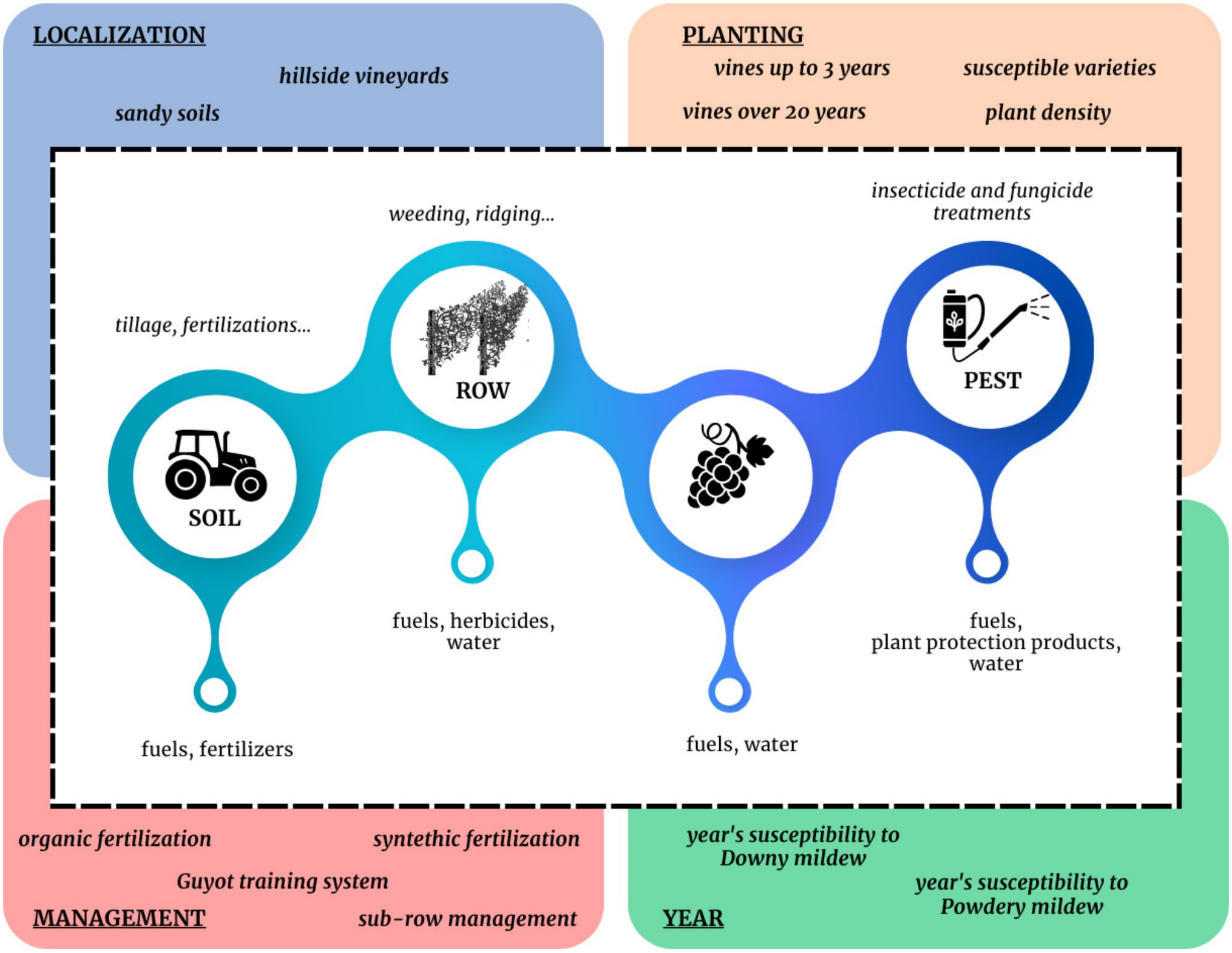

Fig. 3. Assessment framework of the study on the impacts of viticulture on water resources. The centre shows grape production processes and the relevant inputs included within the system boundaries. The four colored boxes contain the context variables under consideration: Localization, Planting, Management and Year.

impact of water extraction from natural systems in a specific area[34]. As to water quality, freshwater ecotoxicity was evaluated using the USEtox method[35]. Freshwater eutrophication and freshwater acidification were assessed according to the Impact 2002 method[36]. The functional unit (FU) chosen for this study is 1 kg of harvested grapes. For inventory structuring, background data were obtained through the Ecoinvent© database, version 3.8[37]. SimaPro v9.4.0.2 LCA software was used to calculate water consumption and quality indicators.

