



# Environmental benefits of ozonated water for sustainable grapevine disease control: A life cycle and carbon sequestration analysis

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## ABSTRACT

The oxidative capacity of ozone makes it a highly effective biocide, widely used in the food and processing industry, as well as in drinking water plants. In a context of tighter restrictions on the use of synthetic plant protection products at the regulatory level, wineries are looking for alternative methods to control diseases, making the application of ozonated water an option to consider. To determine the environmental sustainability of this alternative vineyard disease control treatment, an environmental impact assessment was conducted using the Life Cycle Assessment (LCA) methodology. The assessment was carried out in a vineyard located in the D.O. Rías Baixas of Galicia, located in northwestern Spain. The analysis was conducted on the basis of two functional units: *i*) 1 kg of grapes and *ii*) 1 ha of land managed and using a cradle-to-gate boundary system. Ten impact categories were assessed using the ReCiPe method, except for the water scarcity indicator, which was quantified using AWARE.

The environmental sustainability of the vineyard was further analyzed by measuring its carbon sequestration potential to obtain a more complete environmental profile. The RothC-26.3 model was chosen to estimate absolute carbon sequestration and annual sequestration rate from 2020 to 2040. Since the ozone-only scenarios lost all harvest, no environmental assessment was performed for such scenarios. For the remaining scenarios, the findings suggest that those using a combination of ozonated water and fungicides have the worst environmental performance due to notable reductions in grape yield and more frequent disease control interventions, particularly in certain scenarios. When evaluating environmental performance per hectare of land managed, the scenario using ozonated water with a limited number of disease control interventions exhibited the most favorable environmental profile, primarily due to reduced use of fungicides and disease control passes. In addition, the main contributors to the vineyard environmental profile identified were diesel fuel combustion during field operations, fertilizer use and production, and irrigation. In addition, the research indicates that the vineyard sequesters carbon annually, but this alone is insufficient to offset its greenhouse gas emissions. However, it is estimated that through the application of more appropriate soil management practices, the vineyard could achieve carbon neutrality and potentially increase soil carbon stocks over time.

## 1. Introduction

In 2022, global grape production reached 80.1 million tons, with approximately half of this quantity allocated to wine production, resulting in approximately 259.9 million hectoliters (International Organization of Vine and Wine (OIV), 2022a; OIV, 2022b). Spain, which has the largest vineyard area, is the third-largest wine producer globally,

after Italy and France (OIV, 2023). Collectively, these three countries account for half of the world's wine production and 61% of global wine exports by economic value (OIV, 2023). The economic significance of the viticulture sector in major producing countries, such as Spain, highlights the importance of studying and improving the environmental sustainability performance of this sector.

Spain has an extensive wine heritage, dating back to Roman times

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(Xunta de Galicia, 2020), which explains the strong role of wine in the cultural food identity of the country (Analistas Financieros Internacionales (AFI), 2020). Currently, the Spanish wine industry generates a total annual Gross Value Added (GVA) of more than 23.7 billion euros, which represents 2.2% of the national GVA (AFI, 2020), and supports more than 427,700 jobs (2.4 % of the total employment in Spain) (AFI, 2020).

A Protected Designation of Origin (PDO) is a unique label that identifies food products that have been produced, processed and prepared within a defined geographical area (Conferencia Española de Consejos Regularadores Vitivinícolas (CECRV), 2023). The Council Regulation governing PDOs (European Commission No. 510/2006) specifies that the quality and characteristics of these products are linked mainly or exclusively to the specific geographical area of origin, influenced by both natural and human factors (EUR-Lex, 2006). Spain has a total of 101 PDOs linked to wine production, five of which are located in the northwestern region of the country, Galicia (Ministro de Agricultura Pesca y Alimentación, 2023). Galician viticulture is known for producing a wide variety of excellent quality wines. Among them, the *Albariño* variety is representative of the *Rías Baixas* D.O. (PDO-ES-A1119) influenced by the Atlantic ocean, and *Godello*, *Treixadura* and *Mencía* are the main varieties of inland Galicia (Xunta de Galicia, 2023a).

Vineyards have traditionally been demanding crops on the basis of fertilizers and phytosanitary products and intensive tillage (Dumitriu et al., 2022; European Court of Auditors, 2023; Giffard et al., 2022). These intensive practices contribute significantly to greenhouse gas (GHG) emissions, soil and water pollution, and have a negative impact on biodiversity and soil quality (Giffard et al., 2022). In fact, according to Trioli et al. (2015) the cultivation of grapes for wine production accounts for about 2% of the total emissions of the agricultural sector and about 0.3% of annual GHG emissions.

Plant protection products play a crucial role in protecting grape production against fungal diseases (Dumitriu et al., 2022), such as downy mildew, powdery mildew, black rot and botrytis rot, among others, which can lead to significant economic losses and quality degradation in wine production (Dumitriu et al., 2022). However, regulations increasingly restrict the use of pesticides due to their significant environmental and human health impacts in favor of safer and more sustainable alternatives.

The recent European Commission Regulation on the sustainable use of plant protection products aims to reduce the use and associated hazards of chemical pesticides by 50% by 2030 (European Commission, 2023a). This updated regulation also aims to promote the implementation of Integrated Pest Management (IPM) among users, giving priority to non-chemical strategies and pest prevention methods (European Commission, 2023b). In addition, consumer demand for more sustainable wines, including biodynamic and organic wines, is driving the industry towards rapid growth in organic production at an annual rate of 17% (European Union, 2023; OIV, 2021).

Ozone is widely used as a biocide due to its powerful oxidative potential of 2.07 V (Epelle et al., 2023; Mukherjee et al., 2023; Pérez-Calvo, 2019). Ozonation has a long history of use in drinking water facilities and has been integrated in wastewater treatment plants with favorable results (Díaz-López et al., 2022; Lim et al., 2022). It is also commonly used in the food industry to ensure food safety by disinfecting surfaces and storage areas; in addition to its use in improving food preservation (İbanoğlu, 2023).

In agriculture, ozone has been investigated as a potential substitute for chemical pesticides with promising results (Campayo et al., 2021). Nagatomo et al. (2016) conducted experiments aimed at combating soil pathogens responsible for plant diseases, and found that ozone significantly reduced these microorganisms within the soil. As part of the OXIR project (CORDIS EU research results, 2022), a team of researchers studied the efficacy of ozone spraying on various crops, such as berries, basil, melons, peppers and vineyards, and reported a positive impact on the control of several crop pathogens whereby the use of ozone was

recommended as a cost-effective and environmentally friendly technique. Similarly, Remondino and Valdenassi (2018) endorsed ozonation as a more environmentally sustainable approach to pest and disease control. Beyond the positive results in terms of efficiency, the concern about the direct and indirect environmental consequences associated with this technology may be posed.

To answer this question objectively, a comprehensive environmental impact assessment of this disease control strategy is needed, covering the various stages of production and potential areas of environmental concern, of which, to the best of our knowledge, there is currently none. In this regard, the Life Cycle Assessment (LCA) methodology stands out for covering all stages of production, from raw material extraction to waste disposal, and for the simultaneous use of multiple indicators, which help to avoid displacements between environmental compartments and facilitate the identification of critical processes or activities throughout the entire life cycle (European Commission, 2023c). For the European Commission, LCA is the most important framework for assessing potential environmental impacts (European Commission, 2023c).

On the other hand, as pointed out by Liu and Bakshi (2019), environmental sustainability depends not only on the environmental impacts of the activity, but also on the capacity of ecosystems to mitigate and withstand these impacts. Therefore, protecting and enhancing the capacity of ecosystems to provide these services is an essential part of sustainable performance. In this sense, soils are considered an important carbon sink (European Commission, 2011; Yuan et al., 2023). Moreover, agricultural practices greatly affect soil carbon stocks, either increasing or decreasing depending on the type of management performed, and thus have a key role in climate change mitigation, one of the main environmental priorities worldwide (European Union, 2023).

In this context, the present study aims to evaluate the effectiveness of ozone treatment in reducing the environmental impact on vineyards compared to traditional pest control methods. In addition, the ability of the vineyard to mitigate climate change will be estimated in order to obtain a more complete picture of vineyard sustainability. This will help determine whether the vineyard is currently operating within its carrying capacity or whether its management practices need to be adjusted to ensure crop and soil resilience and long-term sustainability of wine production.

