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Prospective life cycle assessment of viticulture under climate change scenarios, application on two case studies in France

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Abstract

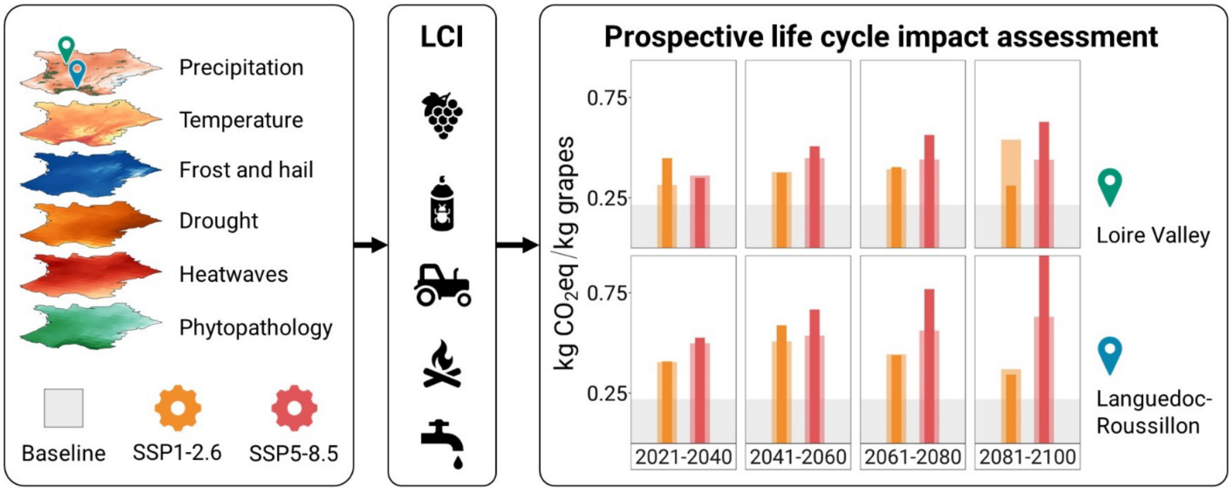
Viticulture needs to satisfy consumers' demands for environmentally sound grape and wine production while envisaging adaptation options to diminish the impacts of projected climate change on future productivity. However, the impact of climate change and the adoption of adaptation levers on the environmental impacts of future viticulture has not been assessed. This study evaluates the environmental performance of grape production in two French vineyards, one located in the Loire Valley and another in Languedoc-Roussillon, under two climate change scenarios. First, the effect of climate-induced yield change on the environmental impacts of future viticulture was assessed based on grape yield and climate data sets. Second, besides the climate-induced yield change, this study accounted for the impacts of extreme weather events on grape yield and the implementation of adaptation levers based on the future probability and potential yield loss due to extreme events. The life cycle assessment (LCA) results associated with climate-induced yield change led to opposite conclusions for the two vineyards of the case study. While the carbon footprint of the vineyard from Languedoc-Roussillon is projected to increase by 29% by the end of the century under the high emissions scenario (SSP5-8.5), the corresponding footprint is projected to decrease in the vineyard from the Loire Valley by approximately 10%. However, when including the effect of extreme events and adaptation options, the life cycle environmental impacts of grape production are projected to drastically increase for both vineyards. For instance, under the SSP5-8.5 scenario, the carbon footprint for the vineyard of Languedoc-Roussillon is projected to increase fourfold compared to the current footprint, while it will rise threefold for the vineyard from the Loire Valley. The obtained LCA results emphasized the need to account for the impact of both climate change and extreme events on grape production under future climate change scenarios.

Keywords: Climate change, Life cycle assessment, Environmental impacts, Viticulture, Prospective LCA

Highlights:

- Proposed approach for assessing environmental impacts of viticulture under climate change.
- Climate-induced yield changes point in opposite directions in the case studies.
- Future life cycle impacts of grape production are projected to increase.
- Potential adaptation levers are assessed.
- Extreme events are key determinants of the environmental impacts of future grape production.

Graphical abstract



1. Introduction

1.1. The issue of the effects of climate change on agriculture and its environmental consequences

Agricultural systems are an integral part of the 2030 Agenda for Sustainable Development, a global engagement to eliminate hunger and poverty, and at the same time guarantee a decrease in socioeconomic and environmental impacts (Sala et al., 2017). However, this goal constitutes a prominent challenge since agriculture causes considerable environmental impacts, being a key contributor to land-use change, biodiversity loss, pollution of terrestrial and aquatic ecosystems, depletion of freshwater resources, and climate change (Springmann et al., 2018). Greenhouse gas (GHG) emissions from Agriculture, Forestry, and Other Land Use (AFOLU) activities represent 23% of total anthropogenic GHG (IPCC, 2021), and it has been estimated that climate change has caused a loss of agricultural productivity of around 21% since 1961 (Ortiz-Bobea et al., 2021). Hence, agriculture is a major contributor to climate change, while concurrently being affected by it. Climate change affects agricultural systems in direct and indirect ways. Direct impacts correspond to changes in abiotic factors, namely the effects of increased atmospheric CO_2 concentration and temperature, and changes in precipitation regimes, as well as the impact of extreme weather events such as hail, heatwaves, and flooding on crop yield. Indirect impacts are related to changes in environmental conditions such as the timing of weeds, pests and diseases, irrigation needs, and changes in soil organic matter (Niero et al., 2015a; Ortiz-Bobea et al., 2021). Besides ambitious mitigation policies to limit global warming to 1.5 °C above the pre-industrial level, adaptation strategies will be required in the agricultural sector due to substantial shifts in the local climate for the coming decades (IPCC, 2018). For this reason, evaluating the environmental impacts of agriculture under future climate conditions constitutes a pressing need to devise adequate mitigation and adaptation strategies for the forthcoming years (Lee et al., 2020; Sala et al., 2017).

Life cycle assessment (LCA) is a holistic method that quantifies the potential environmental impacts of a product or service throughout its entire life cycle, from raw material extraction to end of life (ISO, 2006a, 2006b). LCA has been recognized as a crucial decision-making tool to enhance the environmental performance of agricultural systems (Sala et al., 2017). Furthermore, combining LCA and future-scenarios thinking has been recently advocated in change management and decision-making to tackle global environmental challenges, since LCA facilitates anticipating the potential environmental impacts of novel technologies and products (Bisinella et al., 2021) or assessing them under future environmental conditions (Sala et al., 2017). Three future-oriented LCA studies have explored the environmental impacts of agricultural systems under projected climate change scenarios (Garba et al., 2014; Lee et al., 2020; Niero et al., 2015a). Garba et al. (2014) coupled a crop system model and LCA to investigate the future GHG emissions from corn and soybean production in Gainesville, Florida under projected changes in temperature, precipitation, and CO_2 concentrations. Niero et al. (2015a) evaluated the future environmental impact of spring barley based on the results of experiments simulating future Danish climate. Another study applied machine learning to investigate county-level global warming and eutrophication impacts of corn production for the period 2022-2100 across U.S. Midwest states according to four climate change scenarios ranging from “high emissions or business-as-usual” to “low emissions or strong mitigation” pathways (Lee et al., 2020).

1.2. Grapevine context and specificities

Grapevine (*Vitis vinifera*) is a widely grown perennial crop: as of 2019, it covered an area of 7.3 million hectares and produced 85 million tons of grapes (OIV, 2022). Moreover, viticulture and winemaking constitute an important cultural legacy both economically and socially in many parts of the world (Santillán et al., 2019). Nevertheless, like any economic activity, viticulture and winemaking have an impact on the environment. For instance, in France in 2011, vineyards were responsible for 20% of the pesticides used, while they accounted for only 3.7% of cultivated land (Ugalde et al., 2021). Pesticides lead to multiple environmental concerns such as surface and groundwater pollution, as well as to potential ecotoxicological and toxicological impacts resulting from their fate in the air, water, and soil compartments (Beauchet et al., 2019; Renaud-Gentié et al., 2015; Viveros Santos et al., 2018). These environmental concerns have raised the need for efficient and environmentally sound control of diseases and pests despite difficult climatic conditions (Beauchet et al., 2019; Marín et al., 2021). Adaptation to climate change is another major challenge facing the viticulture sector since climate change has already caused the advancement of harvest dates, a rise of disease in wetter regions, recurrent water stress in Mediterranean vineyards, wines deficient in freshness and aromatic composition, and an excessive increase in alcohol content, loss of production due to more frequent extreme events, and an increased concern for spring frost damage in some winegrowing regions (Leolini et al., 2018; Marín et al., 2021; Santillán et al., 2019; Santos et al., 2020; van Leeuwen et al., 2019). However, the projections of European grapevine productivity point in both directions. Increased dryness across southern regions will favour decreased yields, while increased CO_2 may partially compensate for dryness effects, leading to yield increases in central and northern Europe (Fraga et al., 2016; van Leeuwen et al., 2019). Additional concerns are related to repercussions on profits and production costs through the logistics network (Sacchelli et al., 2017) and to potential changes in the suitability of land for viticulture (Moriondo et al., 2013).

Because of the potential negative impacts of climate change on grape yields, as well as on major crops, namely wheat, rice, maize, and soybean, several studies have addressed this question by employing statistical models and process-based crop models (Fraga et al., 2016; Kukal and Irmak, 2018; Lobell and Burke, 2010; Moriondo et al., 2015; Zhao et al., 2017). Statistical regressions have been used to relate time series of crop yield to changes in selected climate variables. More specifically, detrending methods have been employed in regression models to eliminate the influence of non-climatic factors such as genetic improvements, crop and soil management advancements, and technological improvements (Kukal and Irmak, 2018; Zhao et al., 2017). It has been shown that statistical models reproduce well the process-based model responses to changes in temperature. Besides, regression models seem to be more suitable for wider geographical scales of analysis, which is in line with the scales at which climate projections are more available and reliable (Lobell and Burke, 2010). In the case of grapevines, various process-based models have been developed to simulate the entire phenological cycle or to study particular processes such as water dynamics in the soil and plant gas exchange (Moriondo et al., 2015). For instance, a grapevine growth simulator was used to calculate current and future projections of wine production in Chianti Classico region

(Sacchelli et al., 2017). The STICS model was used to assess the impact of climate change on viticultural yield and phenology for European vineyards under two climate change scenarios. While some model deviations were identified, the model outputs showed a good agreement with records of phenology, leaf area index, yield, and water/nitrogen stress conditions. However, running STICS for the whole European vineyard for a period of 26 years is computationally very expensive (around two million iterations), consequently, some computational strategies must be implemented to decrease the number of required iterations (Fraga et al., 2016).

