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Version of Record: https://www.sciencedirect.com/science/article/pii/S1364815222000482
Manuscript_7c88323ffe2a654f948852e9ed0ca59d

Participatory modeling to assess the impacts of climate change in a Mediterranean vineyard watershed

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Highlights

- Participation allowed model design tailored to stakeholders' concerns.
- A new grape yield model (GraY) resulted from the participatory modeling approach.
- Without adaptation grape production would decrease from 5 to 16% by 2100.
- Irrigation water needs would double by the end of the century.

Abstract

The diversity of both pedoclimatic and socio-economic contexts in agricultural landscapes makes evaluating the impacts of climate change a challenge. Models are pertinent tools to quantitatively explore possible futures, and participatory approaches help account for local diversity. We developed a model through an approach that involves stakeholders in the model's construction and testing and in the discussion of results. We simulated spatially explicit impacts of climate change on water balance, grape phenology, and yield in a Mediterranean vineyard watershed for two climate scenarios. Results show a decrease in grape production of 7 to 14% by 2100. Yield decrease would be higher in irrigated high-yield areas despite a doubling of irrigation water supply. A forecasted 6°C increase in temperature during berry ripening would threaten wine quality. The approach allows the communication of model results and limitations to stakeholders. It is a promising means of identifying potential local adaptations to climate change.

Keywords: climate change, grapevine, landscape, multi-scale evaluation, spatially explicit model, stakeholders

1 Introduction

Viticultural systems are experiencing previously unseen conditions resulting from climate changes at a global scale. Higher temperatures move phenological stages to earlier periods; warmer conditions during berry growth and increased water deficits alter yield and grape quality (van Leeuwen and Darriet, 2016). Understanding how grapevines are, and will be, impacted by climate change is challenging and requires a combination of approaches (Naulleau et al., 2021). Although process-based crop models such as STICS (Brisson et al., 2003) and VineLOGIC (Walker et al., 2020) provide advantages in the use of climate projections at large scales, they often do not simulate local growing conditions that might permit viable viticulture under marginal conditions (Mosedale et al., 2016). Participatory approaches can help take account of local constraints and diversity and give pertinent information to decision-makers (Delay et al., 2015).

Dynamic crop models are important tools for evaluating long-term impacts from an unprecedented combination of change factors – climatic, technical, economic – with multiple uncertainties. Existing crop models for grapevines at field and regional scales have been used with climate projections to evaluate the impacts of climate change on phenology (Caffarra and Eccel, 2011;

Garcia De Cortazar Atauri et al., 2017; Webb et al., 2007), water status (Pieri et al., 2012; Tissot et al., 2017), yield (Fraga et al., 2016), and hydrological resources (Carvalho-Santos et al., 2016). In a comprehensive review of grapevine models developed in a context of climate change, Moriondo et al. (2015) argue for the use of low-input dynamic models in order to limit data needs for impact studies at a regional scale. Although such existing models are able to consider several management practices (mainly water, nutrient, and canopy management) (Knowling et al., 2021), their application is still limited to a small number of production systems (e.g., trellis systems, bare soil). These systems may not be representative of local and diverse biophysical and socio-economic contexts. Thus they neglect the interplay between local conditions and practices (Knowling et al., 2021), interactions that have been highlighted as key factors of climate change vulnerability (van Leeuwen et al., 2013). As a consequence, the lack of more detailed and spatially explicit information in previous model-based evaluations of climate change impacts limits their contribution to the design of adaptation policies (Santillán et al., 2019).

Modeling is an iterative process in which the involvement of stakeholders can help offset the limits of crop models by creating a shared representation, enhancing the understanding of a dynamic system, and supporting decision making (Voinov, 2008; Voinov et al., 2018). Participatory modeling allows the integration of local knowledge in fine-resolution analyses (Murgue et al., 2016), discussions about model functioning with stakeholders (Hossard et al., 2013), and the production of meaningful indicators (Allain et al., 2018). Involving stakeholders in modeling processes also helps us consider different scales, which is crucial to agricultural system analysis (Delmotte et al., 2013). For example, the field scale is needed to identify the relationship between plant water requirements and production when adapting management practices, while up-scaling to the regional level enables the consideration of connectivity (hydrology, biodiversity), spatial heterogeneity (climate, soil, slope), and aggregated indicators that facilitate decision-making at the policy level (e.g., extension of irrigated areas, evolution of total production). Previous studies have shown that participatory modeling is particularly suitable for analyzing the effects of complex and uncertain situations such as climate change on various agricultural systems like rice (Delmotte et al., 2017), mixed cropping and grazing (Rodriguez et al., 2014), and livestock systems (Duru et al., 2012).