## 2. Methodology

### 2.1. Study area and evaluation scenarios

This study was performed in collaboration with a local winery located in Ribadumia, within the D.O. Rías Baixas wine region of Galicia, Northwest Spain (coordinates: 42° 32' 23.81" N, 8° 44' 7.10" W) (Fig. 1). The winery grows its own grapes to produce the renowned *Albariño* wine, with the D.O. Rías Baixas seal of quality, a traditional variety with international reputation (Decanter, 2023; Fells, 2023; Suárez et al., 2023). The region is characterized by constant rainfall and moderate temperatures throughout the year, which translates into the manifestation of fungal diseases in the vineyards, including downy mildew (caused by *Plasmopara viticola*), powdery mildew (caused by *Erysiphe necator*) and botrytis or gray rot (caused by *Botrytis cinerea*) (Boso et al., 2009; Villanueva-Rey et al., 2019). The vineyard studied is particularly subject to both downy mildew and powdery mildew, which can significantly reduce yield and crop quality (Vázquez Abal et al., 2022).

In the 2020/2021 season, several scenarios were set up in the winery's vineyard to analyze the effects of replacing traditional chemical disease control methods with ozone-based treatments. In the 2020/2021 campaign, several scenarios were established in the vineyard to analyze the effects of replacing traditional chemical disease control methods with ozone-based treatments. These scenarios were designed considering the predominant diseases in the vineyard (downy mildew

and powdery mildew), the three most sensitive phenological stages of the vine (when the surrounding vegetation has grown approximately 10 cm, at flowering and when the grapes reach pea size) and the periods of greatest risk of infection as indicated by the epidemiological model of the Monet platform (Monet Viticultura, 2023). The seven scenarios initially considered are described below, starting with the one in which ozonated water is most representative, and concluding with a scenario in which traditional chemical-based treatment is used exclusively (Table 1).

- **Ozone treatment** (i). The first treatment consisted solely of the application of ozonated water.
- **Ozone-downy mildew treatment** (ii). In a second scenario, ozonated water was used to control downy mildew while chemical fungicides were used to control powdery mildew.
- **Ozone-powdery mildew treatment** (iii). Unlike the second scenario, in the third scenario ozone was used for powdery mildew and chemical fungicides for downy mildew.
- **Mixed ozone-chemical treatment** (iv). In a fourth scenario, the chemical treatment was applied in the most sensitive phenological stages and ozonated water in the rest, taking into account the level of risk of infection.
- **Ozone-chemical alternation treatment** (v). In this case, ozone and chemical treatments were alternated, taking into account the risk of infection indicated by the Monet platform.
- **Harvest treatment with ozone** (vi). A conventional treatment based on chemical fungicides was followed, except for one application at harvest, which was carried out with ozonized water.
- **Conventional treatment** (vii). Finally, a chemical-only scenario was defined to represent the conventional treatment. It was applied, as in scenarios (i) and (ii), taking into account the risks foreseen by the Monet platform and the most sensitive phenological stages.

The scenarios corresponding to strategies (i), (ii) and (iv) resulted in significant yield losses, suggesting that the continued use of ozonated water (i) was ineffective for disease control. As also concluded in field

**Table 1**  
Summary of the treatment strategies considered and final scenarios studied.

Code	Treatment	Studied scenario	Description
i	Ozone treatment	–	Treatment using solely the application of ozonated water.
ii	Ozone-downy mildew treatment	A	Ozonated water was used to control downy mildew while chemical fungicides were used to control powdery mildew.
iii	Ozone-powdery mildew treatment	–	Ozone was used for powdery mildew and chemical fungicides for downy mildew.
iv	Mixed ozone-chemical treatment	–	The chemical treatment was applied in the most sensitive phenological stages and ozonated water in the rest, taking into account the level of risk of infection.
v	Ozone-chemical alternation treatment	B	Ozone and chemical treatments were alternated, taking into account the risk of infection indicated by the Monet platform.
vi	Harvest treatment with ozone	C	Conventional treatment based on chemical fungicides, except for one application at harvest with ozonated water.
vii	Conventional treatment	D	Chemical-only scenario that represents the conventional treatment. It was applied, as in treatments (i) and (ii), taking into account the risks foreseen by the Monet platform and the most sensitive phenological stages.

experiments, the success of ozone treatment depended on factors such as the application period and the chosen strategy, with (iii), (v) and (vi) being superior to (ii) and (iv) (Vázquez-Abal et al., 2022). However, additional in-depth agronomic studies should be conducted to identify the causes of the significant yield reductions in these scenarios.

Since the main objective of the system studied is the cultivation of grapes for wine production, the evaluation of the environmental sustainability of systems with significant yield losses (e.g., i, ii, and iv) is beyond the scope of the study, and environmental assessments were not conducted for them. Therefore, this study focuses on the evaluation of potential sustainability improvement by replacing chemical treatments with ozonated water for disease control, considering scenarios (ii), (v), (vi) and (vii). From this point on, the analyzed scenarios (ii), (v), (vi) and (vii) will be referred to as A, B, C and D, respectively (Table 1).

Apart from the different strategies used in the various scenarios, they all apply identical soil and aerial crop management practices. From a viticultural point of view, the first management activity of the season is pruning (winter pruning), which is carried out between November and January with the objective of improving vine regeneration by removing damaged or dry branches. Parallel to pruning, the vines are trellised by tying them with strips of wire coated with a biodegradable plastic material (30 coils·ha<sup>-1</sup>) on trellises to shape them and balance their vegetative development. Around January, the soil is plowed with a rotary tiller to remove the soil between the vines. This breaks up the compacted soil, oxygenates the soil and improves water absorption. The path between the trellises is covered with permanent vegetation, which is mowed four times a year, between January and May, with a tractor-mounted brush cutter to reduce competition from the plant cover on the vines and facilitate access for workers and machinery.

In spring, between March and June, the vineyard is fertilized in a single pass using a sprayer (Pulverizadores FEDE, Spain). The fertilizers applied include calcium nitrate (15.5% N) at a dose of 263 kg ha<sup>-1</sup>, magnesium nitrate (11% N) at 213 kg ha<sup>-1</sup>, a complex fertilizer at 70 kg ha<sup>-1</sup> (complex fertilizer, NPK 12-45-12) and 54 kg ha<sup>-1</sup> (complex fertilizer, NPK 8-5-44), and potassium nitrate (13% N) at 18 kg ha<sup>-1</sup>. During the same period, the shoots are pruned twice with a pruner attached to a tractor. This is done to prevent the shoots from growing longitudinally, favor grape development and facilitate the application of phytosanitary products.

Disease control is carried out between March and August, simultaneously with fertilization and top pruning, using a different approach depending on each scenario. As indicated above, the conventional treatment relies solely on chemical agents for disease control, while the other two strategies involve a combination of chemical plant protection products with ozone, varying the intensity of application, the period and the type of chemicals used. Table 2 summarizes the doses of chemicals and ozone applied per scenario. All treatments, whether chemical or ozone-based, are applied using a Fede Orange sprayer, but in separate units.

In ozone-treated scenarios, an ozone generator powered by tractor power is used to produce ozone through the application of high-voltage electrical discharges to air in a confined space. This process results in the dissociation of oxygen and the addition of an atom from another dissociated oxygen molecule, ultimately resulting in the formation of ozone. The ozone generator is attached to the sprayer, where ozone is combined with water and subsequently applied to the vineyards.

As a complement to winter pruning, green pruning was performed manually between June and August to regulate vine production, improve grape quality and minimize diseases and pests by removing shoots. Throughout the year, the vines were irrigated by drip irrigation to manage water stress, with a total of 180 m<sup>3</sup> of water used during the season studied. Finally, the season ended with the harvest in mid-September, using reusable plastic boxes to collect grapes with a capacity of 20 kg. Harvest yielded 9646 kg ha<sup>-1</sup> in A, 11,441 kg ha<sup>-1</sup> in B, 21,109 kg ha<sup>-1</sup> in C and 18,517 kg ha<sup>-1</sup> in D. Table 1 in the Supplementary Material details all field operations and related inputs.

**Table 2**

Summary of chemical fungicides and ozonated water used per scenario, including manufacturer and composition.