Data analysis

The statistical analysis procedure consisted of three phases. In the first phase, the association or correlation between explanatory variables was assessed, considering their large number and the potential for significant multicollinearity. Explanatory variables were analyzed in terms of correlation or association, and multicollinearity was evaluated using the Variance Inflation Factor (VIF). Any regressor with a VIF value greater than 5 was excluded. Relationships between quantitative and dichotomous qualitative variables (see Table 4) were assessed through box-and-whisker plots and, when necessary, by calculating the point-biserial correlation coefficient[38]. Additional statistical tests, such as the Chi-square test[39] and Cramér's V test[40], were also applied.

In the second phase, the relationship between explanatory variables and the response variables was analyzed. The response variables included indicators of impact on water resources, such as water scarcity, acidification, freshwater eutrophication, and freshwater ecotoxicity. Given the nature of the variables in the model, which precluded the application of a standard multiple linear regression, Generalized Linear Models (GLMs) were employed. A bidirectional stepwise selection process, based on minimizing the Akaike Information Criterion (AIC), was used to identify the subset of explanatory variables that best explained the variance in the response variables. The significance of the GLMs was assessed using McFadden's pseudo-R-squared[41].

Finally, in the third phase, a tenfold cross-validation was applied to enhance the robustness of the model results, with k k set to 10. The statistical analysis was performed using R software (version 4.3.2) in the tidyverse and caret ecosystem packages[42,43].

Inventory data	Mean (± SD) [min; max]
Calcium ammonium nitrate (kg)	67.08 (± 43.86) [36.00; 117.25]
Inorganic nitrogen fertilizer, AS N (kg)	1457.78 (± 2622.52) [2.74; 8228.41]
Inorganic phosphorus fertilizer, AS P_2O5 (kg)	581.39 (± 919.51) [4.10; 3162.00]
Inorganic potassium fertilizer, AS K_2O (kg)	929.80 (± 1227.26) [8.20; 4556.00]
Manure (tons)	732.04 (± 471.93) [569.00; 1573.00]
Single superphosphate (kg)	490.00 (± 579.83) [80.00; 900.00]
Urea (kg)	1299.83 (± 603.43) [690.00; 2116.00]
Benzimidazole-compound (kg AS)	13.09 (± 5.33) [9.32; 16.86]
Copper (kg AS)	191.28 (± 219.50) [2.3; 883.50]
Dithiocarbamate-compound (kg AS)	13.84 (± 14.20) [2.10; 40.00]
Fosetyl-Al (kg AS)	297.55 (± 295.43) [0.53; 960.45]
Fungicide unspecified (kg)	23.85 (± 44.00) [0.03; 326.33]
Insecticide. unspecified (kg AS)	15.86 (± 28.19) [0.16; 117.67]
Organophosphorus compound. unspecified (kg AS)	30.01 (± 39.12) [0.45; 160.00]
Pyrethroid-compound (kg AS)	10.49 (± 13.55) [0; 42.80]
Imidazole (kg AS)	24.38 (± 9.37) [17.75; 31.00]
Mineral oil (kg)	65.25 (± 92.70) [0; 330.40]
Sulfur (kg)	5136.07 (± 5606.01) [246.25; 19,079.51]
Sodium bicarbonate (kg)	478.18 (± 51.29) [441.92; 514.45]
Fuels for field work (kg)	11,860.81 (± 20,157.07) [0; 88,316.28]
Fuel for other vehicles (km)	15,497.24 (± 40,052.74) [0; 274,080.00]
Glyphosate (kg)	60.99 (± 63.26) [0.21; 189.95]
Herbicide unspecified (kg)	0.45 (± 0.35) [0.08; 0.83]
Water for plant protection treatments (m^3)	46.73 (± 44.83) [5.93; 199.74]
Water for young vines or emergency irrigation (m^3)	222.26 (± 290.21) [56.00; 655.65]

Table 2. Mean, standard deviation (SD), minimum and maximum values of vineyards. AS, Active substance.