To date, there have been few quantitative evaluations involving stakeholders that examine the impacts of climate change on grapevine systems. We found only two examples (Delay et al., 2015; Tissot et al., 2017) using agent-based modeling approaches. Delay et al. (2015) studied the evolution of grape acidity at field and cooperative-cave scales in a medium-sized area (39 km²). Tissot et al. (2017) studied the evolution of grape phenology, water balance and ripening, as well as work organization at field and farm scales in a small-sized area (1 km²). We believe a new modeling approach that includes stakeholders in a specific vineyard can help coordinate the attention to spatial scale and simulated processes in a way that allows the quantitative evaluation of climate change impacts (including on grape yield). Such an approach should be particularly attentive to both model transparency (Voinov and Bousquet, 2010) and the representation of model outputs (Allain et al., 2018). With respect to transparency, part of our study was dedicated to reducing the model complexity for grape yield in order to improve the understanding of results, especially by the stakeholders. Recent developments show that yield components can be expressed as functions of water stress indicators at critical periods. Van Leeuwen et al. (2019) proposed a model based on expert knowledge, and Guilpart et al. (2014) incorporated more experimental data, demonstrating a relationship between yield components and grapevine water status during critical periods over the course of two years. In a recent review, Knowling et al. (2021) give an overview of the relationship between berry weight and irrigation practices. Overall, evidence seems to indicate that semi-empirical modeling with limited parameters would be judicious and appropriate for a participatory approach to simulate grapevine yields.

The research reported in this paper proposes a new modeling approach that integrates stakeholders in the process of quantifying site-specific climate change impacts. It was applied to a viticultural watershed in southern France and designed to fulfill the following objectives: (1) to use dynamic modeling to incorporate climatic predictions provided by the IPCC over a long time period, (2) to involve stakeholders in an effort to increase local pertinence that represents spatial diversity and several scales, from the field to the watershed, and (3) to produce meaningful indicators that show the impacts of climate change on viticulture and water management in the watershed. The participation of stakeholders for conceptualization, model testing in the reference situation, and discussion of the simulations under future climatic conditions helped improve simulation quality and understanding. Our study also led to the development of an *ad hoc* grapevine yield model, called GraY (Grape Yield), included in an original watershed model. Our results could be useful for local stakeholders and decision makers (wine growers, public institutions, technical adviser, etc.) to identify the most vulnerable areas and then assess site-specific solutions for adaptation.

2 Materials and Methods

2.1 Study area

The study took place in southern France (Figure 1), where viticulture is an important economic activity and is particularly sensitive to climate change. We chose the Rieutort watershed (45 km², 43.5° N, 3.1° E) as a case study because of its location between the southern coastal plain (581 mm mean annual rainfall, data Puisserguier weather station 2000-2019) and the relief of the hinterland to the North (705 mm mean annual rainfall, data Cabrerolles weather station 2000-2019). This area encompasses a diversity of active viticultural systems (1,500 ha): 20 % of the vineyards are located on shale soils in the mountainous area to the North, 60 % are on mainly clay-limestone soil in the central foothills, and 20 % are on more or less differentiated terraces of alluvial soil in the southern part of the watershed. The total vineyard area is divided into two main production types: a protected designation of origin (PDO) characterized by low yields of high-quality wine, and a protected geographic indication (PGI) characterized by higher yield objectives. Irrigation is used in 10 % of the vineyard area (southern portion of the study area).