Fungicide/Ozone	Manufacturer	Composition	Unit	Dose applied per scenario			
				A	B	C	D
Collis SC	BASF	20% Boscalid, 10% Kresoxim Methyl (700 L H <sub>2</sub> O·ha <sup>-1</sup> )	L·ha <sup>-1</sup>	0	0.8	0.8	0.8
Microthio Special Dispers	KENOGARD	Sulfur 80% p/p (1000 L H <sub>2</sub> O·ha <sup>-1</sup> )	kg·ha <sup>-1</sup>	0	0	15.75	15.75
Flint Max	BAYER	50% Tebuconazole, 25% Trifloxystrobin (800 L H <sub>2</sub> O·ha <sup>-1</sup> )	kg·ha <sup>-1</sup>	0	0.4	0.4	0.4
Black rot Dynali	SYNGENTA	5,57% p/p (60 g L <sup>-1</sup> ) Difenoconazole, 2,79% p/p (30 g L <sup>-1</sup> ) Cyflufenamid (600 L H <sub>2</sub> O·ha <sup>-1</sup> )	L·ha <sup>-1</sup>	0	0	0.65	0.65
Electis	GOWAN	33% p/p Cyamoxanil, 33% p/p Zoxamide (600 L H <sub>2</sub> O·ha <sup>-1</sup> )	kg·ha <sup>-1</sup>	0.4	0.4	0.4	0.4
Profler	BAYER	66,67% Fosetyl-Al, 4,44% Fluopicolide (1143 L H <sub>2</sub> O·ha <sup>-1</sup> )	kg·ha <sup>-1</sup>	3	0	3	3
Zorvec Vinable	CORTEVA	Zorvec, Zoxamide [4% p/v (40 g L <sup>-1</sup> ) Oxathiapiprolin, 30% p/v (300 g L <sup>-1</sup> ) Zoxamide (750 L H <sub>2</sub> O·ha <sup>-1</sup> )	kg·ha <sup>-1</sup>	0.5	0	0.5	0.5
Enervin Duo	BASF	30% Ametoctradin (Initium), 22.5% Dimetomorph (700 L H <sub>2</sub> O·ha <sup>-1</sup> )	L·ha <sup>-1</sup>	0.8	0.8	0.8	0.8
Milraz Pro	BAYER	33% Cyamoxanil, 33% Zoxamide (600 L H <sub>2</sub> O·ha <sup>-1</sup> )	kg·ha <sup>-1</sup>	0.8	0.8	0.8	0.8
Ampexio	SYNGENTA	25% p/p (250 g kg <sup>-1</sup> ) Mandipropamid, 24% p/p (240 g kg <sup>-1</sup> ) Zoxamide (575 L H <sub>2</sub> O·ha <sup>-1</sup> )	kg·ha <sup>-1</sup>	1	0	1	1
Mildicut	BELCHIM	2.5% Cyazofamide (1125 L H <sub>2</sub> O·ha <sup>-1</sup> )	L·ha <sup>-1</sup>	4.5	4.5	4.5	4.5
Ampexio C	SYNGENTA	2.5% p/p (25 g kg <sup>-1</sup> ) Mandipropamid, 13.95% p/p (139.5 g kg <sup>-1</sup> ) Copper oxychloride (650 L H <sub>2</sub> O·ha <sup>-1</sup> )	kg·ha <sup>-1</sup>	0.5	0	0.5	0.5
Ozonate water	–	Ozonated water (900 L H <sub>2</sub> O·ha <sup>-1</sup> )	m <sup>3</sup>	12600	4.500	900	0

## 2.2. Environmental impact assessment

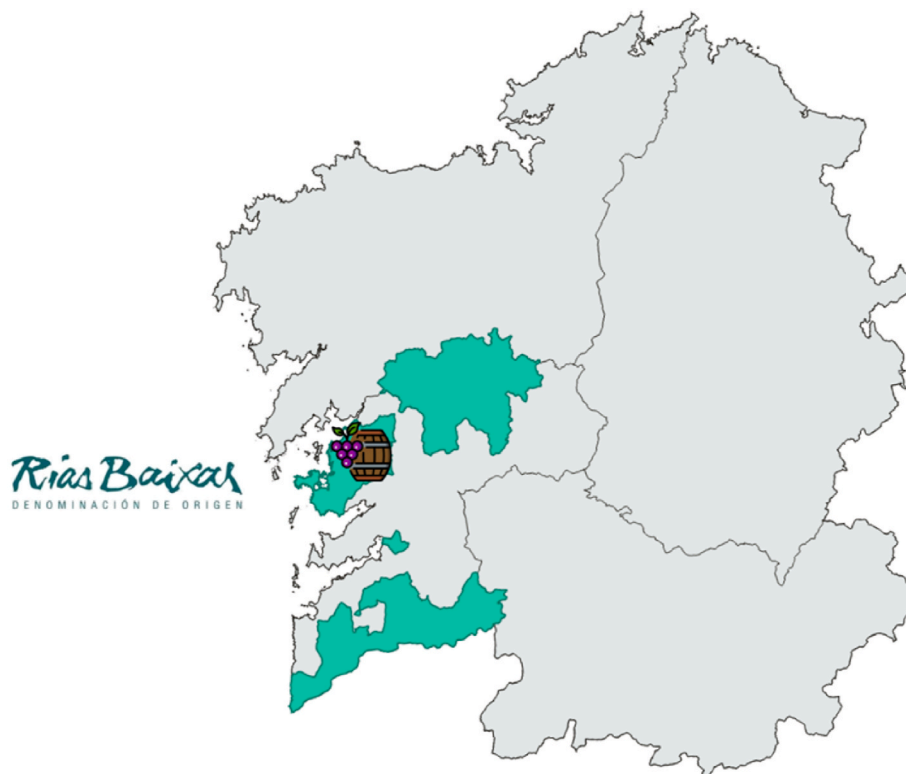
The environmental impacts of the scenarios studied were assessed using the attributional approach of the Life Cycle Assessment methodology. The following sections describe the different methodological phases according to ISO 14040 and 14044 (ISO, 2006a, 2006b).

### 2.2.1. Goal and scope definition

The objective of the environmental assessment is to determine whether the use of ozonated water for disease control improves the environmental sustainability of the viticulture system. Bearing in mind that the primary objective of the winery is to maximize grape production while minimizing environmental impact, the functional unit 1 kg of

grapes produced by the vineyard (FU1) was selected as main FU. However, since this FU penalizes agricultural systems with lower yields and favor those with higher yields (Nemecek et al., 2015; González-García et al., 2021), a complementary, land-based functional unit, 1 ha of managed land (FU2), was also selected. This second FU allows to identify the most environmentally sustainable agronomic practices without the influence of grape yields, thus providing a more comprehensive understanding of the environmental performance of the studied systems.

The vineyard system at the winery was analyzed using a cradle-to-gate approach (Fig. 2), ranging from the extraction of raw materials (e.g., water and fossil fuels), the manufacture and use of inputs (e.g., mineral fertilizers and fungicides), the manufacture of agricultural



**Fig. 1.** Map of the Galician region highlighting the Rías Baixas Designation of Origin in green, where the winery under study is located. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

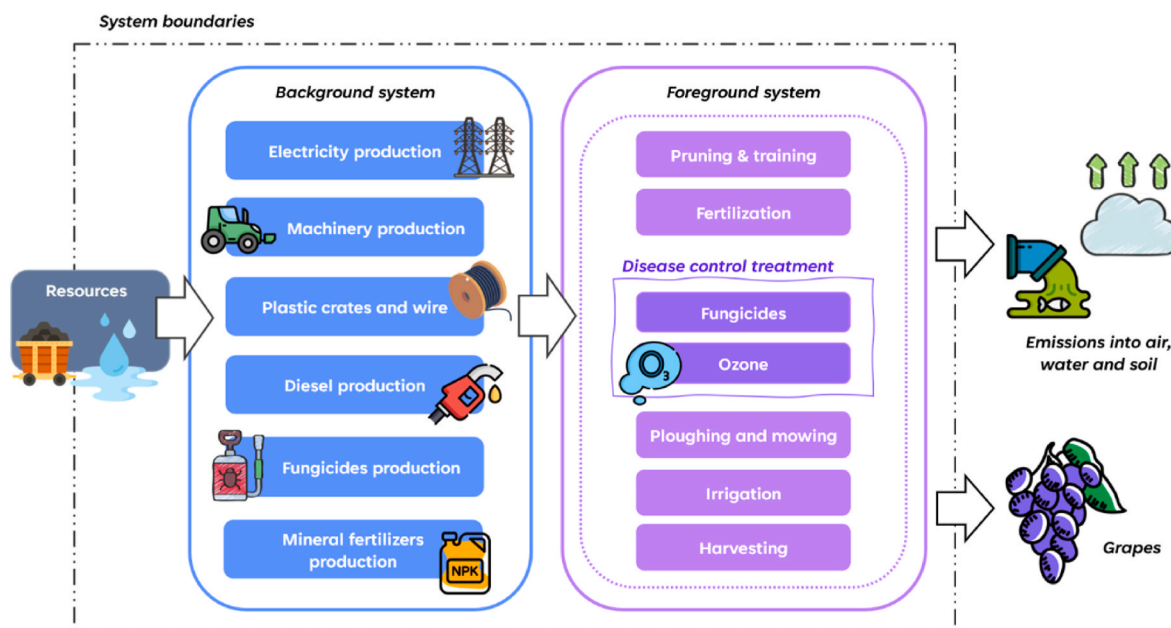


Fig. 2. System boundaries of vineyard with the main activities and processes considered.