Input category	Emission	Sources
Synthetic and organic fertilizers in water, air and soil	Dinitrogen monoxide	Nitrogen emissions to air and water, phosphate leachates and run-offs were computed using the emission factors proposed by Zampori and Pant[26]. In the case of organic fertilizers, the content of nitrogen and phosphates was determined using data from organic matrices collected in the Franciacorta study area during the LIFE VITISOM Project[27]
	Ammonia	
	Nitrate	
	Phosphate	
Fuel consumption	Carbon dioxide	Emissions from fuel consumption were estimated using data from the Department for Environment Food & Rural Affairs[28]
	Carbon monoxide	
	Hydrocarbon mixtures	
	Nitrogen oxide	
	Particulate	
Plant protection products in water, air, and soil	Active substance in water, air, and soil	In accordance with the studies conducted by Margni et al.[29] and Audsley[30], it is assumed that leaching of the active substance from the soil into water is at most 10% of the applied dose. The 10% fraction of active substance is emitted into the air and the remaining fraction enters the soil

Table 3. Direct emissions related to the input and the source generating them.

Results

Descriptive analysis

From the preliminary analysis, the regressors related to Bunch rot were excluded due to multicollinearity issues (it has a VIF value of 8.48). The other regressors have VIF values below five.

Table 5 provides a summary of the inventory assessment for the calculation of water footprint indicators. Contextual variables and water footprint indicator results for each inventory are available in Supplementary File S2.

GLMs analysis

Water scarcity

The GLM demonstrated a good fit to the data, explaining almost half of the variability in Water Scarcity values (adjusted pseudo-R-squared = 0.54). Table 6 lists the variables that proved to be significant in the model: Vines

Context variables	Mean (±SD) [min; max]	Dichotomous variables
Localization		
Sandy soils	0.78 (±0.30) [0;1.00]	
Hillside vineyards	0.14 (±0.19) [0;0.80]	
Planting		
Vines up to 3 years	0.14 (±0.14) [0;0.48]	
Vines over 20 years	0.10 (±0.12) [0;0.34]	
Susceptible varieties	0.89 (±0.02) [0.85;0.95]	
Plant density		11 HIGH; 27 REGULAR
Management		
Sub-row management		15 HERBICIDES; 23 TILLAGE
Organic fertilization		17 NO; 21 YES
Synthetic fertilization		17 NO; 21 YES
Guyot training system	0.26 (±0.29) [0;1.00]	
Year		
Year's susceptibility to Downy mildew		19 NO; 19 YES
Year's susceptibility to Powdery mildew		32 NO; 6 YES
Year's susceptibility to Bunch rot		22 NO; 16 YES

Table 4. Context variables for each case study. Minimum and maximum values are provided for continuous variables, mean and standard deviation (SD). The counting of the two options is reported for dichotomous variables.

Indicator	Mean (±SD) [min; max]	
Water scarcity	3.94E−02 (±4.39E-02) [5.07E-03; 2.42E-01]	m^3 freshwater/FU
Acidification	6.99E−04 (±5.55E-04) [1.15E-04; 3.08E-03]	kg SO$_2$/FU
Freshwater eutrophication	2.18E−04 (±5.33E-04) [1.02E-05; 2.52E-03]	kg PO$_4$/FU
Freshwater ecotoxicity	5.80E−00 (±4.85E-00) [1.57E-01; 2.37E+01]	CTUe/FU

Table 5. Mean, standard deviation (SD) and minimum and maximum values of water footprint indicators for the case studies being analyzed.