Mitigation and adaptation are complementary actions for decreasing and controlling the impacts of climate change on agriculture. For instance, a lever of GHG mitigation is decreasing the use of tractor for viticultural operations (Beauchet et al., 2019). However, defining adaptation options for viticulture is more challenging than for other crops because the grapevine is a perennial crop, which implies that investments in adaptation must persist for many decades (Santillán et al., 2020). Naulleau et al. (2021) classified technical adaptation options according to their long- or short-term characteristics. The former options relate to perennial practices, while the latter correspond to annual practices. Long-term options include site selection, farm strategy, and selection of plant material (Gutiérrez-Gamboa et al., 2021; Naulleau et al., 2021; Neethling et al., 2017; Wolkovich et al., 2018). Among the short-term adaptation options for viticulture to climate change are irrigation, new vine management practices, and protection against extreme weather events (anti-hail nets, fans, heaters) (Gutiérrez-Gamboa et al., 2021; Naulleau et al., 2021; Santillán et al., 2019; Wolkovich et al., 2018). However, the distinction between short- and long-term adaptation levers is site-dependent. For instance, in the Anjou-Saumur winegrowing sub-region, France, irrigation was identified as a long-term option rather than a short-term one (Neethling et al., 2017).

Previous studies have used different approaches to evaluate adaptation strategies in viticulture, namely suitability mapping, empirical models, agent-based models, and process-based models (Naulleau et al., 2021). Even though suitability maps derived from bioclimatic indices point to a remarkable change in the landscape for European viticulture under future climate change, it has been acknowledged that adaptation strategies can attenuate these potential shifts in viticulture suitability (Moriondo et al., 2013). Santillán et al. (2019) developed a framework based on agro-climatic indices to assess the relative magnitude of adaptation effort for the major winegrowing regions. Subsequently, the required level of adaptation needs to be refined at finer scales, accounting for local conditions, winegrowers' perceptions of climate change, and available resources. An agent-based model was developed to investigate grapevine phenology and grape ripening under future environmental conditions driven by climate change. The model accounts for viticultural practices, adaptation strategies, and technical constrains at plot scale. Even though the model provides relevant output for analysis at the local level, the main constraint to deploy the model corresponds to the large amount of required data (Tissot et al., 2017). Sacchelli et al. (2017) developed a mix-method approach combining an economic model, a grapevine growth simulator, and a cognitive mapping technique to assess the economic performance of a viticultural farm when it implements adaptation measures to climate change.

1.3. Objectives of the study

This study aims to conduct a prospective life cycle assessment of viticulture under climate change scenarios, according to Shared Socioeconomic Pathways (SSPs) developed by the Intergovernmental Panel on Climate Change (IPCC). SSPs are emissions scenarios driven by diverse socioeconomic assumptions (IPCC, 2021). More specifically, we considered two SSPs (SSP1-2.6 and SSP5-8.5) corresponding to trajectories of low and high GHG emissions, according to four periods from 2021 to 2100. In the first level of analysis, we considered a *ceteris paribus* situation in which only projected changes in temperature and total precipitation drive changes in future grape yield. The underlying research questions addressed at this level of analysis were: (1) What is the potential role of climate-induced yield change on the environmental performance of viticulture? (2) How does this projected environmental performance compare to reported inter-annual variability? In the second level of analysis, we accounted for the impact of extreme weather events (hail, drought, heatwaves, frost, and phytopathology) on grape yield and the implementation of adaptation options based on future probability and potential level of damage of these extreme weather events. At this level of analysis, the research question was: (3) What is the influence of adaptation options on the environmental performance of viticulture under climate change?

2. Methods

2.1. Case studies description

Two vineyards located in two French winegrowing regions, associated with different production characteristics and climates, were analyzed in this study, one from the Loire Valley region in western France and another from Languedoc-Roussillon in southern France (Fig. 1, Table 1). The pathway of technical operations (PTO), that is the set of viticulture practices, implemented annually for a given production objective on each plot are examples chosen within the range of technical options employed in each winegrowing region. The PTO applied in the analyzed vineyard from the Loire Valley is representative of low-input conventional vineyard management. It is characterized by minimum application rates of phytosanitary products, and by a low number of interventions on the field (Renaud-Gentié et al., 2014). However, in the Loire Valley region, the oceanic temperate climate could promote pest and disease development, as well as vine vigour, which subsequently could lead to a higher number of viticulture operations, namely treatments for disease and pest control, and weeding (Renaud-Gentié et al., 2020). In contrast, the PTO implemented in the studied vineyard from Languedoc-Roussillon is representative of high-input conventional vineyard management. It is characterized by a high application rate of phytosanitary products, as well as the use of herbicides for weed control (Table S1). The Languedoc-Roussillon winegrowing region is characterized by a Mediterranean climate and maritime effects limit summer temperature extremes or winter frost during key grapevine phenological growth stages (Lereboullet et al., 2014).

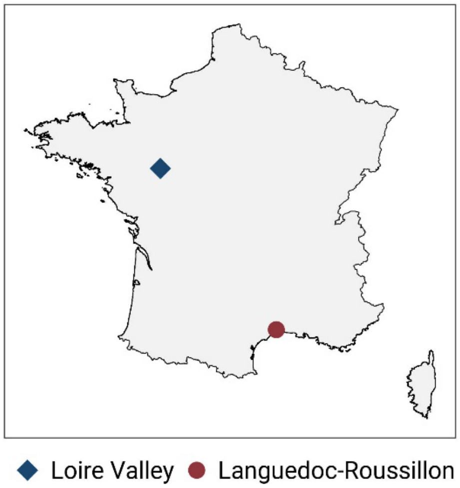


Fig. 1. Location of the analyzed vineyards in this study.

Table 1. Climatic characteristics of the analyzed vineyards in this study (Data Météo-France).

Case study	**Loire Valley**	**Languedoc-Roussillon**
Annual T_{mean} (°C)	12.4	15.1
Annual T_{min} (°C)	7.8	10.3
Annual T_{max} (°C)	17.1	19.8
Growing season T_{mean} (°C)	16.2	18.6
Annual precipitation (mm)	556	629
Summer precipitation (JJA) (mm)	123	79
Average solar irradiation (kWh m^{-2} day^{-1})	3.5	5.1

2.2. Goal and scope

The goal and scope of the study were deployed on two contrasting vineyards located in the Loire Valley (temperate oceanic climate), and Languedoc-Roussillon (dry and warm temperate Mediterranean climate), France. The effects of projected climate change on pollutant emissions, natural resource consumption, and yield were modelled for these two examples to calculate the resulting environmental impacts using the LCA framework. The system boundaries for both vineyards were cradle to farm-gate (Figs. S1 and S2). Furthermore, in order to account for yield differences between baseline and future scenarios, the functional unit was defined as one kilogram of grapes produced.

2.3. Life Cycle Inventory (LCI)

The life cycle inventory (LCI) consists in quantifying all pollutants emitted to air, water, and soil, and natural resources used during the entire process of winegrowing (cradle to gate). The LCI relied on data obtained from winegrowers. The collected data includes the characteristics of the farm, the operations (fertilization, crop protection, harvesting), and their frequency, as well as the amount of agrochemical products applied, the labour times, the materials used, as well as the agricultural machinery and equipment used. In the case of the vineyard from Languedoc-Roussillon, data was gathered directly from Agreo, a traceability system used in that vineyard domain (Bellon-Maurel et al., 2015).

Direct field emissions resulting from the application of fertilizers, soil amendments, and metal-based fungicides were calculated with the models shown in Table 2, and the employed equations are presented in section SI.2.1 of the supporting information. These emission models were programmed in *AGEC-LCI*, a Visual Basic for Applications (VBA) Excel tool that generates inventory reports compatible with LCA software such as openLCA and SimaPro (Viveros Santos et al., 2020). Apart from copper, active-substance emissions from pesticides were computed with PestLCI 2.0, using a version customized to viticulture, which includes spraying equipment and pesticide active ingredients generally used in viticulture. Besides, the customized version of the model accounts for pesticide interception by a mixed canopy, namely the combination of grass and vines (Renaud-Gentié et al., 2015). Section SI.2.2 describes the parametrization of PestLCI 2.0 for the computation of pesticide emissions. The foreground inventory data was modelled in SimaPro v8.5.2.2 software according to the product systems shown in Figs. S1 and S2. The inventory of background processes relied on ecoinvent v3.5 database and Agribalyse® (Colomb et al., 2015) for some agricultural machinery contextualized to France (Section SI.2.3).

Table 2. Emissions models for computing direct environmental emissions with AGEC-LCI (Viveros Santos et al., 2020) *(https://iviveros.github.io/agec-lci-tutorial).*

Modelled phenomenon	**Unit**	**Model or method**	**Reference**
Soil erosion	[t soil/ha/year]	RUSLE2	Foster (2005)
Ammonia emissions	[kg NH_3/ha]	Tier 2 of EMEP/EEA	EMEP (2009)

Modelled phenomenon	Unit	Model or method	Reference
Nitrogen oxides emissions (NOx: NO and NO_2)	[kg NO_2/ha]	Tier 1 of EMEP/EEA	EMEP (2009)
Nitrate emissions	[kg NO_3^-/ha]	SQCB	Faist Emmenegger et al. (2009)
Nitrous oxide emissions	[kg N_2O/ha]	Tier 1 of IPCC (2006)	Eggleston et al. (2006)
Phosphorus emissions	[kg P/ha] and [kg PO_4^{3-}/ha]	SALCA-P	Nemecek and Schnetzer (2011)
Trace metals (TMx) emissions {x|x= Cd, Cr, Cu, Hg, Ni, Pb, Zn}	[kg TMx/ha]	SALCA-ETM	Freiermuth (2006)

2.4. Data sources

2.4.1. Grape yield and vineyard surface

Data sets of viticultural yield at the level of French Departments for the period 2000-2020 were retrieved from the French Ministry of Agriculture and Food Statistics Service (Agreste, 2021). The beginning of the study period corresponds to the earliest year with grape yield records. In total, Agreste database of viticultural yield holds 36450 records according to 21 reported years, 121 geographic identifiers, 3 categories of vines, and 5 indicators (Table S6). Even though this study focuses on vineyard plots within only two French Departments, to take advantage of the extent of data availability, we extracted a set of 1260 records from Agreste database of grape yield, according to 21 years and 60 Departments of Metropolitan France (filter criteria shown in Table S7). Grape yields obtained from Agreste are reported in quintals per hectare, consequently, a conversion was made to metric tonnes per hectare to make the data suitable for further computations.

The vineyard area over Europe was obtained from the CORINE program of the European Environment Agency (EEA, 2017) and Python was used to extract the coverage of French vineyards using the clip algorithm from GeoPandas module (Jordahl et al., 2020) with a shapefile of Metropolitan France as a mask layer. Subsequently, since the spatial resolution of available viticultural yield is at the French Department level, GeoPandas (Jordahl et al., 2020) was employed to relate vineyard surface and administrative divisions defined by a shapefile of French Departments (Table S8 and Fig. S4).