machinery, its maintenance and final disposal, and operational activities up to the harvest of grapes. Although the establishment of the vineyard should be included in a cradle-to-gate system boundaries, its impact was assumed to be negligible in comparison to the annual operations. This is due to the fact that the vineyard is established only once, and the associated impact should be allocated to the lifetime of the vineyard, which can span several decades.

Moreover, no type of allocation was performed since only one product was obtained from the system.

### 2.2.2. Inventory analysis

The life cycle inventory was compiled using a combination of primary and secondary data. Primary data, which make up the foreground system (Fig. 2), were collected through a questionnaire delivered to the winery. These data included information on field operations, including types of operations, machinery models and intensity of use, as well as input consumption (e.g., water, fertilizer doses, diesel). On the other hand, secondary data were used to model processes that are outside the direct control of the winery, such as mineral fertilizer, fungicide, diesel and machinery production, as well as tire and tailpipe wear emissions. These data served as the basis for the background system and were obtained from ecoinvent® database version 3.9.1 (Wernet et al., 2016). In the case of the ozone generator, the instrument was modelled based on a generic water pump (water pump production, 22 kW GLO) dataset documented by ecoinvent. Further details on the ozone generator modeling can be found in the Supplementary Material.

In addition, several empirical models were used to estimate field emissions resulting from the application of mineral fertilizers and fungicides, decomposition of pruning residues left in the field, and land use changes. The Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (IPCC, 2019) were followed to quantify nitrous oxide ( $N_2O$ ) emissions from nitrogen-based fertilizers and pruning waste. In particular, both direct and indirect  $N_2O$  emissions, including nitrogen volatilization/deposition and leaching, were estimated. Emissions of ammonia ( $NH_3$ ) and nitrogen dioxide ( $NO_2$ ), resulting from the use of nitrogen fertilizers, were calculated according to the guidelines of the European Environment Agency (EEA) and the European Monitoring and Assessment Program (EMEP) (EMEP/EEA, 2019). In the case of  $NH_3$  emissions, they were estimated considering a slightly acidic soil pH (6.1–6.5) and a warm climate. In

addition, nitrate leaching ( $NO_3^-$ ) emissions were calculated using the (Faist et al., 2009) model, assuming a clay content of 15% and a vineyard root depth of 1.5 m (JJ. Cancela, personal communication, 2023), and an annual rainfall regime of 1210 mm (Meteogalicia, 2023). Fertilizer application also resulted in phosphate leaching and runoff emissions, which were estimated using the SALCA-P method developed by Agroscope, the Swiss agricultural research center (Prasuhn, 2006). For the emissions of various active ingredients associated with fungicides, the European Commission Product Environmental Footprint Category Rules (Commission, 2018) were used to assess their release to the air, water and soil compartments. Further details on the specific factors considered can be found in Table 2 of the Supplementary Material.

In regard to on-field emissions resulting from land-use changes, the study considered two types of emissions based on their source: emissions from indirect land use change (iLUC) and emissions from direct land use change (dLUC). The former refers to emissions resulting from the transformation of land use elsewhere as a result of the occupation of the land under study for grape production (Schmidt et al., 2015). Emissions were quantified using the methodology of Schmidt et al. (2015), which incorporated data on the amount and duration of land occupation, as well as the productivity capacity factor provided by Haberl et al. (2007). Finally, the production capacity of the region obtained was converted into  $CO_2$  equivalent emissions using a specific factor for agricultural land ( $0.042 \text{ t } CO_2\text{-pw ha}^{-1}\text{-y}^{-1}$ ). As for emissions from direct land use change, these are emissions resulting from the management practices applied to the land under study (Schmidt et al., 2015). The RothC 26.3 model was used in this case, and its detailed explanation will be provided in Section 2.3 on Carbon Sequestration Analysis.

### 2.2.3. Impact assessment

The environmental performance of the vineyard was evaluated across ten impact categories as considered to be relevant for the agriculture sector. The impact categories selected are as follows: Global Warming (GW), Stratospheric Ozone Depletion (SOD), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Terrestrial Ecotoxicity (TET), Freshwater Ecotoxicity (FET), Marine Ecotoxicity (MET), Mineral Resource Scarcity (MRS) and Water Scarcity (WS). Except for water scarcity, which was quantified using the AWARE (Available Water Remaining) method v1.04 (Boulay et al., 2018), the others were quantified using the ReCiPe 2016 v1.06

Hierarchist Midpoint World (2010) method (Huijbregts et al., 2017). The rationale for selecting the AWARE method for quantifying water scarcity is that, in contrast to ReCiPe method, which solely considers water consumption, the AWARE method considers both water consumption and the availability of water in the region where it is consumed. All impact categories were assessed using SimaPro software version 9.4 (PRé Sustainability, 2022).

### 2.3. Carbon sequestration analysis

Soil carbon sequestration includes both organic and inorganic carbon sequestration. This study focuses on soil organic carbon (SOC) sequestration, recognizing the scientific evidence underlining the prominent influence of land use and land-use change on the organic fraction (Food and Agriculture Organization (FAO, 2019b). Furthermore, organic carbon stocks are significantly more abundant than inorganic carbon stocks in temperate soils (FAO, 2019a).

Among the various models available to estimate SOC stocks, (e.g., DayCent, Century, Yasso, etc.), the RothC Carbon model v26.3 (Coleman and Jenkinson (1996) was selected for its simplicity and relatively easy access to the required site-specific data, but for its reliable and robust performance, as reported by Farina et al. (2013), FAO (2019a) and Shirato (2020). RothC simulates soil organic carbon dynamics under different environmental and management conditions through mathematical modeling of the soil processes involved (Coleman and Jenkinson, 1996). The model specifically measures five SOC compartments, four active compartments, e.g., decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO), and humified organic matter (HUM), and one inert compartment: inert organic matter (IOM), which is resistant to decomposition (Coleman and Jenkinson, 1996).

The RothC model function of the SoilR package (Sierra et al., 2012, 2014) was used to implement the RothC model through the RStudio software version 2023.09.0 Build 463. In addition, the georeferenced data was processed using QGIS software, version 3.28.10. To estimate the SOC sequestration potential of the different scenarios studied, the FAO modeling approach proposed in its *Technical Manual* was followed (Peralta et al., 2022). There, FAO describes three modeling steps that must be performed sequentially to determine the final SOC sequestration potential. A first "inverse" run of the model should be performed, in case direct soil measurements are not available, to determine the initial SOC levels (and the ratios between the different SOC compartments) at equilibrium under the given soil, climate, vegetation, and land management conditions in the simulated geographic location and time

period. In the initialization phase, the analytical solution was run for 2000 years under the assumption of constant soil, climate and management conditions. For this first run, climate and land use data for the period 1992–2000 were used, as well as SOC stocks for the year 2000 obtained from the FAO database, as specified in Table 3. Before determining the final SOC stocks, an additional initialization run was performed to update the SOC value obtained in the previous run (for the year 2000) to the starting year of the final simulation (2020) to reflect variations in climate and land use during the intermediate period (2001–2020). For this second run, climate data for the period from 2001 to 2020 were used, in addition to land use data for the period 2001–2020, the most recent available.