Coefficient	Estimate	Standard Error	*p*-Value
Vines of over 20 years	0.153	0.055	0.009**
Susceptible varieties	0.978	0.309	0.004**
Organic fertilization	0.023	0.012	0.069
Plant density: regular	−0.061	0.023	0.013*
Sub-row management: tillage	−0.043	0.016	0.012*
Sandy soils	−0.065	0.026	0.018*
Hillside vineyards	0.081	0.036	0.029*

Table 6. Results of the multiple stepwise linear regression model for the water scarcity indicator. '***' $p<0.001$; '**'$p<0.01$; '*' $p<0.05$; '.' $p<0.1$.

of over 20 years, Susceptible varieties, Organic fertilization, Plant density 'regular', Sub-row management 'tillage', Sandy soils, Hillside vineyards. The effects of each variable should be interpreted based on the consideration that all the other variables are equal.

Acidification
The GLM applied to acidification demonstrated an adaptation to the data that explains a lower amount of variability compared to water scarcity (pseudo-R-squared = 0.27). Table 7 shows the only significant variable is 'Plant density: regular', with a negative effect (p < 0.001).

Freshwater eutrophication
Table 8 lists the variables that are found to significantly influence freshwater eutrophication: 'Guyot training system', 'Plant density: regular', 'Sub-row management: tillage', and 'Hillside vineyards'. As with water acidification, the GLM showed an even lower fit for the water scarcity data (pseudo-R-squared = 0.26).

Coefficient	Estimate	Standard Error	*p*-Value
Plant density: regular	< -0.001	< 0.001	< 0.001 ***

Table 7. Results of the multiple stepwise linear regression model for the acidification indicator. '***' $p < 0.001$; '**' $p < 0.01$; '*' $p < 0.05$; '.' $p < 0.1$.

Coefficient	Estimate	Standard error	*p*-Value
Guyot training system	< − 0.001	< 0.001	< 0.001 ***
Plant density: regular	< 0.001	< 0.001	0.041 *
Sub-row management: tillage	< 0.001	< 0.001	0.016 *
Hillside vineyards	0.001	< 0.001	0.058

Table 8. Results of the multiple stepwise linear regression model for the freshwater eutrophication indicator. '***' $p < 0.001$; '**' $p < 0.01$; '*' p < 0.05; '.' p < 0.1.

Coefficient	Estimate	Standard error	*p*-Value
Plant density: regular	− 6.754	1.612	< 0.001 ***
Hillside vineyards	7.248	3.981	0.077

Table 9. Results of the multiple stepwise linear regression model for the freshwater ecotoxicity indicator. '***' $p < 0.001$; '**' $p < 0.01$; '*' $p < 0.05$; '.' $p < 0.1$.

Freshwater ecotoxicity

The GLM for freshwater ecotoxicity showed a better fit to the data compared to acidification and eutrophication, explaining the variability reasonably well (pseudo-R-squared = 0.33). The variables 'Plant density: regular' and 'Hillside vineyards' proved to be significant and are shown in Table 9.