2.4.2. Climate data

One specific objective of this study was to investigate the impacts of recent climate on grape yield to subsequently estimate the impacts of projected change in temperature and precipitation on future grape yield. The former analysis was performed based on a climate data set retrieved from the Agri4Cast Resource Portal, established and maintained by the Joint Research Centre of the European Commission (Biavetti et al., 2014). The Agri4Cast data set comprises eight daily meteorological variables from 1979 to the last calendar year completed, interpolated to a 25 x 25 km regular grid over Europe (Table S9). The Agri4Cast data set has been extensively employed in agricultural studies (Bradshaw et al., 2019; Charalampopoulos et al., 2021; Korycinska and Baker, 2017) because of its consistency and high accuracy in temporal and spatial resolution, which makes it a convenient resource for agroclimatic and agrometeorological analyses (Mavromatis and Voulanas, 2021). From the Agri4Cast data set, we collected mean air temperature (°C) and the sum of precipitation (mm) over France for the period 2000-2020 (so the temporal scale is coherent with that of Agreste data set), which generated a subset of 7,694,013 rows across 1003 grid points (Fig S4). Then, the data set was filtered according to the growing season of wine grapes (March to September), which reduced the data set to 4,507,482 rows.

Monthly values of average temperature (°C) (Fig. S6) and total precipitation (mm) (Fig. S7) were retrieved from WorldClim 2.0 for five periods at 2.5 min resolution (Fick and Hijmans, 2017) to calculate the difference between future and present climate during the growing season of wine grapes. The first period extends from 1970 to 2000 and corresponds to present climate or baseline scenario. The other four periods are 20-year periods of projected climate for the near future (2021-2040), mid-century (2041-2060, 2061-2080), and the end of the century (2081-2100) derived by the CMIP6 (Coupled Model Intercomparison Project Phase 6) (Fick and Hijmans, 2017; Petrie et al., 2021). The climate change scenarios included in this study are derived from the Global Circulation Model (GCM) IPSL-CM6A-LR and two Shared Socioeconomic Pathways (SSPs) (SSP1-2.6 and SSP5-8.5) corresponding respectively to trajectories of "low GHG emissions or strong mitigation" and "high GHG emissions or business-as-usual" (Table S10). In line with Wolkovich (2018), we considered only one GCM to calculate projected changes in temperature and precipitation since the purpose of our study is to compute the relative impact of climate change on grape production. Moreover, projections of climate change derived from IPSL-CM5A-LR have been used to compute robust climatic indices for the Mediterranean region (Santillán et al., 2020).

2.4.3. Agroclimatic indicators

Apart from hail, to project the potential impacts of extreme events on future grape yield, we used agroclimatic indicators data sets obtained from the Climate Data Store (CDS) of the Copernicus Climate Change Service (C3S) (Copernicus, 2021), namely consecutive frost days (CFD, Fig. S8), consecutive dry days (CDD, Fig. S9), warm-spell duration index (WSDI, Fig. S10), and warm and wet days (WW, Fig. S11).

2.5. Climate-induced yield impacts

To assess the relationship between the time series for grape yield and climate, it is required that both grape yield and climate data sets are at the same temporal and spatial scales. We selected a French department as an adequate scale for intercomparison since grape yields from Agreste (2021) are reported at this spatial resolution. Moreover, calculating the impacts of climate on grape yields on a department scale entails a potential increase in the application of these results on future planning scenarios in viticulture. Surface data sets of average temperature and total precipitation corresponding to the growing season of grapes were calculated according to 1003 grid points from the Agri4Cast data set (Fig. S5) (Biavetti et al., 2014), using the inverse distance weighting (IDW) interpolation technique implemented in the R package "gstat" (Gräler et al., 2016; Pebesma, 2004) (Fig. S12 and Fig. S13). After interpolating climate variables, zonal statistics at department resolution were calculated using the R package "exactextractr" (Baston, 2020). Overall, we obtained data sets of department-averaged total precipitation and average temperature for 60 French Departments for the 2000-2020 period, which corresponds to the temporal and spatial scales of the Agreste data set (Table S6).

With both climate and grape yield data sets at the same spatial and temporal scales, to evaluate the sensitivity of grape yields to climate, grape yields and climate variables were detrended by means of linear regression. Detrending is a common method in agricultural research based on the first-difference time series for yield and climate (namely the difference in values from one year to the next) as the dependent variable and time as the independent variable (Kukal and Irmak, 2018; Lobell and Field, 2007). The purpose of this operation is to minimize the effects of other non-climatic variables, such as genetic improvement, technological advancement, and soil and crop management progress (Lobell and Field, 2007). Detrending produced residuals of yield ($\Delta Yield$) (kg ha^{-1} yr^{-1}), average temperature (ΔT_{avg}) (°C yr^{-1}) and total precipitation (Δppt) (mm yr^{-1}). Successively, we performed linear regressions with yield residuals ($\Delta Yield$) as the dependent variable and residuals of average temperature (ΔT_{avg}), and total precipitation (Δppt) as explanatory variables (see Fig. S14 and Fig. S15 along with a brief description of detrending). The slope coefficients of these linear regressions correspond to yield change per unit change in mean temperature (kg ha^{-1} °C^{-1}) and total precipitation (kg ha^{-1} mm^{-1}).

Next, we generated maps of change in average temperature (Fig. S16) and total precipitation (Fig. S18) during the growing season of wine grapes by calculating the difference between current and future climate, according to four future periods and two SSPs (SSP1-2.6 and SSP5-8.5) derived by the GCM IPSL-CM6A-LR (Table S10). Successively, zonal statistics of these maps were computed in R v4.1.2 using the package "exactextractr" (Baston, 2020), resulting in department-level values of projected climate change.

According to Eq. (1), the expected change in grape yield ($E(YC)_{t,s}$), in kg ha^{-1}, due to projected climate change for each period (t) and SSP (s) was computed by adding the product of the sensitivity of grape yield β_c to each climate variable (c) (i.e., the slope coefficients of linear regressions, kg ha^{-1} °C^{-1} and kg ha^{-1} mm^{-1} for average temperature and total precipitation, respectively) and the projected change in average temperature (°C) and total precipitation (mm) ($\Delta C_{c,t,s}$) (Fig. S17 and Fig. S19). This approach is consistent with other LCA studies that have used historic trends to forecast the environmental performance of product systems under future conditions, whether technical (Beloin-Saint-Pierre et al., 2020) or environmental (Lee et al., 2020). Finally, according to Eq. (2), the expected future grape yield ($E(Y)_{t,s}$), in kg ha^{-1}, for period (t) and SSP (s) was obtained by the algebraic addition of expected change in grape yield ($E(YC)_{t,s}$) to the grape yield of baseline scenarios ($Y_{baseline}$), in kg ha^{-1}.

$$\mathrm{E}(YC)_{t,s} = \sum_{c} \beta_{\mathrm{c}} \cdot \Delta \mathrm{C}_{c,t,s} \tag{1}$$

$$E(Y)_{t,s} = Y_{baseline} + E(YC)_{t,s} \tag{2}$$

2.6. Effects of extreme events and adaptation strategies

In this study, we adapted the methodological approach developed by Sacchelli et al. (2017) to account for the impact of extreme events on future grape yield. According to Eq. 3, the expected yield loss rate ($E(YLR)_{t,s}$) (%) for each period (t) and SSP (s) due to an extreme event – e – was calculated as a function of the future probability of the extreme events – $P(e)_{t,s}$ (%) – and the potential level of damage - d_e. In line with Sacchelli et al. (2017), the probability of extreme events was treated as an independent variable, consequently, the probabilities of change in grape yield resulting from extreme events were aggregated (Eq. 3). However, this approach does not allow to account for potential synergistic effects of drought and heatwaves that have been reported in the literature (Fraga et al., 2018).

$$E(YLR)_{t,s} = \sum_{e=1}^{m} P(e)_{t,s} \cdot d_e \tag{3}$$

As described in Table 3, for frost, drought, heatwaves, and phytopathology, we computed the future probability $P(e)_{t,s}$ (%) of extreme event e during the growing season of wine grapes based on agroclimatic indicators for future periods (2021-2040, 2041-2060, 2061-2080, and 2081-2100) derived from the GCM IPSL-CM5A-LR and two SSPs. Whereas for hail, we used data on projected changes in summer mean temperature (Fick and Hijmans, 2017). Therefore, a total of eight combinations of periods and SSPs were considered. Regarding the potential level of damage (d_e) (%), we considered reported values in the literature (Table 3).

Table 3. Definition of extreme events

Extreme events	**Note**
Hail	The current probability of hail was based on literature review (Berthet et al., 2011; Raupach et al., 2021). Likewise, the current hail damage on grape yield was extrapolated from an empirical study on table grapes that reported a yield reduction of 39% after a hail event (Petoumenou et al., 2019). For future hail damage, we considered a correlation between summer mean temperature and hail damage in France, according to which, an increase of one degree leads to a 40% rise in hail damage (Berthet et al., 2011; Raupach et al., 2021).
Frost	Based on the maximum number of consecutive frost days (CFD) for the season March-April-May (MAM). For a frost day, the minimum daily air temperature is < 0°C (Copernicus, 2021) (Fig. S8), which is in line with the temperature threshold defined in other studies assessing spring frost damage (Molitor et al., 2014). The probability of frost (p_f) was approximated by $p_f = CFD/n$ where n is the number of days during the season MAM and CFD is the mean value of this parameter for a given period (historical or future). The underlying assumption was that spring frost risk increases with CFD. This does not allow us to account for the duration of sub-zero temperatures on the severity of frosts; however, the number of CFD are projected to decrease. Regarding the level of yield damage caused by spring frost, we considered a historical value in European vineyards of 39% by frost episode (Molitor et al., 2014).
Drought	Based on the maximum number of consecutive dry days (CDD) during the grape-growing season (approximated by the period of March-August) (Copernicus, 2021) (Fig. S9). A threshold of drought (D) was defined according to the reported CDD for most wine regions in France over the period 1986-2015 (Yang et al., 2022). Then, the probability of drought was calculated as $p_{drought} = CDD/D$. Moreover, we considered the mean potential yield loss rate due to seasonal drought of 30% for France over the period 1986-2015 (Yang et al., 2022).