Finally, a "forward" run of the model was performed to simulate the evolution of the SOC population from the current time (understood as the time when the case study took place, i.e., the 2020/2021 season) to equilibrium, given the vineyard management in the scenarios evaluated. A period of 20 years was considered to be the time required to reach equilibrium, as recommended by the Intergovernmental Panel on Climate Change (IPCC) (FAO, 2019b), and no climate change variations were considered during this period. Monthly climate and land use maps from 2001 to 2020 were used in this last run. The data layers used in all stages of the modeling were the administrative boundaries of the study area (the province of Pontevedra, where the winery is located), the clay content of the topsoil (0–30 cm), and the monthly vegetation cover. Table 3 summarizes all data used in the modeling process. In addition, a more detailed description of the methodology used, and other valuable material can be found in Peralta et al. (2022). After modeling carbon stocks, the absolute SOC sequestration ( $\Delta \text{SOC}$ ,  $\text{t C}\cdot\text{ha}^{-1}$ ) in the soil was calculated by subtracting the estimated baseline SOC stock in 2020 (year 0) from the projected SOC stock in 2040 (year +20) (Equation (1)). Furthermore, the annual sequestration rate ( $\text{t C}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$ ) was determined by dividing the absolute SOC sequestration by the length of the simulated period (20 years) (Equation (2)).

$$\Delta \text{SOC} (\text{t C}\cdot\text{ha}^{-1}) = \text{SOC}_{t20} - \text{SOC}_{t0} \quad (\text{Eq. 1})$$

$$\text{Annual sequestration rate} (\text{t C}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}) = \Delta \text{SOC} / 20 \text{ years} \quad (\text{Eq. 2})$$

**Table 3**  
Summary of the input data used, specifying the modeling phase in which they were applied.

Data	Variables	Time series	Unit	Resolution	Modeling phase	Reference
Administrative limits	Pontevedra province	–	–	–	All	Xunta de Galicia (2023b)
Climatic data	Monthly temperature	1981–2000	°C	4 km	First initialization phase Forward & second initialization phases	TerraClimate (Abatzoglou et al., 2018)
		2000–2020	mm	4 km		
	Monthly precipitation	1981–2000	mm	4 km	First initialization phase Forward & second initialization phases	
		2000–2020	mm	4 km		
Monthly evapotranspiration	1981–2000	mm	4 km	First initialization phase Forward & second initialization phases		
	2000–2020	mm	4 km			
Soil data	Current soil organic carbon stock (SOC)	2000	t C·ha <sup>-1</sup>	1 km	First initialization phase	FAO (2020)
	Topsoil clay content (0–30 cm)	–	%	500 m	All	European Soil Data Center (ESDAC) (Ballabio et al., 2016)
Land use/cover	Monthly vegetation cover	2015–2020	–	–	All	NASA EOSDIS Land Processes Distributed Active Archive Center (2015)
	Land use/cover	1992–2000 2000–2020	– –	300 m 300 m	First initialization phase Forward & second initialization phases	Copernicus Climate Change Service and Climate Data Store (2019)

### 3. Results and discussion

#### 3.1. Environmental impact profile

##### 3.1.1. Overall profile

Since the main goal of the winery is to achieve high yields of grapes for winemaking, the evaluation of the environmental yield per unit of production (FU1) is crucial. This approach is key to identifying scenarios with minimal environmental impact per unit, allowing the winery to achieve a balance between productivity and environmentally sustainable practices. According to the FU1-based environmental assessment (see Fig. 3), Scenario C demonstrated the lowest environmental impact per kg of grapes harvested and therefore shows the best environmental performance. It is closely followed by Scenario D, with slight variations depending on the impact category. Scenario A shows the worst environmental performance, while Scenario B falls in between.

The scenarios that heavily relied on chemical fungicides (C and D) exhibited higher yields (21,109 kg ha<sup>-1</sup> and 18,517 kg ha<sup>-1</sup>, respectively) compared to those using ozonated water more extensively throughout the season (A and D), which yielded 9646 kg ha<sup>-1</sup> and 11,441 kg ha<sup>-1</sup>, respectively. These agronomic findings suggest that the use of ozonated water as a technique for disease control has proven to be ineffective, resulting in a substantial decrease in grape yields. Specifically, Scenario A experienced an average yield reduction of 51%, while Scenario B had an average yield reduction of 42%.

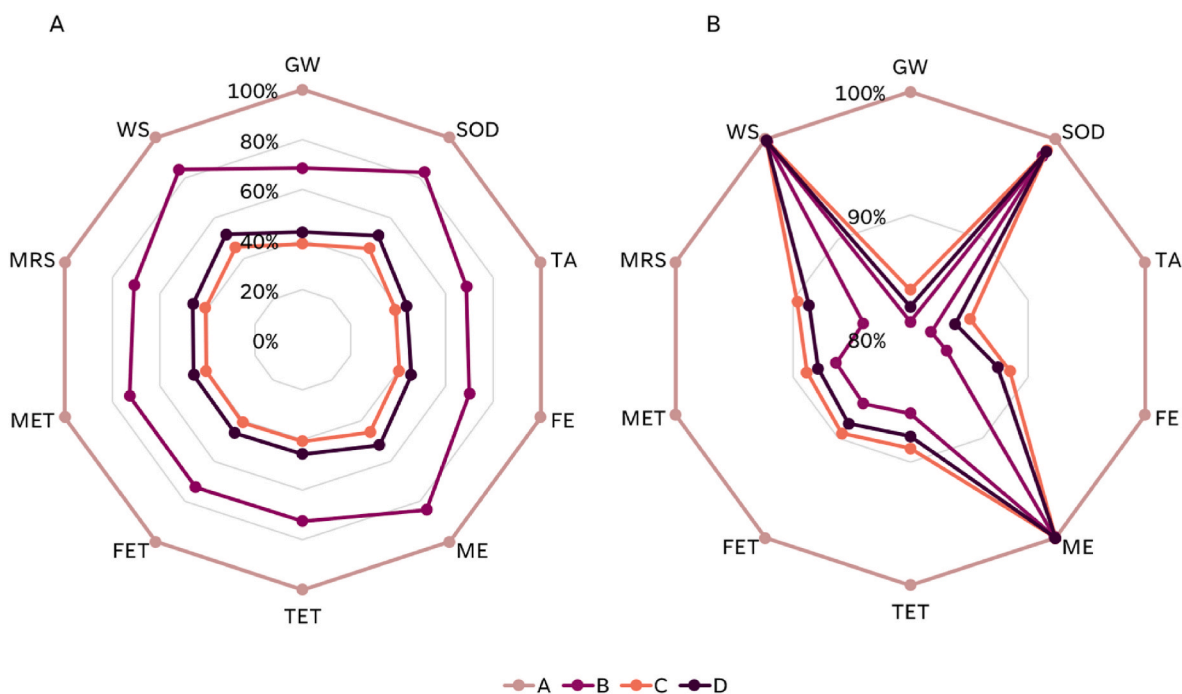
From an environmental perspective, the reduction in grape yield had a significant influence on the environmental performance per kg of grapes, with the higher yield scenarios showing a better environmental performance than the lower yield scenarios, as expected. This aligns with Vázquez-Rowe et al. (2012) findings, which emphasize the large dependency of environmental outcomes on vineyard productivity. Falcone et al. (2016) also reported similar conclusions when comparing conventional and organic vineyards, in addition to González-García et al. (2021) and Lago-Oliveira et al. (2023) while assessing several wheat-based crop rotation regimes.

When assessing the environmental impacts from a land management perspective (i.e., considering 1 ha of managed land as functional unit; FU2), scenario B presents the most favorable environmental profile (Fig. 3), while scenarios C and D exhibit a decline in performance. By evaluating scenarios based on FU2, the environmental burdens are exclusively attributed to the agricultural practices, disregarding any influence from grape yields. Therefore, the discrepancies from the results under FU1 rely mainly on the fact that scenario B uses a lesser amount of fungicides (a total of 7.7 kg compared to 10.4 kg in C and D, and 8.5 kg in A) and embodied water (a total of 6625 kg compared to 13,917 kg in C and D, and 7318 kg in A), while maintaining similar frequency of disease control passes as C and D. Scenario A consistently presents the worst environmental profile irrespective of the selected functional unit, owing to its significantly higher number of disease control operations (24 disease control passes compared to 11 on C, and 10 in B and D; see Table 1 in the Supplementary Material). The absolute environmental impacts for FU1 and FU2 are shown in Tables 3 and 4 in the Supplementary Material.