Discussion

Water footprint indicators values

In Life Cycle Assessments (LCA), such factors as the data reference period, geographical context and the level of development and technological innovation can influence the results[44]. The variability of values obtained for different impacts, considering the diversity of study contexts, results in a wide range of values. From the calculation of water footprint indicators, an average value of 3.94E−02 m3 freshwater/FU was obtained for water scarcity, with a minimum of 5.07E−03 and a maximum of 2.42E−01. This average value is in agreement with that resulting from previous studies which,, for the same functional unit, include a 2021 study on table grape production in integrated management vineyards in the Mediterranean area[45], which reported an average of 3.93E−02 for water scarcity, against an average of 7.48E−01 m3/kg as resulting from a 2017 study on Peruvian grape production conducted by Ian Vázquez-Rowe et al.[46]. As far as acidification is concerned, an average value of 6.99E−04 kg SO_2/FU was obtained, with a minimum of 1.15E-04 and a maximum of 3.08E−03. Highly variable values are observed in the studies available in literature with regard to this indicator. For example, Canaj et al. (2021) reported an average of 5.56E−02. A more similar value was obtained in a study on the water footprint in a winery in northeastern Italy, where Borsato et al.[4] (observed a value of 8.45E−04 for acidification, considering only the impact fraction associated with the vineyard phase. Regarding freshwater eutrophication, an average value of 2.18E−04 kg PO4/FU was obtained, with a minimum of 1.02E−05 and a maximum of 2.52E−03. Similarly, a study by Ferrari et al.[47] analyzed the impacts of Lambrusco grape production, observing 3.23E−04 for freshwater eutrophication. Other studies, however, have observed highly variable values. Ian Vázquez-Rowe et al.[48] reported 4.23E−02, while Canaj et al.[45] reported an average of 1.61E−03. A previous Life Cycle Assessment (LCA) on red wine production in Spain highlighted that freshwater eutrophication resulting from the grape production phase could amount to 1.47E−03[49]. Finally, for freshwater ecotoxicity, an average value of 5.80E−00 CTUe/FU was obtained, with a minimum of 1.57E−01 and a maximum of 2.37E + 01. Variable results have also been observed in the literature for this value; Ferrari et al.[47] calculated a value of 3.23E-04, while Ian Vázquez-Rowe (2017) reported 1.27E + 00 while Canaj et al.[45] reported an average of 4.27E + 01. Compared to what has already been explored in various studies, the results of this work investigate the impacts of water footprint management in a nonirrigated context, a relatively underexplored area.

Influence of contextual variables on water impacts

In the detailed analysis of significant variables, a positive effect ($p < 0.01$) is noted for Water scarcity in vineyards with a higher presence of plants over twenty years old. This could be associated with a greater need for maintenance and replacement of new vines to sustain vineyard productivity. As the vineyard ages, there is a need to replace diseased or dead vines, often more frequently than replanting the entire vineyard. In fact, in the study area, there is a tendency to carry out replacements rather than complete replanting. The higher presence of 'Susceptible varieties' shows a positive correlation with Water scarcity ($p < 0.01$). This can be associated with an increase in water consumption, most likely linked to a greater use of phytosanitary treatments in areas where high susceptible variables were cultivated[50]. Organic fertilization has a positive effect on water scarcity, although with low significance ($p < 0.1$). A negative influence emerges for 'Plant density: regular', indicating that low plant density (< 7000 vine/ha) is associated with low water consumption. Low vineyard density of vineyards and low canopy volume per hectare can actually lead to reduced water consumption in nonirrigated settings due to less requirements associated with other practices, such as plant protection treatments[51]. Vineyards managed using sub-row tillage ('Sub-row management: tillage') also showed negative significance, indicating lower water consumption than in vineyards treated with herbicides. Furthermore, a negative effect is observed in 'sandy soils,' probably due to improved drainage and, consequently, less soil moisture, requiring increased inputs and treatments. In better drained vineyards, not too much water available prevents excessive vigor, which can lead to an increased incidence of pressure from fungal infections[52,53]. The variable Hillside vineyards showed a positive effect ($p < 0.05$). This could be attributed to the fact that in terraced settings, inefficiency in surface management is greater than in flat settings. This can lead to wastage of products and water in the distribution of plant protection products.

Regarding Acidification, the relevance of fossil fuel combustion in relation to this phenomenon has already been reported in the literature[54]. Low or regular planting density (< 7000 plants/ha) could result in reduced fuel consumption for field operations; however, this is closely related to the size of the machinery used and the time required to carry out operations in the field[55].

Freshwater eutrophication, as previously mentioned, primarily depends on the use of fertilizers. Although, similar to acidification, the GLM showed a poorer fit to the data, several significant relationships with contextual variables were observed in this case. It is interesting to note that no significant differences were found between management practices using organic or synthetic fertilizers, suggesting that the impact may be influenced more by the timing and quantities of application rather than the type of fertilizer used.