Extreme events	**Note**
Heatwaves	Following Fischer and Schär (2010), multi-day heatwaves were calculated based on the warm-spell duration index (WSDI) (Copernicus, 2021) (Fig. S10). However, instead of a spell of six days, we considered the definition of a heatwave as a spell of at least nine consecutive days (Fraga et al., 2020). Furthermore, we considered the highest level of damage (35%) by heatwave on grape yield, simulated for France over the period 1986-2015 (Fraga et al., 2020).
Phytopathology	Warmer conditions combined with precipitation may trigger pests and disease pressure in viticulture, particularly downy mildew (Fraga et al., 2013; Santos et al., 2020). However, there are still uncertainties on the correlation between disease occurrence and climatic data (Ollat et al., 2018). For this reason, in line with Sacchelli et al. (2017), we considered a low-level increase in pesticide application with respect to the application rate of baseline scenarios. We hypothesized a 5% increase in pesticide application per warm and wet days (WW) during the growing season (Copernicus, 2021) (Fig. S11). This assumption corresponds to one of the approaches used to account for the relationship between pesticide application and climate change, which applies an adjusted treatment index to the current pesticide application to estimate future pesticide application rates (Niero et al., 2015a). We acknowledge that a second approach is to consider present pesticide application rates in areas with a climate akin to the projected climate for the analyzed regions (Dijkman et al., 2017; Niero et al., 2015a). Nonetheless, due to a lack of data on pesticide application for regions with a climate comparable to the forecasted climate for the regions of this study, the last approach was not used.

According to the literature review, we identified some adaptation levers that correspond to incremental changes in viticulture to attenuate the impacts of extreme weather events (Table 4). For the implementation of the adaptation levers, we considered that farmers have a high level of risk aversion and activate the corresponding adaptation option when the expected yield loss rate is greater than 1% (the term $P(e)_{t,s} \cdot d_e$ of Eq. 3) for a given extreme event (e). Besides, we considered that activating the corresponding adaptation option completely mitigates the associated yield loss rate. Consequently, the expected future grape yield $E(Y*)_{t,s}$ (kg ha^{-1}) for period t and SPP s when adaptation options are activated was calculated according to the second case of Eq.4, reflecting the fact that no adaptation was considered for heatwaves (Table 4) and that adaptation levers are activated if their potential yield reduction is greater or equal than one. Finally, the first case of Eq. 4 corresponds to the situation in which no adaptation is activated.

$$E(Y*)_{t,s} = \begin{cases} E(Y)_{t,s} \cdot \left(1 - \sum_{e=1}^{m} P(e)_{t,s} \cdot d_e\right) \\ E(Y)_{t,s} \cdot \left(1 - \sum_{e=1}^{m} P(e)_{t,s} \cdot d_e\right) \;\; if \left(P(e)_{t,s} \cdot d_e < 1 \; and \; e = heatwave\right) \end{cases} \tag{4}$$

The LCIA results of adaptation levers were computed according to the description presented in Table 4 and with the IMPACT World+ methodology as described in section 2.1. Furthermore, the LCIA results account for the projected increased in phytosanitary treatments as described in Table 4.

Table 4. Adaptation strategies

Extreme events	**Adaptation lever**	**Note**
Hail	Anti-hail net	The LCI of anti-hail nets was modelled according to an LCA study on HDPE nets (Dassisti et al., 2016).
Frost	Among the adaptation options against frost are fans, heaters, candles (Sacchelli et al., 2017), and wood-burning (Frota de Albuquerque Landi et al., 2021).	In this study, we considered oak wood-burning as the selected anti-frost lever. The wood-burning system was modelled according to a study that estimated that 5000 kg of wood could supply 315 W/m^2 to protect one hectare of a vineyard for 8 hours (Frota de Albuquerque Landi et al., 2021).
Drought	Irrigation	Irrigation demands were estimated based on a study that computed irrigation requirements under future climatic

Extreme events	**Adaptation lever**	**Note**
		conditions in a French vineyard watershed (Naulleau et al., 2022). It was calculated that under RCP8.5 scenario, the future base irrigation requirement is 25.2 mm (intercept), which increases by 1.01 mm per each decreased mm in precipitation (slope). While irrigation demands depend on other factors such as soil types, research has shown that irrigation requirements follow the patterns of precipitation during the growing season of grapes (Fraga et al., 2018), which justifies using this proxy for computing the irrigation requirements.
Heatwaves	Modification of pruning (Santillán et al., 2019) and adoption of heat-tolerant varieties (Wolkovich et al., 2018) are adaptations levers against heatwaves.	In this study, we did not consider adaptation options against heatwaves since they imply transformative changes. While changing variety is a foreseen adaptation lever, it will require new laws and regulations that currently restrict what varieties can be cultivated in a given region (Wolkovich et al., 2018). Moreover, it is difficult to estimate the effect of pruning modification and new grape varieties on grape yield under future climate change scenarios.
Phytopathology	Increase of phytosanitary treatments	We considered the estimated increase in pesticide application described in Table 3.

2.7. Life Cycle Impact Assessment (LCIA) and sensitivity analyses

The life cycle impact assessment (LCIA) was calculated using IMPACT World+ methodology, which is the update of the IMPACT 2002+, LUCAS and EDIP methods (Bulle et al., 2019). In order to facilitate the interpretation of the LCIA results of both present and future scenarios, their environmental performance was assessed according to one midpoint (v1.28) and two endpoint indicators (v1.49) from IMPACT World+. Regarding midpoint indicators, we selected the category climate change in the short term (over the first 100 years after the emission) for the carbon footprint (kg CO_2 eq). Concerning the endpoint indicators, we considered the impacts on ecosystem quality (EQ) measured in terms of the potentially disappeared fraction of species over a surface area of one square meter over one year ($PDF \cdot m^2 \cdot yr$), and the impact on human health (HH) measured in disability-adjusted life years (DALY). The EQ endpoint encompasses freshwater ecotoxicity, freshwater acidification, marine acidification, terrestrial acidification, freshwater eutrophication, marine eutrophication, ionizing radiation, land transformation and land occupation, and water availability. The HH endpoint comprises human toxicity cancer, human toxicity non-cancer, particulate matter formation, photochemical oxidant formation, ozone layer depletion, ionizing radiation, and water availability (Bulle et al., 2019). The contribution of climate change to EQ and HH endpoints was excluded to prevent double counting.

Furthermore, two sensitivity analyses were performed to evaluate the robustness of the trends of the environmental profile of the analyzed vineyards. The first sensitivity check corresponded to the computation of the LCIA with another impact method. The LCIA of the base scenarios and those that account for climate-induced yield impacts were calculated with the ReCiPe (H) methodology (Goedkoop et al., 2009). The hierarchical (H) perspective of this method was selected because it has been used in other studies assessing the environmental impact of grape production (Bellon-Maurel et al., 2015). The second analysis aimed to assess the influence of the level of damage of extreme events (Table 3) on the LCIA of future scenarios accounting for the impact of extreme events and the implementation of adaptation levers. The analysis was performed by decreasing and increasing the level of damage of the extreme events presented in Table 3 by an arbitrary value of 25%.

3. Results and discussion

3.1. Projected climate-induced yield impacts

Fig. 2 shows the spatial variability of grape yield sensitivity to climate variables at the scale of French Departments, that is, the change in grape yield (kg/ha) per 1 °C rise in temperature (Fig. 2a) and per 10 mm rise in precipitation (Fig. 2b). Negative values indicate that the grape yields decrease with temperature or precipitation increase, whereas positive values indicate that they increase with temperature or precipitation rise. Concerning grape yield sensitivity to temperature, it was found that 38 out of 60 Departments exhibited negative values, accounting for approximately 54% of the French vineyard surface. A similar figure was found for grape yield sensitivity to precipitation, for which 37 out of 60 Departments showed negative values, corresponding to around 57% of the French vineyard surface.

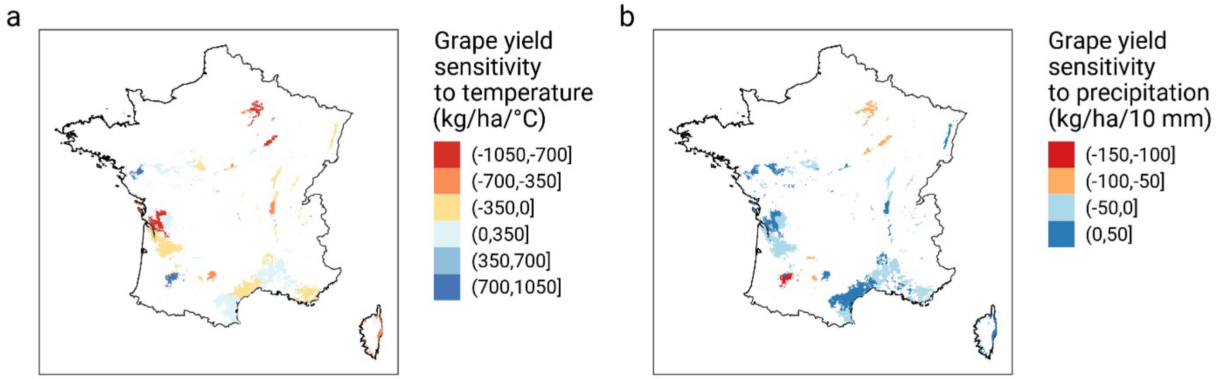


Fig. 2. Grape yield sensitivity to temperature (kg ha^{-1} °C^{-1}) (a) and precipitation (kg ha^{-1} 10 mm^{-1}) (b) over the period 2000-2020.

The computed grape yield sensitivities to climate variables at the level of French Departments (Fig. 2) were used as a proxy of the grape yield sensitivity to climate of each vineyard of the case study (Fig. 1) and were combined with the projected changes in mean temperature and total precipitation (Table 5) to compute climate-induced yield impacts. We acknowledge that doing so introduces spatial uncertainty at the level of the plot vineyard, however, this scale issue is not exclusive to this study, since climate projections at coarser scales do not perfectly replicate local growing conditions (Naulleau et al., 2022). Regarding the vineyards of the case study, temperature increase was found to adversely affect grape yield in Languedoc-Roussillon, with a value of -233.7 (kg ha^{-1} °C^{-1}). On the other hand, in the Loire Valley, the sensitivity of grape yield to temperature was estimated to be 151.9 (kg ha^{-1} °C^{-1}), which implies that temperature rise in this vineyard is favourable to grape yield. Concerning grape yield sensitivity to precipitation, both vineyards of the case study have positive values of 13.4 (kg ha^{-1} 10 mm^{-1}) in Languedoc-Roussillon and 38.8 (kg ha^{-1} 10 mm^{-1}) in the Loire Valley (Fig. 1 and Fig. 2).

Table 5. Projected changes in mean temperature (°C) and total precipitation during the grape-growing season in the vineyards of the case study by SSP and period (Fig. S17 and S19 show the variability arising from the computation of zonal statistics).