It is worth mentioning that the present study was conducted during a particularly rainy year, which required increased fungicide application in response to increased fungal proliferation. In drier years with lower fungal incidence (García Castellanos et al., 2022), it is possible that the disparity in yield performance between scenarios could be reduced, potentially leading to more favorable outcomes for scenarios using ozonated water in terms of both agronomics and environmental sustainability. In this line, the application of ozone treatment in arid regions should be further investigated to find out its potential effectiveness under these conditions.

##### 3.1.2. Contributing parameters to the environmental impact

Upon examination of the factors contributing to the environmental profile (Figs. 4–6), it was identified that field operations and fertilization are two significant factors. The contribution of field operations is particularly noteworthy in GW, MRS, TA, and FE. SOD and ME are largely affected by on-field emissions derived from fertilizer application.



**Fig. 3.** Comparative environmental profile (%) per scenario (A, B, C, and D) based on a productive functional unit (shown in the diagram on the left; A), and a land management functional unit (shown in the diagram on the right; B). Acronyms: Global Warming (GW), Stratospheric Ozone Depletion (SOD), Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Terrestrial Ecotoxicity (TET), Freshwater Ecotoxicity (FET), Marine Ecotoxicity (MET), Mineral Resource Scarcity (MRS) and Water Scarcity (WS).

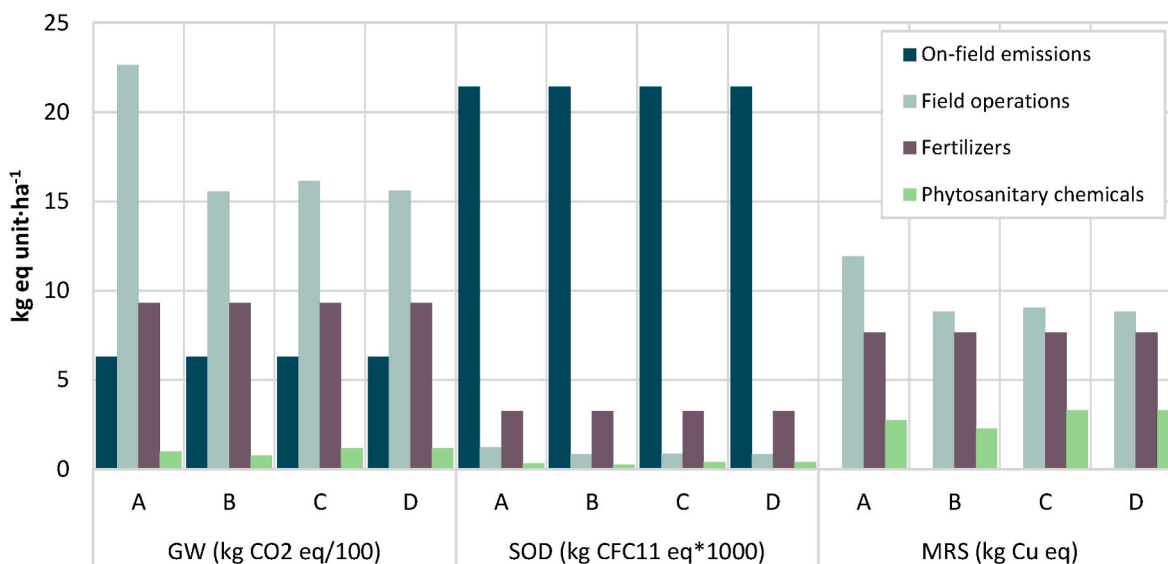


Fig. 4. Distribution of environmental impacts among the factors involved and by scenario. Acronyms: Global Warming (GW), Stratospheric Ozone Depletion (SOD), Mineral Resource Scarcity (MRS).

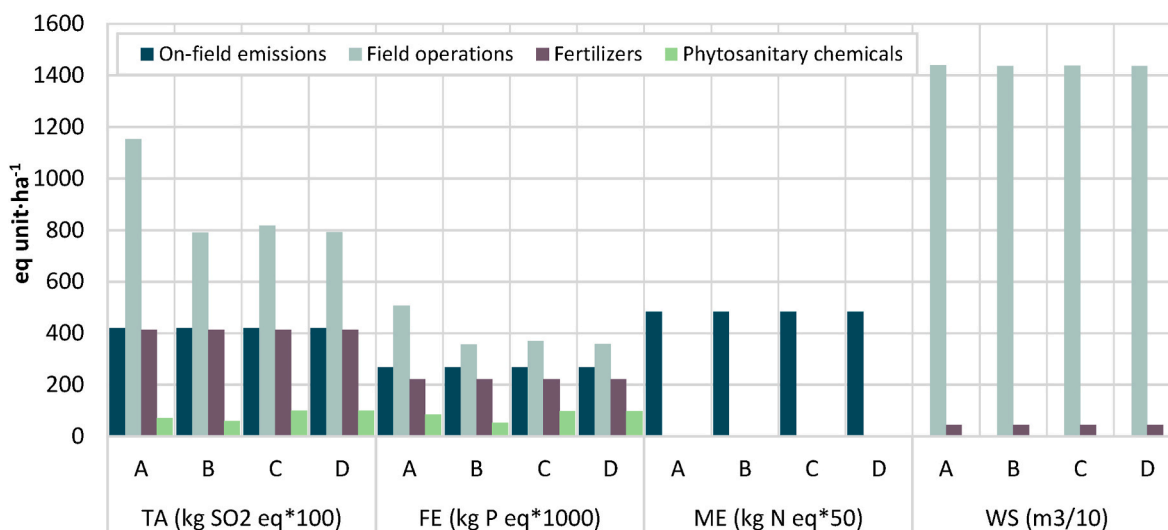


Fig. 5. Distribution of environmental impacts between involved factors and per scenario. Acronyms: Terrestrial Acidification (TA), Freshwater Eutrophication (FE), Marine Eutrophication (ME), Water Scarcity (WS).

Moreover, fertilizer production is the primary contributor to toxicity impact categories (e.g., TET, FET, MET), and irrigation to water scarcity.

Within field operations, emissions from diesel combustion have a major impact on the environmental profile. Specifically, CO<sub>2</sub> emissions contribute to GW, while NO<sub>x</sub> and SO<sub>2</sub> emissions are responsible for the impact on TA. The production of machinery also consumes metals (nickel, iron) that affect MRS, and emits several pollutants that impact FE (COD, BOD<sub>5</sub>). The latter originate from the extraction and refining of metals that are required for machinery production. During the extraction process, organic and inorganic substances are released into the water, increasing the oxygen demand in water bodies (COD, BOD<sub>5</sub>). Additionally, field operations contribute to the impact on toxicity categories due to the emission of various metals during machinery production, including chromium, copper, and zinc, and particularly nickel, which results from the manufacture of steel coils (used for tying vines).

In examining the factors behind the impact associated to phytosanitary application operations, the production of agricultural machinery, including tractors and tillage items, represents a primary contributor to

the categories of MRS and toxicity, and the responsibility for the impact on FE is shared between the production of agricultural machinery and diesel.