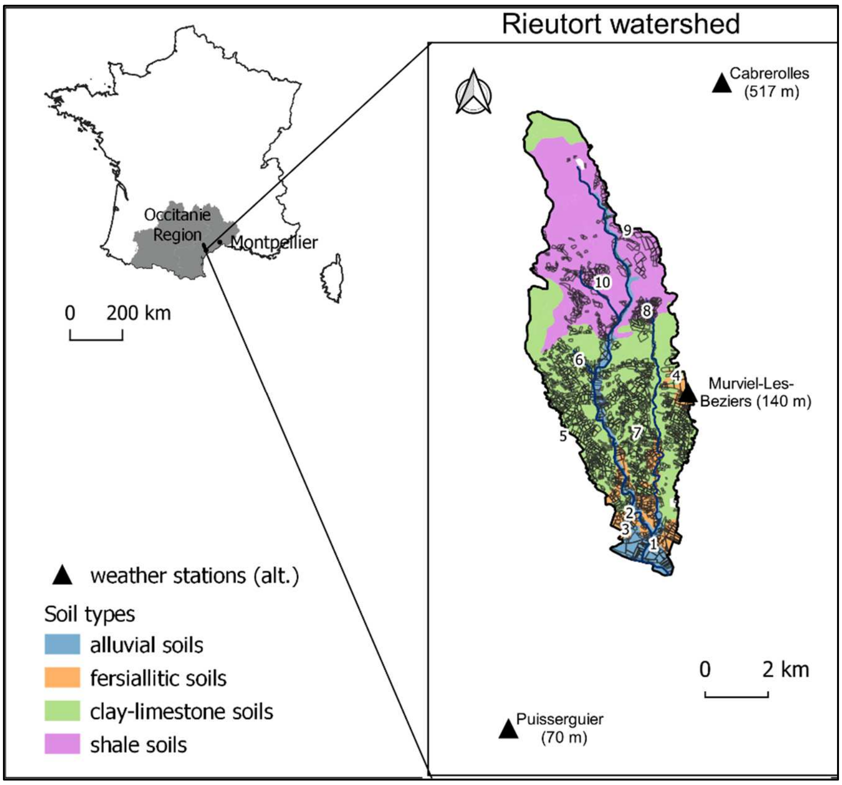

Figure 1: Case study area. Blue lines: main streams; black lines: vineyard plots (based on the French Land Parcel identification system, RPG 2017), other lands being mainly forest and scrubland. Soil types are derived from the 1:100 000 soil map of Lodève (Bonfils, 1993). Numbers corresponds to the location of the 10 experimental plots (see 2.2.2.2). alt: altitude above sea level.

2.2 Participatory modeling approach

Our modeling approach was designed according to the key principles of participatory modeling (Voinov, 2008). It took place in alternating collective workshops and model development phases. A preliminary phase of individual interviews was dedicated to the identification of key stakeholders and to the understanding of the main features of the territory and its cropping systems. The modeling framework was divided into three main steps which were accomplished over the course of four workshops (WS) (Figure 2). The involvement of stakeholders began early in the process. The first step was devoted to the construction of the model, including the conceptualization of the system with stakeholders, the selection of the model components (referred as modules hereafter), their numerical implementation, and the transformation of model outputs into evaluation indicators. In the second step, the model was parameterized and tested, relying on field measurements and the baseline simulation of historical climatic conditions developed with stakeholders. Analysis of the results from model testing led to refinements of the numerical model. A third step entailed simulating the baseline situation in future climatic conditions and discussing its results with the stakeholders.

Table 1 presents the participation of stakeholders. Participants were drawn from the viticulture and water management sector. Researchers participated as "scientists," according to terms described by Leenhardt et al. (2012), to provide scientific knowledge on the investigated processes and the corresponding computer models. One researcher acted as a facilitator. The participants in WS3 and WS4 were divided into two sub-groups: local and regional (number of participants was limited by Covid-19 restrictions), leading to six WS in total (July-2019, Oct-2019, two in June-2020 and two in Feb-2021). The period between workshops varied from three to eight months, resulting in a certain amount of time being needed to review the previous discussions.