Vineyard	**SSP1-2.6**				**SSP5-8.5**			
	2021-2040	**2041-2060**	**2061-2080**	**2081-2100**	**2021-2040**	**2041-2060**	**2061-2080**	**2081-2100**
	Temperature change (°C)							
Loire Valley	1.3	1.9	2.2	2.1	1.5	3.1	4.9	6.7
Languedoc-Roussillon	1.4	2.2	2.4	2.3	1.6	3.4	5	7.2
	Precipitation change (mm)							
Loire Valley	-16.1	-18.5	-11.8	-3	-7	-11.2	-31.7	-57.5
Languedoc-Roussillon	-9.1	-19.5	-20.5	-14.1	-16.2	-35.5	-27.4	-63.8

Fig. 3 shows the average projected climate-induced yield impacts (kg/ha) in both vineyards of the case study, according to both emission scenarios and the four periods included in the analysis. Under the low emission scenario (SSP1-2.6), the higher reduction in grape yield for Languedoc-Roussillon is projected to be approximately -594 kg/ha for 2061-2080, the rise in mean temperature being responsible for 95% of the predicted yield decrease. Likewise, the high emission scenario (SSP5-8.5) projects significant reductions in grape yield in Languedoc-Roussillon, reaching a maximum decrease of -1777 kg/ha by 2081-2100. In contrast, in the Loire Valley, grape yield is expected to increase regardless of the emission scenario because of the positive grape yield sensitivity to mean temperature in this wine-growing region. Under SSP1-2.6, grape yield is projected to increase, ranging from 127 kg/ha for 2021-2040 to 302 kg/ha for 2081-2100. Similarly, the high emission scenario (SSP5-8.5) predicts higher increases in grape yield in the Loire Valley, ranging from 203 kg/ha for 2021-2040 to 800 kg/ha for 2081-2100. However, we acknowledge that the rules of Protected Designation of Origin (PDOs) set the maximum grape yield according to the target quality of the wine. Hence, even if our results indicate potential increases in grape yield in the Loire Valley, PDOs rules may limit them, where more than 80% of the vineyards are included in one of the 51 different wine PDOs of the region (InterLoire, 2022). As depicted in Fig. 3, the projected net climate-induced yield impacts are mainly driven by the projected change in mean temperature; accordingly, their direction of change (increase or decrease) is determined by the direction of grape yield sensitivity to temperature (positive or negative) since mean temperature during the wine grape growing season is projected to increase in both vineyards of the case study (Table 5).

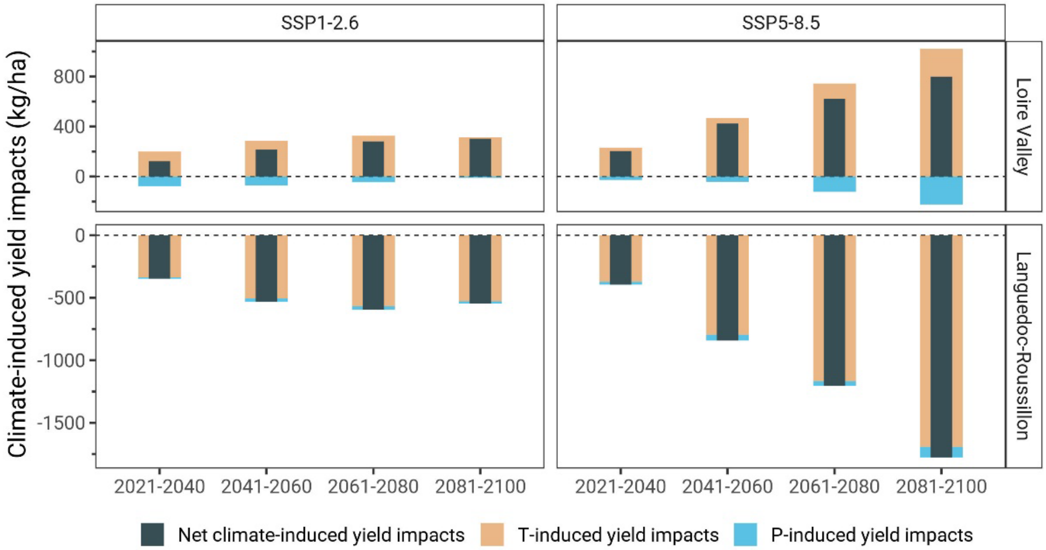


Fig. 3. Climate-induced yield impacts (kg/ha) in the vineyards of the case study by SSP and period.

3.2. Influence of projected climate-induced yield impacts on LCIA results

In this section, we present the LCIA results obtained at the first level of our analysis, in which a *ceteris paribus* situation was considered, therefore, the projected changes in average temperature and total precipitation are the drivers of grape yield variation. Accordingly, the pathways of technical operations (POTs) for future scenarios remained the same as those of the baseline scenario of each vineyard of the case study.

The spatial and temporal variability of the projected climate-induced yield impacts reflected on the life cycle impacts for producing 1 kg of grapes in the two analyzed French vineyards, for which an increase in mean temperature during the grape-growing season led to opposite outcomes in grape yield. Because of the spatial uncertainty resulting from computing zonal statistics of projected climate change, we present the LCIA results, for both midpoint and endpoint impacts, in the form of bullet graphs showing the minimum, median, and maximum impact scores calculated according to the same statistics for mean temperature and total precipitation. The LCIA results follow the main diagonal (from the top left corner to the bottom right corner) of the heat map of projected changes in grape yield (Fig. S20).

Fig. 4a shows a moderate decrease in the carbon footprint of the vineyard from the Loire Valley under the two emission scenarios and during the four periods included in this study. The current carbon footprint of the vineyard from the Loire Valley is higher (0.215 kg CO_2eq kg grapes^{-1}) than the median values under the low (SSP1-2.6) and high (SSP5-8.5) emissions scenarios. The highest decrease in the carbon footprint for the vineyard from the Loire Valley is projected under SSP5-8.5 for the period 2081-2100 (0.195 kg CO_2eq kg grapes^{-1}), which corresponds to a decrease of around 10% compared to the baseline scenario. In contrast, the median values of carbon footprint under both emissions scenarios of the vineyard from Languedoc-Roussillon are higher than the current value (0.220 kg CO_2eq kg grapes^{-1}). For the period 2021-2041, the carbon footprint of the vineyard from Languedoc-Roussillon increases by 4.9 and 4.4% compared to the baseline scenario under the SSP1-2.6 and SSP5-8.5 scenarios, respectively. Under the lower emissions scenario (SSP1-2.6), the higher increase in carbon footprint in Languedoc Roussillon is projected for the period 2061-2080 (0.238 kg CO_2eq kg grapes^{-1}), which corresponds to an increase of 8.2%. The SSP5-8.5 scenario projects higher increases in the carbon footprint of the vineyard from Languedoc-Roussillon, of approximately 18% and 29% for 2061-2080 and 2081-2100, respectively.

The sensitivity analysis on the choice of the impact method confirmed that there is no difference between the current carbon footprint of grape production computed with IMPACT World+ (Bulle et al., 2019) and that obtained with ReCiPe (H) (Goedkoop et al., 2009) for both vineyards of the case study (Fig. 4, Fig. S21, and Fig. S22). This is linked to the fact that both methods use the global warming potentials for a 100-year time horizon (GWP100) derived by the IPCC. Furthermore, the mean carbon footprint calculated in the present study for the baseline scenarios of both vineyards is within the range of values previously reported. For instance, Beauchet et al., (2019) obtained a carbon footprint of 0.18 kg CO_2eq kg grapes^{-1} and 0.29 kg CO_2 eq kg grapes^{-1} for a vineyard of the Middle Loire Valley, while in the present study, the mean carbon footprint for the vineyard from the Loire Valley is 0.215 kg CO_2 eq kg grapes^{-1}. Nevertheless, the current carbon footprint for the vineyard from Languedoc-Roussillon (0.220 kg CO_2 eq kg grapes^{-1}) is low compared to the range reported for a case study on five vineyards conducted in the same region (0.461 – 1.392 kg CO_2 eq kg grapes^{-1}) (Bellon-Maurel et al., 2015).

Fig. 4b shows a similar trend for the ecosystem quality impacts resulting from grape production as the carbon footprint shown in Fig. 4aFig. 4. Nevertheless, there is an important difference in the magnitude of ecosystem quality impacts for the analyzed vineyards. The ecosystem quality impact associated with the baseline scenario of grape production in Languedoc-Roussillon (2.31 PDF·m^2·yr·kg grapes^{-1}) is approximately 6-fold the value computed for the vineyard in the Loire Valley (0.37 PDF·m^2·yr·kg grapes^{-1}). These results are driven by the sharp difference between the number and amount of pesticide applications in each vineyard (Table S1). Regarding the vineyard from Languedoc-Roussillon, pesticide protection treatments account for around 67% of ecosystem quality impacts, while the contribution of this operation accounts for approximately 22% in the vineyard from the Loire Valley. Regarding future scenarios, under the high emissions scenario (SSP5-8.5), the greatest increase in ecosystem quality impacts for the vineyard from Languedoc-Roussillon is projected for the period 2081-2100, being around 33% greater compared to the baseline scenario. Conversely, under the same emission scenario (SSP5-8.5), the highest reduction in the ecosystem quality impacts for the vineyard from the Loire Valley is projected for 2081-2100, which is around 9% compared to the baseline scenario.

Regarding the sensitivity check on the choice of the impact method, since IMPACT World+ and ReCiPe do not use the same units for the ecosystem quality endpoint, a direct comparison of the scores for this category is not straightforward. While the ecosystem quality impact calculated with IMPACT World + of the vineyard from Languedoc-Roussillon is around six times the value calculated for the vineyard from the Loire Valley (Fig. 4b), this ratio is around 2.3 times according to the computed scores with ReCiPe (H) (Fig. S21b and Fig. S23). Furthermore, this ratio decreases according to other perspectives of the ReCiPe method, with values of 1.3 and 1.04 for the egalitarian (E) and individualist approaches (I), respectively (Fig. S23).

Similar trends were found for the human health impacts (Fig. 4c) to those shown in Fig. 4aFig. 4 for the carbon footprint and in Fig. 4b for ecosystem quality impacts. However, to put our LCIA results derived from climate-induced yield impact into perspective, an LCA of organic viticulture in France showed that the influence of interannual variability in the environmental profile of grape production can reach up to 52% per impact category because of changes in management practices according to different climatic conditions and pests and disease pressure (Renaud-Gentié et al., 2020), compared to around 33% of maximal variability shown here. However, Beauchet et al., (2019) reported that organic PTOs are more subject to interannual variations compared to conventional PTOs, especially because of the sensitivity of treatment frequency to the wash-off by the rain of the pesticides used in organic viticulture.