In the case of ozone treatment, the factor that can contribute to the environmental impact is the production and disposal of the ozone generator, since the energy required is obtained from the tractor's engine power, it uses air as a raw material, and the ozone itself decomposes rapidly, typically within minutes to hours, reverting to oxygen and leaving no residual pollutants. Moreover, as with the other agronomic activities in which the tractor is used, diesel consumption and tractor use can also influence the environmental profile. In this sense, the results indicate that the production (including maintenance and end-of-life disposal) of the ozone generator instrument has a negligible influence on the environmental profile of the phytosanitary application activity compared to the predominant factors: the production of agricultural machinery and diesel (Figure 1 in the Supplementary Material). It is possible that the assumptions made in the modeling of the ozone generator instrument may lead to changes in the distributional shares of

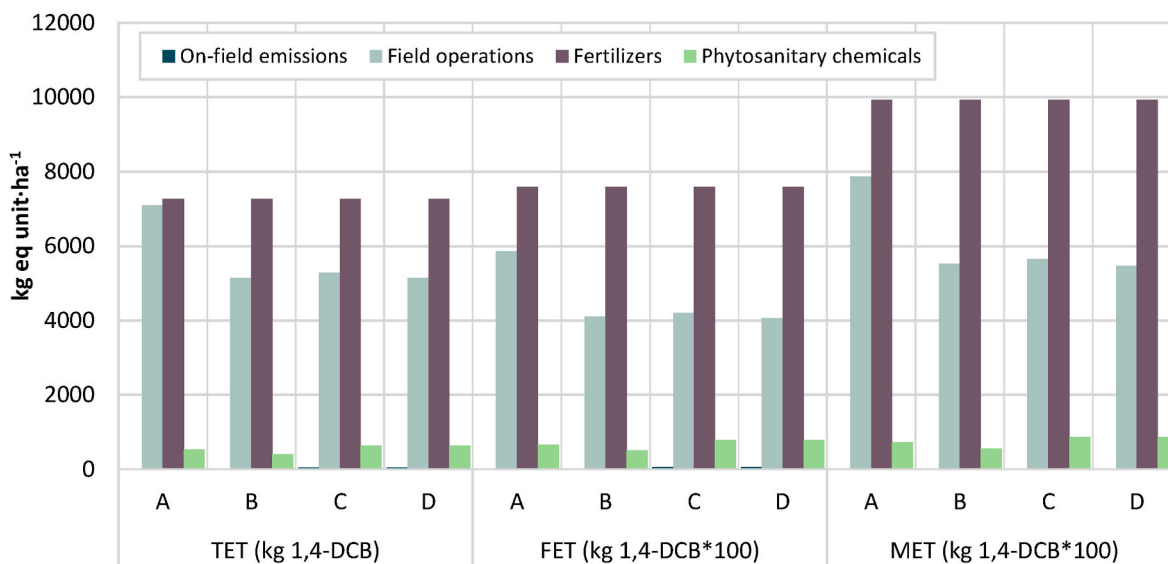


Fig. 6. Distribution of environmental impact between involved factors and per scenario. Acronyms: Terrestrial Ecotoxicity (TET), Freshwater Ecotoxicity (FET), Marine Ecotoxicity (MET).

the impact contributions. However, given the relatively greater influence of other factors, it seems unlikely that these changes will result in the displacement of the most important factors identified.

Vázquez-Rowe et al. (2012), García Castellanos et al. (2022), and Fusi et al. (2014) identified diesel consumption as a major burden on vineyards. Moreover, Falcone et al. (2016) noted that frequent pesticide application resulted in high environmental impact due to the intensive use of machinery (e.g. tractors, sprayers) and associated combustion emissions. This is consistent with the present study, where disease control operations occur with high frequency and are responsible for most of the contribution from field operations. Similarly, Villanueva-Rey et al. (2014) and Volanti et al. (2022) identified diesel production and consumption as the main critical point in grape production and stated that it was highly dependent on pesticide application.

On-field emissions include those from the application of mineral fertilizers, pesticides (fungicides), the decomposition of pruning residues, and emissions resulting from iLUC. Of these, emissions from mineral fertilization have the greatest impact on the environmental profile, particularly on SOD due to the release of  $N_2O$  into the air and on ME due to nitrate leaching. In fact, as noted by Müller (2021) and Solomon (2021), the application of nitrogen-based fertilizers in agriculture has substantially increased atmospheric  $N_2O$  emissions, posing a threat to the stability of the stratospheric ozone layer.

In addition,  $N_2O$ ,  $NH_3$ , and phosphate emissions from fertilization also affect GW, TA, and FE, although, consistent with other studies, there are discrepancies as to whether fertilization or field operations are primarily responsible for the environmental impacts in these categories. Some argue that fertilizer use and production is the largest contributor to GW, while diesel combustion plays a more limited role (Casson et al., 2022). In contrast, another study stated that diesel burning from field operations is primarily responsible for the largest share of environmental impact across all impact categories, while fertilization (both use and production) and pesticide emissions are reported as the second most relevant hotspot (Vinci et al., 2022). The relative dominance of one factor over the other may depend on the balance between the frequency of field operations, specifically pest and disease management operations, and the dose and type of fertilizers administered. In this regard, Litskas et al. (2020) reported that high-dose fertilizer scenarios showed mainly fertilizer-related impacts, with diesel ranking second, while scenarios with organic or low-dose fertilizers revealed that diesel consumption was the main concern. On the other hand, as pointed out by Lago-Oliveira et al. (2023), environmental results are site-dependent,

meaning that area-specific climatic, hydrological and edaphic conditions influence the type and frequency of agricultural practices, which may partly explain the discrepancies between studies. Although it may vary which of the two factors is dominant in the environmental profile of the vineyard, the crucial point is that both play a vital role and should be taken into account in the formulation of improvement strategies.

Fertilizer production has a relevant contribution to the impact categories related to toxicity due to the release of copper, zinc, chromium and nickel into air and water. This parameter also affects the remaining impact categories (GW, SOD, MRS, TA, and FE) to varying degrees, with the exception of ME. These findings align with the results reported by García Castellanos et al. (2022), who concluded that fertilizer production significantly influenced all categories related to toxicity, in line with Rouault et al. (2020).

Regarding irrigation, this practice is recognized as the main contributor to SS, while water consumption in disease control practices, either for fungicide or ozone application, and in fertilizer production has negligible implications. This conclusion is supported by Volanti et al. (2022), which claims that the embodied water in other non-irrigation processes did not significantly impact WS.

The impact of producing and using fungicides is minimal across all impact categories, with only minor contributions to MRS, FE, TA, TET, FET, MET, and GW. This finding is consistent with the results of Fusi et al. (2014), who also concluded that pesticide application was not significant, even after conducting sensitivity analysis. On the other hand, several studies, some located in Galicia, found a significant impact of pesticide emissions on ecotoxicity (Vázquez-Rowe et al., 2012; Villanueva-Rey et al., 2014; Vinci et al., 2022). Specifically, the use of copper, folpet, glyphosate, and terbuthylazine was reported to play a major role in these impact categories, while the use of other plant protection products in similar amounts did not have a substantial contribution. This may partly explain why pesticide emissions were not relevant in this study, as the pesticides linked to higher levels of toxicity were either not used or used in significantly reduced concentrations, such as copper in the form of Amplexio C.

The negligible impact of fungicides compared to other factors, such as field operations and fertilization, may suggest that there is no need to focus on alternative disease control strategies to replace chemical fungicides and improve the overall environmental performance of the vineyard. However, it is crucial to identify the limitations of fungicide modeling and impact assessment before reaching any conclusions.

Regarding fungicide modeling, it should be noted that it is currently

somewhat limited due to the absence of some fungicides in the ecoinvent database, in addition to the fact that the ReCiPe method does not consistently consider some active ingredients involved in impact characterization, as evidenced by a characterization factor (CF) of zero for such substances. To address these limitations, efforts have been made to improve the modeling by utilizing the chemical family to which the compound belongs when specific data is unavailable, and by using the generic process “pesticide production, unspecified” provided by the ecoinvent database when no other data is available.

In addition, there is substantial evidence to suggest that fungicide use can have a significant impact on biodiversity by indiscriminately damaging non-target species, leading to their decline and the degradation of associated ecosystem services. (e.g. pollination, natural pest/disease control, and nutrients cycling, among others). For instance, [Cornejo et al. \(2020\)](#) conducted a study on the effects of chlorothalonil fungicide on detritivores invertebrate communities, whose results indicated a significant decline in both invertebrate population and taxon diversity, leading to a notable decrease in the rate of litter decomposition. Insect pollinators are also significantly affected by exposure to these substances, exhibiting substantial reductions in population levels after such exposure ([Fisher et al., 2023](#)). Moreover, [de la Cruz et al. \(2022\)](#) pointed out that non-target soil fungi are threatened by applied fungicides (isopyrazam and triticonazole) and argued that this threat extends beyond agricultural fields to surrounding areas due to spray propagation. In a parallel field study, a higher abundance of soil microbiota was revealed in areas where a combination of ozonated water and chemicals was used for disease control, compared to those areas where only phytosanitary chemicals were applied ([Bodegas Martín Codax, 2022](#)). Consequently, the impact of fungicides and other alternative disease control treatments on biodiversity should be assessed, which could result in higher impacts than those obtained here. As there are currently no LCA indicators to measure these effects, the only thing that is clear at this point is that the frequency of disease control applications has a significant impact on environmental performance, and therefore it is critical to consider this factor when developing pest and disease control strategies.