For Freshwater ecotoxicity, like Water scarcity, a negative effect is observed on the variable 'Plant density: regular', probably in relation to the reduced consumption of plant protection products in low-density vineyards. A wide in-row spacing results in a reduced tree row volume (TRV), taken as plant canopy volume per hectare of vineyard[56]. Canopy volume and plant density, along with the growth stage and the application method, can actually influence the metering of plant protection products[57]. This results in less product being applied in reduced density or regularity for the same surface area. A slight significance also exists for 'Hillside vineyards', which may still be attributable to difficulties in working in terraced vineyards. The use of sprayers equipped with product recovery systems can significantly reduce wastewater, particularly by minimizing the runoff of active ingredients into water bodies and their leaching into aquifers. These advanced spraying systems are designed to capture and recycle excess pesticides that do not adhere to the target vegetation, thereby minimizing environmental contamination. In vineyards, sprayers with air-droplet separators for mist recovery have shown promise by improving spray recovery and target coverage while reducing pesticide dispersion into the environment[58].

The inclusion of more specific information on viticultural practices, such as soil management or the type of machinery used for phytosanitary treatments, could have further enhanced the understanding of how context variables influence different water footprint indicators.

Water footprint: implications of management strategies

Other studies have examined the water footprint in viticulture, focusing on the effects of management practices. Among these, a study conducted by Tomaz et al.[59] in Portugal evaluated the water footprint in irrigated vineyards, analyzing the environmental impact of irrigation practices and proposing sustainable management strategies to mitigate these effects. While this study focuses on a nonirrigated context, the impacts of viticultural practices on water resources remain closely linked to management decisions. These impacts extend beyond emergency irrigation to include water usage in plant protection treatments. Furthermore, the application of fertilizers and plant protection products can contribute to the eutrophication, acidification, and ecotoxicity of water bodies. Given the limited availability of water resources, it is critical to evaluate the effects of management not only in terms of withdrawals but also regarding their broader environmental impacts. The results highlight the significant influence of vineyard structural factors, such as planting density and varietal composition, can significantly influence the effects on water resources. From a sustainability perspective, these elements should be carefully considered in vineyard design and in adapting practices to an integrated resource management framework.

Conclusions

The result of this study emphasizes the importance of calculating the water footprint even in nonirrigated vineyard contexts, thereby providing a better understanding of how agronomic practices beyond vineyard irrigation can have an impact on water resources. An integrated statistical approach involving data collected from various companies over several years was applied, the aim being to understand how the contextual variable leads to different impacts assessed through the water footprint calculation. As a result, this methodology highlighted how water scarcity is associated with contextual variables. It also explained, though to a lesser extent, the association of some variables with indicators of freshwater acidification and ecotoxicity. Among the most relevant contextual variables, vine density and the presence of hillside vineyards emerge as major factors influencing water consumption and associated water footprint impacts. In addition, there is clear evidence that such variables as variety susceptibility, vineyard age, vineyards on sandy soils and the sub-row management with cultivation can influence water scarcity rather than herbicides. Results obtained allow to increase knowledge about the influence of management, excluding irrigation, on reported water footprint, providing useful information for viticulturists. Furthermore, the study can contribute to raising awareness in the sector about issues related to the impacts of management on water footprint, an aspect often overlooked in traditional investigations. Future research could benefit from including more detailed data on viticultural practices, such as specific soil management strategies or the types of machinery used for phytosanitary treatments. These additions could provide deeper insights into how context variables influence water footprint indicators, ultimately enhancing the precision and applicability of the findings. Expanding the analysis to incorporate alternative methodological approaches or broader datasets could also contribute to a more comprehensive understanding of the environmental impacts of viticulture. Such advancements would support the development of more specific and sustainable management strategies, addressing the challenges posed by climate change and increasing resource pressures.

Data availability

All data generated or analysed during this study are included in this published article.

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Author contributions

Conceptualization, I.G., A.S. and G.G.; Methodology, M.T., P.D., M.D., I.G., L.F. and L.V.; Formal analysis, I.G., A.S., M.M., L.F. and G.G.; Investigation, I.G., M.T., P.D., M.D. and L.V.; Data curation, I.G., A.S., M.M. and L.F.; Writing—original draft, I.G., M.M. and L.F.; Writing-review & editing, M.T., P.D., L.V. and G.G.; Supervision, G.G. All authors have read and agreed to the published version of the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

Additional information

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