Concerning the sensitivity analysis on the selection of the impact method, the human health impacts computed with IMPACT World+ are higher compared to the values obtained with the hierarchical (H) approach of the ReCiPe method (Fig. S24). The computed human health impacts for the vineyard from Languedoc-Roussillon is 9-fold the score obtained with ReCiPe (H), and the human health impact of the vineyard from the Loire Valley is around 5-fold the one obtained with ReCiPe (H). However, the human health impact scores for both vineyards are lower than the scores obtained with the egalitarian approach (E) of ReCiPe method (Fig. S24). Nevertheless, the ratios of the human health of the vineyard from Languedoc-Roussillon over that of the vineyard from the Loire Valley are close according to both impact methods, 1.8 with IMPACT World+ and 1.5 with ReCiPe.

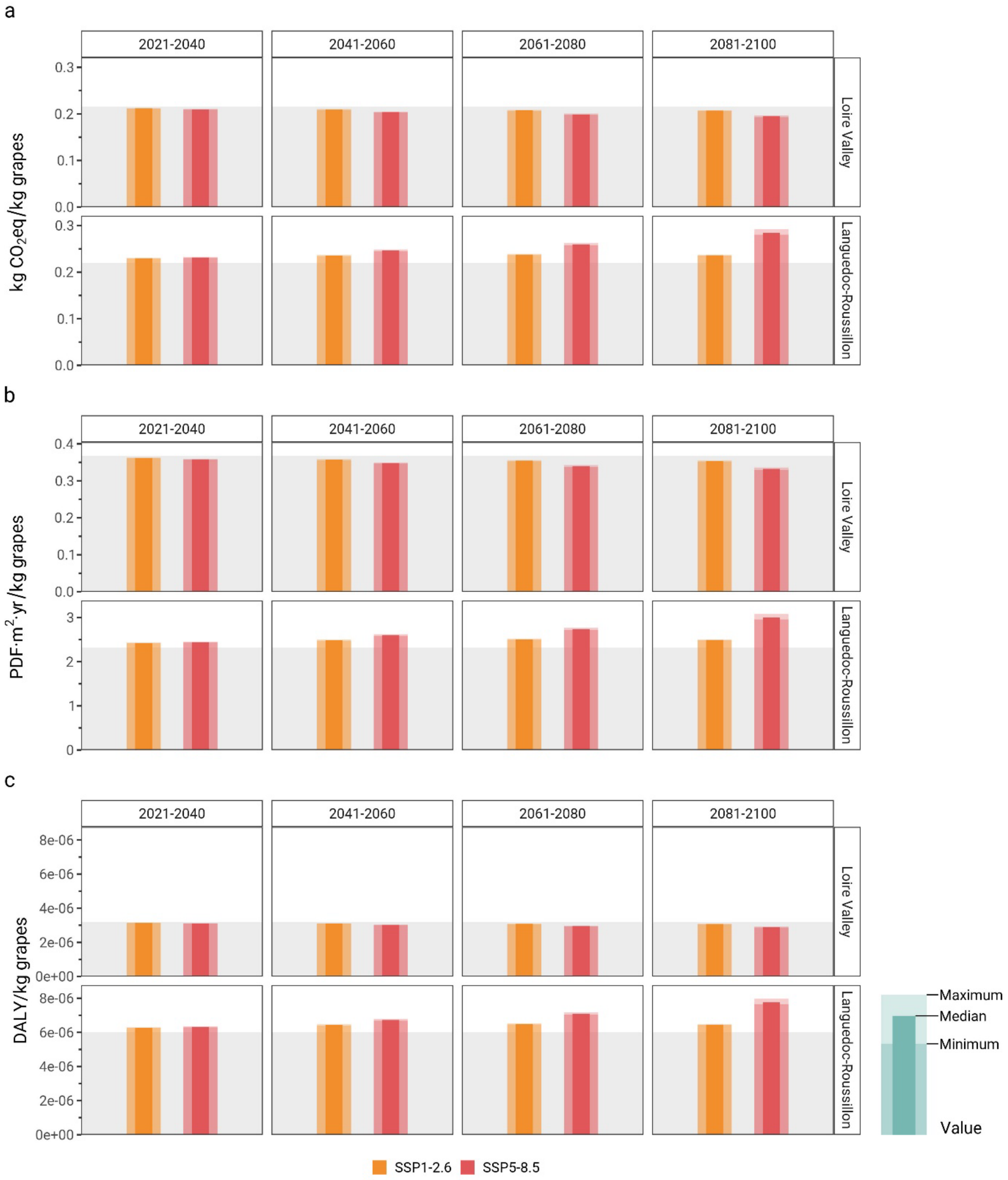


Fig. 4. Carbon footprint (kg CO_2eq·kg grapes^{-1}) (a), ecosystem quality (EQ) impacts (PDF·m^2·yr·kg grapes^{-1}) (b) and human health (HH) impacts (DALY·kg grapes^{-1}) (c) of grape production for future periods under two emissions scenarios in two French vineyards. Impact scores were calculated with IMPACT World+ (Bulle et al., 2019). *The height of the lighter shaded envelope behind the bars represents the impact per kg of grapes of baseline scenarios. The bullet graph shows the spatial variability arising from the computation of zonal statistics of projected climate change. Please note that the panel (b) the y-axis is not at the same scale.*

With regard to ecosystem quality and human health potential impacts resulting from pesticide emissions, we observe a large variation in the number and amount of pesticides applied in each analyzed vineyard, and the number of active ingredients varies in the same way. Overall, 17 active ingredients are applied in the vineyard from Languedoc-Roussillon (Table S11), while 9 different active ingredients are applied in Loire Valley (Table S12). For the vineyard from Languedoc-Roussillon, 7 out of 17 active ingredients were not characterized due to the lack of characterization factors, whereas for the vineyard from Loire Valley, 4 out of 9 active ingredients were not characterized. We acknowledge that the potential environmental impact of pesticide emissions is underestimated due to the lack of characterization factors for some active ingredients, still, the vineyard from Languedoc-Roussillon showed larger impacts related to pesticide emissions due to the high application rate. Besides, the fact that no impact assessment method covers characterization factors for all pesticides is a current challenge when modelling agricultural systems in LCA (Nemecek et al., 2022).

3.3. Influence of extreme events and adaptation strategies on LCIA results

Fig. 5 reports the potential yield loss rate due to extreme events (Eq. 3) for grape production under future climate change scenarios without the implementation of adaptation levers. For both vineyards, regardless of the climate change scenario and period, spring frost is expected to produce the lowest yield loss rate. In fact, the greatest impact of spring frost amounts to 1.1% in the Loire Valley by the end of the century. However, the assessment of climate change impact on spring frost risk has led to a contentious debate in the scientific literature. Spring frost arises when budburst precedes the occurrence of the last frost event in the spring of a grape-growing season. According to the projected impacts of climate change on viticulture, these events will occur earlier (Santos et al., 2020), leading to lessen spring frost risk in the future (Molitor et al., 2014; Santos et al., 2020), while other studies found conflicting results among models or projected increased risks for spring frost damage in viticulture (Leolini et al., 2018; Mosedale et al., 2015).

With respect to yield loss rates due to hail (Fig. 5), the values for both vineyards are under 3% for the near- and mid-term future, whereas the highest impacts were found for both vineyards under the high emissions scenario (SSP5-8.5), which correspond to 4.7 and 5% for the Loire Valley and Languedoc-Roussillon, respectively. Because hailstorms are site-specific events, there are still uncertainties in predicting the potential impact of hail on agriculture (Petoumenou et al., 2019). However, hailstorms will likely increase under climate change because of the rise of low-level moisture and convective instability driven by anthropogenic warming (Raupach et al., 2021). The low potential yield loss rates due to frost and hail are associated with their low probability, consequently, they represent the average impact of a given period and not a precise point in time (Tables S13, S14, and S15).

Regarding the potential yield loss rate due to drought, the same level of damage was computed for both vineyards under the low emissions scenario (SSP1-2.6), which is around 20% (Fig. 5). On the other hand, the impact of drought under the high emissions scenario (SSP5-8.5) is expected to increase steadily, and by the end of the century the potential yield loss rate is estimated at 28.9 and 29.4% for the Loire Valley and Languedoc-Roussillon, respectively. Fig. 5 shows that the highest potential yield loss rates due to heatwaves are projected under the high emissions scenario (SSP5-8.5) for both vineyards. In fact, under the latter scenario, in the case of the Loire Valley, the potential yield loss rate doubles from the near-future period to the subsequent periods, while it is always at the highest level in Languedoc-Roussillon (35%) for future periods. Nonetheless, these estimates are potentially conservative since they do not account for the occurrence of multiple heatwaves. For example, under the high emissions scenario (SSP5-8.5), six and seven heatwaves (spell of nine consecutive days) are projected for the Loire Valley and Languedoc-Roussillon by the end of the century, respectively (Table S19). In fact, Fraga et al. (2020) have stressed the need to account for multiple heatwaves when modelling the impact of climate change on European viticulture.

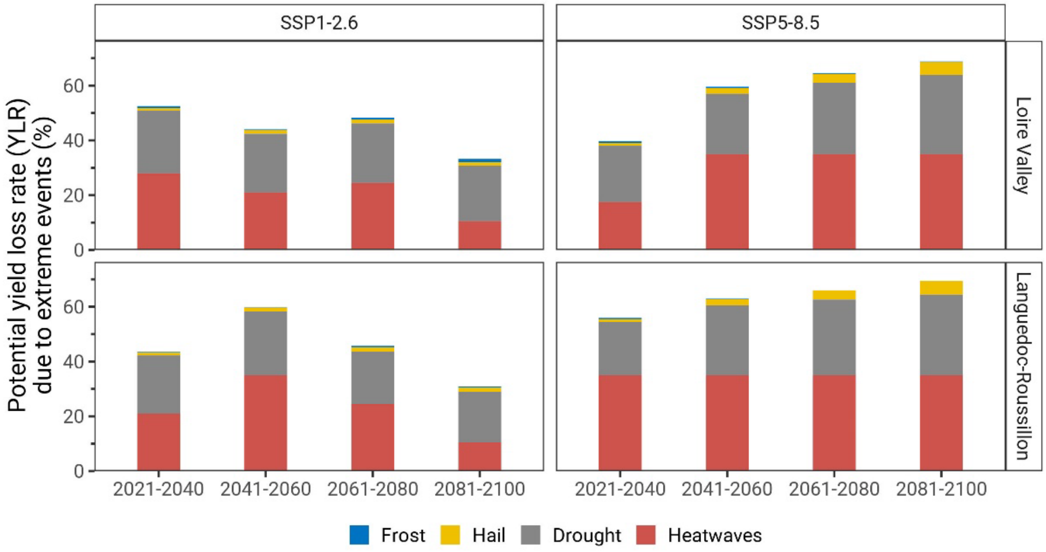


Fig. 5. Potential yield loss rate (YLR - %) due to extreme events on future grape yields for the vineyards of the case study.