### 3.2. SOC sequestration

To evaluate the global environmental sustainability of human activities, ecosystem services that support those activities shall be considered in the environmental assessment. The present study specifically focusses on the SOC sequestration potential of the vineyard and in its capacity to mitigate climate change. To estimate SOC sequestration potential, the absolute SOC sequestration and corresponding annual sequestration rate were calculated for the period of 2020–2040, as detailed in the Methodology section. No differences were found among the scenarios since they all implement the same soil management practices, such as the type of tillage operations and quantity of pruning residues returned to the field. As is depicted in [Fig. 7](#), and in more detail in [Table 5](#) of the Supplementary Material, the analyzed vineyard is estimated to sequester 0.8 tons of SOC per year, resulting in a saving of 2817 kg of CO<sub>2</sub> eq emissions per hectare and year. By balancing the total carbon dioxide emissions released by the vineyard activities with the annual carbon sequestration, the global warming impact is estimated to be reduced by 72%–87%, depending on the scenario.

The carbon sequestration rate obtained is comparable to that of [Schultz \(2022\)](#) for a vineyard in Germany using the RothC model (0.75 t C·ha<sup>-1</sup>·y<sup>-1</sup>). However, the SOC stock estimated in the present study (109 t C·ha<sup>-1</sup>·y<sup>-1</sup>) differ from those reported by [Calvo de Anta et al. \(2020\)](#) for croplands in temperate regions and acid soils that received organic amendments (ranging from 120 to 200 t C ha<sup>-1</sup>, between 37% and 120% more than quantified here). Along these lines, numerous studies indicate that agricultural soils around the world have significant potential to increase their carbon sequestration. In a global analysis of recalcitrant carbon saturation in soils, [Georgiou et al. \(2022\)](#) estimated that soils are at 18% of their maximum capacity in the Galician region. A study focused specifically on Galicia showed that croplands had 30–50% less carbon stocks compared to soils in natural areas with similar climate and lithology ([Macías and Camps Arbustain, 2010](#)). Furthermore, according to a study conducted by [Miguéns et al. \(2007\)](#) in Galician vineyards, soil organic matter content in these areas was considerably lower than that of soils in their natural state (86% less).

This context provides an opportunity to increase carbon stocks in soil and mitigate climate change by implementing appropriate practices that



**Fig. 7.** Representation of the impact of global warming with and without the annual SOC sequestration (GW1 and GW2, respectively) for each scenario (A, B, C, D) and level soil practices performed (BAU, SP1, SP2, SP3). BAU refers to the current scenario without modifications in soil management, while SP1, SP2, and SP3 correspond to the simulated scenarios where more sustainable soil practices are implemented (first, second, and third level of sustainable practices, respectively).

increase carbon inputs and prevent soils from being a source of CO<sub>2</sub> emissions (Ontl and Schulte, 2012; FAO, 2017c). Numerous sustainable soil practices can aid in achieving this objective, including strategies that aim to decrease SOC loss through conservation or no-tillage, the use of cover crops or fallow periods, those that strive to increase production by minimizing nutrient and soil losses, ensuring water availability, and implementing balanced and organic fertilization (FAO and ITPS, 2021; Jordan and Smith, 2022; Tao et al., 2023). Additionally, these practices should aim to increase organic carbon matter in soils through the management of crop remnants, the application of carbon-rich amendments, the use of mulches and permanent covers, among other methods (FAO, 2017a, 2017b; Costantini et al., 2020).

To evaluate the potential benefits of adopting the aforementioned practices in the vineyard, the carbon sequestration potential of the vineyard under those practices was computed using the FAO protocol (Peralta et al., 2022). Accordingly, it was assumed an increase in carbon input of 5%, 10%, and 20% resulting from the application of different types of practices at varying intensities. SP1 represents the soil practices with the lowest increase in carbon input (level 1), while SP3 corresponds to the soil practices associated with the highest carbon input increase (level 3), and in the middle lies SP2 (level 2). Fig. 7 depicts the changes in GW under the three enhanced soil practices (SP1, 5%; SP2, 10%; SP3, 20%). In addition, further details are available in Table 5 in the Supplementary Material. As it can be seen, if implemented, the mentioned management practices could potentially raise SOC stocks in the vineyard by as much as 1 ton per year. Moreover, some of these practices could notably contribute to mitigate the impact of viticulture on global warming by offsetting all related emissions and possibly achieving a net-positive carbon sequestration, as evidenced by the SP3 and SP2 in Fig. 7, except for scenario An under SP2.

Increasing soil carbon content can provide a range of ecosystem services beyond climate change mitigation, such as preventing soil erosion, improving water retention, cycling nutrients, and enhancing overall soil fertility (FAO, 2019b, 2017c; Moinet et al., 2023). As the provision of these services has a direct and positive influence on food yields, farming practices that boost SOC stocks are also crucial in promoting food security (Amelung et al., 2020; Ontl and Schulte, 2012). Furthermore, soil organic matter (SOM) is associated with pollution control since it prevents runoff of sediments, pesticides and nutrients to water bodies (Corsi et al., 2012), as well as retains pollutants through different physico-chemical mechanisms (Ćwieląg-Piasecka, 2023; Ukal-ska-Jaruga et al., 2023). Thus, improving SOC could also lower fungicide residues in the vineyard environment, comprising soil and water, by favoring their retention in SOM, and ultimately alleviate toxicity-related impact categories (TET, FET, and MET).

#### 4. Conclusions

The present study assessed the environmental sustainability of replacing chemical disease control with ozonated water in vineyards. Seven scenarios, with various combinations of alternative (ozonated water) and conventional (chemical fungicide) treatments, were analyzed. These scenarios ranged from complete adoption of the innovative method to some solely using chemical control, and others using a combination of both methods. The findings show that implementing ozonated water leads to a substantial reduction in yield and, subsequently, a greater environmental impact per kilogram of grape production compared to conventional treatment scenarios. In fact, three scenarios, one relying solely on ozonated water and the other two using a combination of methods, experienced almost complete loss of their harvest due to fungal infestations. Upon land management analysis, one of the scenarios that combines both techniques and did not suffer from complete harvest loss (scenario B) outperformed conventional scenarios due to its limited fungicide dosage and fewer disease control passes. On the other hand, the other scenario that uses both techniques (ozone and chemicals) and neither lost all its harvest, remained the worst profile

due to its higher frequency of disease control operations.

Diesel combustion from field operations, particularly disease control activities due to their higher frequency, the use and production of fertilizers and irrigation were found to be the primary factors affecting the environmental profile of the vineyard. Conversely, the impacts of fungicide use, and production were negligible regardless of the impact category. Thus, it is concluded that replacing chemical fungicides with ozonated water may not be as beneficial as initially anticipated due to the lower yields, the increased disease control frequency in certain cases, and the relatively low contribution of fungicides to the impact. However, further investigation is necessary to assess the impact of chemical fungicides on biodiversity, as there is substantial scientific evidence to suggest that they may have significant effects that are currently not being considered within the environmental assessment.

In addition to the environmental impact, the carbon sequestration capacity of the vineyard was analyzed to obtain a more accurate assessment of sustainability. It was demonstrated that while the vineyard sequesters carbon annually, it falls short to mitigate all its global warming impact. Furthermore, results shows that there is significant potential for improvement if the vineyard adopts more appropriate soil management strategies, which could enable the vineyard to reach a carbon-neutral state, and even sequester more carbon than greenhouse gases emit. Furthermore, in line with the environmental impact assessment, additional research is necessary to explore other ecosystem services that may support the vineyard, in order to obtain a more comprehensive and accurate understanding of the analyzed agricultural system.

#### CRedit authorship contribution statement

**Sara Lago-Oliveira:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Javier J. Cancela:** Writing – review & editing, Data curation. **Miguel Tubío:** Funding acquisition, Data curation. **Helena Feijoo Moreira:** Formal analysis. **Maria Teresa Moreira:** Writing – review & editing, Supervision. **Sara González-García:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Conceptualization.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2024.143999>.

## Data availability

Data are provided in the main document and in the supplementary material.

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