While accounting only for the projected climate-induced yields resulted in opposite conclusions about the LCIA results of the vineyard of the case study: a potential decrease of LCIA results in the Loire Valley and an increase in Languedoc-Roussillon under future scenarios (Fig. 4Fig. 4), introducing the impact of extreme events translated into an increase in the life cycle impacts associated with grape production for both vineyards compared to baseline scenarios.

To communicate the impact of extreme events on the LCIA results for both vineyards, Fig. 6 shows the LCIA of the baseline scenarios, the LCIA when no adaptation lever is implemented (grape yield calculated according to the first case of Eq. 4), and the LCIA results when a combination of adaptation options are activated (grape yield calculated according to the second case of Eq. 4 and inclusion of LCIA impacts of adaptation options according to Figure S25). We recall that a combination of adaptation levers for each vineyard may include, besides increasing the number of phytosanitary treatments, the inclusion of irrigation, the installation of anti-hail nets, and oak wood-burning against spring frost according to the expected impact of extreme events for each period and SSP (if their expected yield loss rate is higher than 1%). Fig. S25 shows the combination of implemented adaptation strategies in each vineyard for a given period and SSP. Since our study does not account for adaptation options to mitigate the expected yield loss due to heatwaves, both scenarios of "activated" and "non activated" adaptations account for the yield loss rate due to heatwaves (Eq. 4). Furthermore, the error bars in Fig. 6 correspond to the sensitivity analysis performed on the level of damage of extreme events, which was considered an approximation of the uncertainty arising from the impact of projected extreme events, when the level of damage is increased or decreased by 25% compared to that reported in Table 3.

Fig. 6a shows a sharp increase in carbon footprint for both vineyards due to the impact of extreme events on grape yield. Besides, for this impact category, the implementation of adaptation levers in both vineyards entails lower scores (26% on average) with respect to a situation in which adaptation strategies are not implemented. That is, the avoidance of yield loss by activating adaptation strategies, in most situations, compensates for their related carbon footprint. In fact, other studies have stressed the key influence of yield on the environmental score per kilogram of grapes in both interannual (Renaud-Gentié et al., 2020) and interregional dimensions (Vázquez-Rowe et al., 2012).

The highest increase in carbon footprint for the vineyard from the Loire Valley is projected under the high emissions scenario (SSP5-8.5) by the end of the century, when adaptation levers are not implemented (0.628 kg CO_2eq kg grapes^{-1}), which corresponds to an increase of approximately 191% compared to the baseline scenario. In contrast, the lowest increase in carbon footprint for the Loire Valley is projected under SSP1-2.6 by 2081-2100 when no adaptation strategies are implemented, corresponding to an increase of 44% compared to the baseline scenario. The reason for the latter trend reversal is that the installation of the anti-hail net system and the anti-frost lever increase the related carbon footprint by 73% compared to a situation of inaction (Fig. S25, Fig. 6, see Fig.S26 for the contribution of adaptation levers), whereas the avoidance of the associated yield loss is 2.5%. Because of the uncertainty of spring frost damage and the high carbon footprint of wood-burning (0.21 kg CO_2eq kg grapes^{-1}, Fig. S26), future research may address other adaptation strategies for these events, such as the use of fans, heaters, and changes in the canopy. Regarding the vineyard from Languedoc-Roussillon, the increase in carbon footprint is even more exacerbated under SSP5-8.5 by the end of the century, with an increase of around 326% when adaptation strategies are not implemented (0.935 kg CO_2eq kg grapes^{-1}), and of 187% with adaptation levers (0.630

kg grapes^{-1}) compared to the baseline scenario (Fig. 6a). Under SSP5-8.5, for the vineyard of Languedoc-Roussillon, the related carbon footprint of implementing adaptation strategies is counterbalanced by the prevention of yield loss that these adaptation levers would entail. However, this conclusion is reversed under SSP1-2.6 by 2081-2100 since the expected yield loss rates due to extreme events are lower with respect to other periods (Fig. 5), and particularly that related to heatwaves damage (Table S20).

Fig. 6b shows an opposite trend for the ecosystem quality impacts of grape production in the vineyard from the Loire Valley compared to the carbon footprint shown in Fig. 6a, as including adaptation levers leads to higher impacts, 190% greater on average, compared to a situation of inaction. The latter trend is explained by the high contribution of the anti-hail system and irrigation to ecosystem quality impacts (Fig. S26b). In fact, under the SSP1-2.6, irrigation increases the ecosystem quality impacts by 75% on average, whereas the anti-hail system leads to an increase of around 170% with respect to not adopting adaptation levers, while the potential loss rate due to extreme weather is at most 53% (for the period 2021-2040). Consequently, the related ecosystem quality impacts of implementing adaptation levers are not offset by the avoidance of yield loss due to extreme events. However, in the case of the vineyard from Languedoc-Roussillon under the high emissions scenario SSP5-8.5, the activation of adaptation levers, starting from the period 2041-2060 to the end of the century, leads to lower ecosystem quality impacts with respect to a situation of inaction. The reason of this decrease in ecosystem quality impacts is that including irrigation increases these impacts by 15% on average, and the anti-hail system raises the impacts by 20% in contrast to not activating adaptation strategies, whereas the potential loss rate due to extreme events is 64% on average. Therefore, the associated ecosystem quality impacts of the adaptation strategies are outweighed by the avoided yield loss due to extreme events. In fact, for this vineyard, the increase in ecosystem quality impacts by the end of the century with activated adaptation levers is 255%, whereas the increase is 327% when no adaptation levers are applied, with respect to the baseline scenario.

When considering the human health impacts of grape production (Fig. 6c), the conclusion on the influence of activating adaptation levers to mitigate extreme weather events is similar to the trends of the carbon footprint (Fig. 6a), and in some cases for ecosystem quality (Fig. 6b). The reason for these trends is that human health impacts increase by approximately 7% when adopting adaptation levers in Languedoc-Roussillon (Fig. S26c), avoiding a potential yield loss of around 25%. Likewise, in the case of the vineyard from the Loire Valley, the activation of adaptation options increases the impact by approximately 13%, preventing a potential yield loss of around 25%. However, the impact increases by 34% when including the anti-frost systems, besides the anti-hail system, and irrigation (Fig. S26c). Under these situations, activating adaptation levers counterbalances the influence of yield loss due to extreme events on the environmental profile of grape production. For the vineyard from Languedoc-Roussillon, the human health impacts are approximately 31% lower when adaptation options are applied than in a situation of inaction. Regarding the vineyard from the Loire Valley, the same trend is observed, with a decrease of around 27%. In general, the increase of human health impacts accounting for extreme events and adaptation options are lower with respect to carbon footprint and ecosystem quality impacts. For instance, for the vineyard of Languedoc-Roussillon, the higher expected increase is 116% under SSP5-8.5 by 2081-2100, whereas the highest increase in these impacts for Loire Valley is 69% by the period 2041-2060.

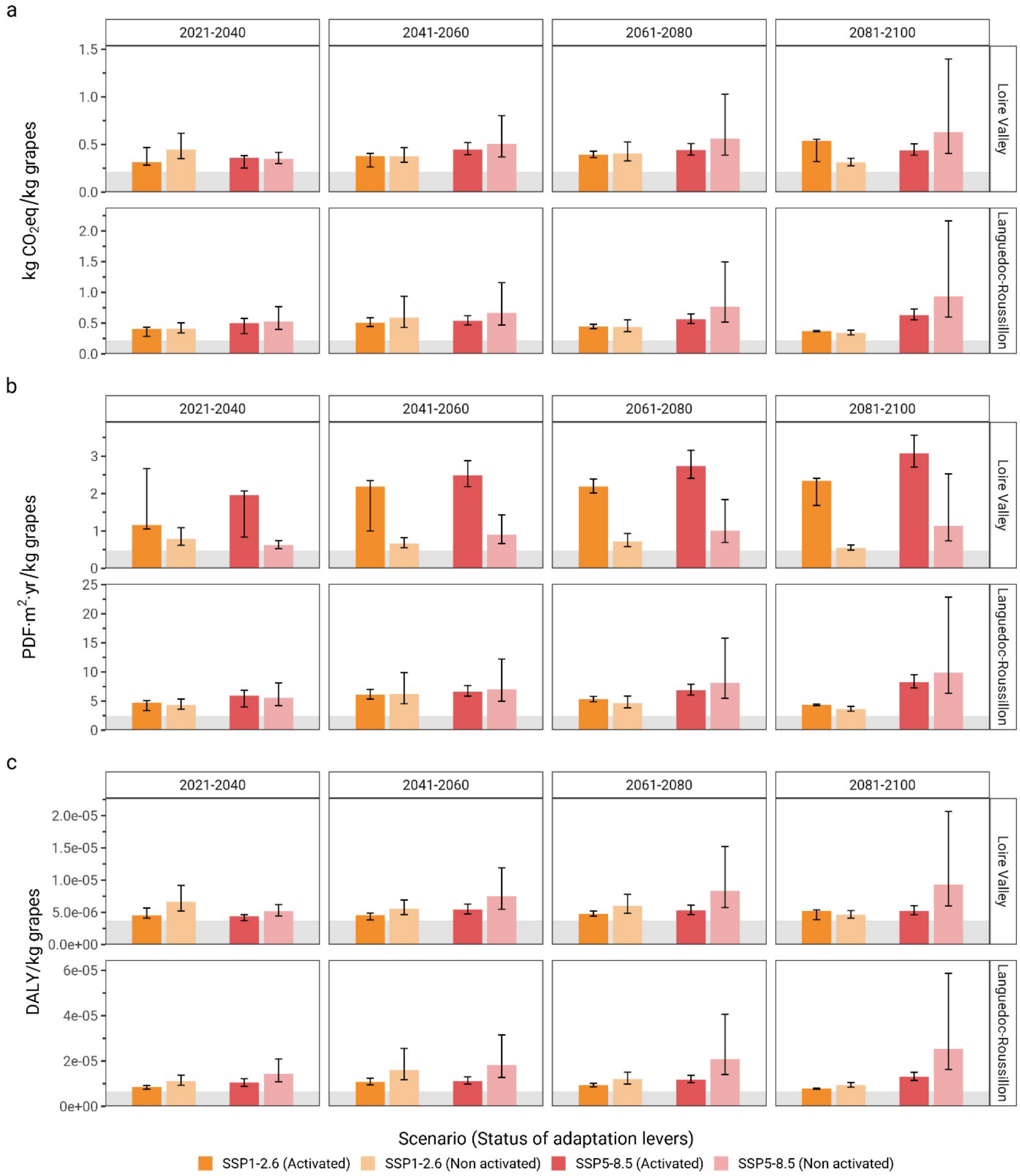


Fig. 6. Carbon footprint (kg CO_2eq·kg grapes^{-1}) (a), ecosystem quality (EQ) impacts (PDF·m^2·yr·kg grapes^{-1}) (b), and human health (HH) impacts (DALY·kg grapes^{-1}) (c) of grape production for future periods under two emissions scenarios in two French vineyards. The height of the lighter shaded envelope behind the bars represents the impact per kg of grapes of baseline scenarios. The lighter bars indicate the impact score when adaptation levers are not activated, while darker bars indicate that adaptation levers are activated. Impact scores were calculated with IMPACT World+ (Bulle et al., 2019). *Please note that in this figure the y-axis is not at the same scale for all the panels.*

Given the exacerbated LCIA results of grape production for the vineyards of the case study when accounting for the impact of both changes in climate variables and extreme events, other adaptation strategies may be required to improve the environmental performance under projected tough climate conditions, and to guarantee grape yield productivity. In this study, due to a lack of data on grape yield, we did not consider introducing grape varieties tolerant to heat and water stress. Shifting to more resistant grape varieties or rootstocks to harsh climate conditions is also an alternative to cope with the effect of extreme events, which would require revising the constraints imposed by current regulations on the allowed varieties in a determined region (Wolkovich et al., 2018). Furthermore, since the analyzed vineyards are examples within the range of technical options implemented in each winegrowing region, future research may address the variability of LCIA results according to the diversity of practices in each territory.

The projected irrigation demands for the vineyards of the case study are relatively low (Table S23), the highest value is 896 m^3/ha under SSP5-8.5 by the end of the century, compared to more water-demanding vineyards where water consumption can reach more than 2600 m^3/ha (Russo et al., 2021). However, regions facing water scarcity, which is the case of the Mediterranean region, should advocate for improved water use efficiency (Romero et al., 2022), or implement low-density systems to cope with projected water scarcity (Naulleau et al., 2021). Although outside the scope of this study, another aspect to consider when envisaging irrigation as an adaptation lever is its impact on wine composition. In the case of high-quality wine, most winemakers are opposed to irrigation, intending to preserve wine typicity (Fraga et al., 2018). While the functional unit of the analyzed product systems is expressed in kilogram of grapes, future research may address the influence of grape quality as a driver of environmental performance.

In this study, we considered that the impacts of extreme weather events on grape yield are additive; however, the synergistic effect of projected extreme water and heat stresses may produce lower grape yields (Fraga et al., 2018). Consequently, the computed LCIA results potentially underestimated the interaction of drought and heatwaves events. Furthermore, this study does not account for changes in vine training systems, which are able to modify the vine microclimate. Still, there is no consensus on the optimal choice of training system to cope with drought (Naulleau et al., 2021).

3.4. Model and data uncertainty and future perspectives

One key objective of models is to help understand the future and to support planning or adaptation. This is particularly important for agriculture, which faces the challenge to mitigate and adapt to the impacts of projected climate change. For this reason, combining the use of future scenarios and LCA is a promising tool to anticipate the impacts and act before the environment is damaged. Still, modelling future scenarios is intrinsically uncertain, without considering the practical challenges associated with their definition. Consequently, in this study, we aimed at projecting plausible future life-cycle environmental impacts of grape production according to the range established by a low and a high GHG emissions scenario and four future periods. While the main goal of this study was to contribute to the scientific discussion on the impacts of climate change on the environmental performance of future viticulture, future research could include participatory approaches to integrate local knowledge, as well as social and economic aspects in the analysis (Naulleau et al., 2021; Rouault et al., 2020).

Several approaches have been used to evaluate the impact of changes in temperature and precipitation on grape yields. We used statistical modelling based on reported grape yields (Agreste, 2021) and climate records (Mavromatis and Voulanas, 2021) to fit linear regressions and to subsequently project grape yield responses. However, we acknowledge some limitations to the application of linear regression to predict future grape yields. Besides precipitation and temperature, other aspects that can influence grape yields such as solar radiation, extreme precipitation and temperature, canopy management, training systems, as well as extreme weather events (though, these were included in the second part of this study). Furthermore, this study does not account for the effects of rising atmospheric CO_2 concentration that potentially stimulate grape yields when nutrients are not limited (Fraga et al., 2016). Still, more multiple-year tests are required to conclude on the effects of CO_2 fertilization on perennial crops (Biavetti et al., 2014). Moreover, the projected changes in grape yields of this study are likely to be conservative since it does not consider nonlinear responses of grape yield to temperature, as has been shown for major crops (wheat, rice, maize, and soybean) (Zhao et al., 2017). In addition, this study does not address the covariability of climate variables, which has been found to play a key role in computing accurate crop-yield sensitivity to climate factors (Leng et al., 2016) and should be addressed in future studies. Nevertheless, this study is consistent with other studies that have analyzed yield sensitivity to climate variables independently (Kukal and Irmak, 2018; Zhao et al., 2017).

We acknowledge some limitations resulting from the quality and availability of input data. Despite the high spatial resolution of the data set of grape yield (Agreste, 2021), the temporal resolution is limited to the period 2000-2020. Even so, the 21-year period for computing grape yield sensitivity to climate of this study is broader compared to the 9-year period considered in a study implementing machine learning techniques for projecting life-cycle environmental impacts of corn production in the U.S. Midwest (Lee et al., 2020). Furthermore, the aggregation of data hindered accounting for the variability of yield sensitivity to climate according to grape variety and agricultural system (conventional, organic). However, this limitation is shared with other studies that have considered a standard grape variety for modelling the impacts of climate change on grape yield at the watershed scale (Naulleau et al., 2022) and European scale (Fraga et al., 2016). Moreover, future research may analyze the influence of introducing grape varieties or rootstock tolerant to severe water and heat stress forecasted under climate change scenarios, as an alternative to decreasing the environmental impacts of grape production under projected climate change. For instance, a study on spring barley production in Denmark showed that the choice of appropriate varieties would be an effective strategy for decreasing the environmental impact of this crop under projected climate change, resulting from keeping or improving crop productivity by 2050 (Niero et al., 2015b). However, grape variety change may have strong consequences on wine organoleptic typicity, which makes this lever still difficult to implement in this sector, specifically in PDO areas. Finally, in this study, we considered wood burning as representative of the adaptation options against frost, which could be a limitation. Indeed, this subject demands further investigations to compare current and emerging active methods against frost, for their diversity suggests that their environmental impacts may be very different from one to the other.

As climate change brings more frequent and longer heat and drought extreme events, there is an increasing concern that these events lead to a decrease in grape yield and quality under future regimes. Nonetheless, it is challenging to quantify the impact of extreme events on agricultural systems, given that it is difficult to adequately set up experiments and calibrate models to estimate the impacts of these events. For instance, the authors of a study assessing the impact of climate change on grape yield at the European scale highlighted the need that future research addresses the influence of extreme weather events on grapevine yield and quality, since it may offer a better understanding of climate change impacts on viticulture (Fraga et al., 2016). In this study, we took a risk approach to account for the impact of extreme events on grape yield, calculated according to the product of their probability occurrence and level of damage. We assumed that farmers have full capacity to respond to these events and that they will make the effort to keep grape yield close to current levels. However, future research could incorporate an economic model to account for different levels of risk aversion among winegrowers (Sacchelli et al., 2017). Even though this study does not account for the interactions of extreme climate change risks, it aimed at providing projections of the impacts of these events on the environmental profile of viticulture under future conditions. Besides, climate change risk assessment is an evolving field that deserves special attention to better account for interactions among several drivers of climate change risks and how these may lead to cascade effects (Simpson et al., 2021).

In this study, we took an attributional approach to estimate the future environmental impacts of grape production in two vineyards, which is consistent with studies that have analyzed small-scale systems (Bisinella et al., 2021). As such, we implicitly extrapolate current system processes to model the background and foreground of viticultural systems under future conditions. As a result, this study does not account for potential changes in the types of pesticides or other agricultural inputs in the future. Hence, this aspect remains part of the “known unknowns” related to climate change, and broadly to future scenario modelling. However, future studies may consider a consequential approach if the aim is to support regulations at a larger scale. For instance, while irrigation is a technical option to mitigate grape yield losses due to drought in the Mediterranean basin, it is expected that the future water demand will not be met for all future vineyards (van Leeuwen et al., 2019). Furthermore, if the aim is to keep future grape production at present levels, this would lead to a snowball effect because of the projected rise of the carbon footprint of grape production, which consequently would lead to higher impacts of climate change on this agricultural system. Other potential impacts of keeping current grape annual production under future less favourable environmental conditions would be competition for land and an increased impact of agriculture due to this feedback loop, which merits further research according to a consequential approach.

Our study addressed the impacts of climate change on future grape production in two French vineyards at the life-cycle inventory level. Nevertheless, projected environmental conditions under climate change, such as increased mean and extreme temperatures, prolonged periods of wetter and drier conditions, changes in soil characteristics, and modified salinity dynamics in estuaries will also alter the fate and effect of pollutants in the environment (Noyes and Lema, 2015). This aspect has not been considered in this paper but merits equal consideration. Therefore, when pertinent, LCIA developers may work on the computation of future characterization factors accounting for projected environmental conditions in the characterization modelling. Some studies have already addressed the development of characterization factors under future scenarios. For instance, Núñez et al. (2015) derived characterization factors for evaluating water use-related impacts of future technologies projected in Spain for a mid-term future scenario by 2030, while Cosme and Niero (2017) computed future characterization factors for marine eutrophication under a high GHG emissions scenario by introducing the impact of future climate-driven changes in the fate, exposure and effect factors.

4. Conclusions

Feasibility of implementing a prospective LCA was demonstrated by using the principle of parsimony (application of relatively simple models with accessible data sets) on two winegrowing case studies. As is often the case in LCA, the lessons learned can be partially counter-intuitive, which is why the approach is interesting in terms of decision support.

The findings of this exploratory research show that projected changes in mean temperature and total precipitation during the wine grape growing season play a key role in influencing grape yield, and consequently in the life cycle impacts of the two analyzed French vineyards. Furthermore, it was shown that the projected increase of extreme weather events, particularly heatwaves and drought, will likely lead to heightened environmental impacts per kilogram of grapes. Finally, including projected climate change when defining agricultural systems appears to be a key aspect to increase the relevance of LCA for supporting decision-making in prospective analysis.

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

Please see the attached file Appendix_A_SD_Viveros-Santos_et_al_2022.pdf containing the supplementary data (SD) for this article.

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