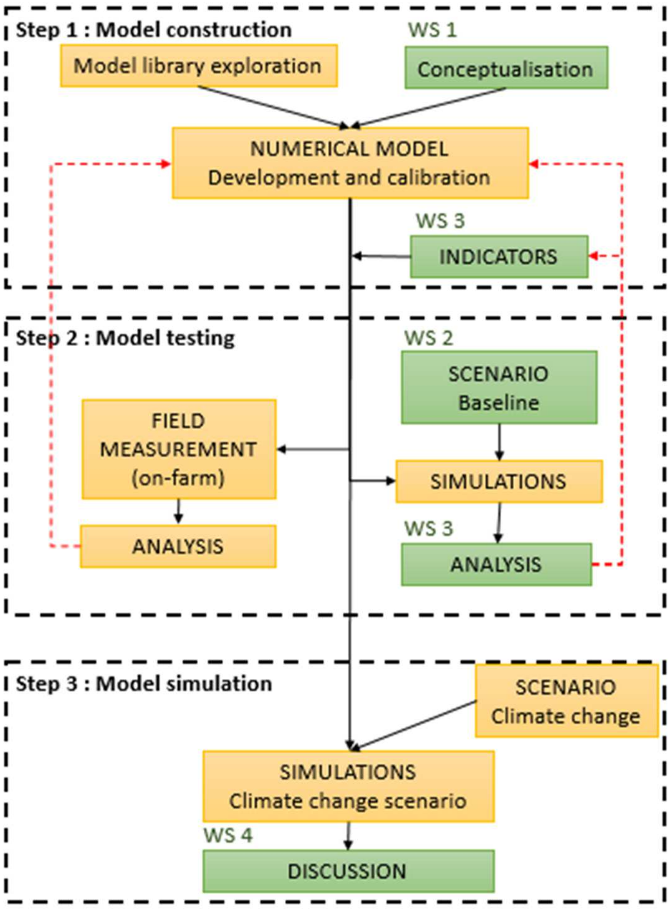

Figure 2: Participatory modeling framework. In green: activities carried out with the stakeholders, in orange: activities conducted by the researchers; WS: collective workshop; black arrows: sequence of activities; red arrows: feedbacks.

Table 1: Number of representatives by type of stakeholders. Int: interviews, WS: workshop, PDO: protected designation of origin. WS3 and WS4 were each carried out in two groups: (a) with regional stakeholders and (b) with local stakeholders

Type of stakeholders	Int.	WS1	WS2	WS3a	WS3b	WS4a	WS4b
Viticulture:							
Wine growers							
-Cooperative cave	3	2	2	-	2	-	2
-Independent cave	5	1	1	-	2	-	2
PDO syndicate	1	1	1	-	1	-	1
Cooperative cellar representative	1	1	1	-	1	-	1
Extension and advisory services	5	-	-	2	1	3	2
Water:							
Agro-environmental coordinator	2	2	2	1	1	1	1
Regional policy maker	2	1	-	1	-	1	-
Local policy maker	1	-	-	-	-	-	-
Researchers	-	4	4	4	2	4	4
Total	**20**	**12**	**11**	**8**	**10**	**9**	**13**

2.2.1 Step 1: model construction

The first workshop (1 day) was dedicated to (1) sharing perceptions on climate change and its impacts, and (2) building a conceptual scheme describing the system. During the workshop, non-researcher participants (9 stakeholders) were asked to describe an outstanding climatic event they associated with climate change, and its consequences. Participants were then divided into two sub-groups and asked to list all adaptation levers they wanted to consider. After pooling the levers, stakeholders selected the most important and detailed the agricultural context that would allow or prevent their implementation. After the workshop, researchers synthesized the collected information into a conceptual scheme in which information was classified as input variables, processes, or output variables. We hypothesized that the coupling of existing models could represent the system described by the stakeholders. So we examined a collection of existing models recently reviewed in Costa et al. (2015) and Moriondo et al. (2011) and made a selection according to the conceptual scheme and the availability of data.

We identified four modules that aligned with the stakeholders' primary aims and could be assembled to constitute a vineyard watershed model (Figure 3): phenology, crop water balance, yield, and hydrology. We chose the grape phenological model recently developed by

Morales-Castilla et al. (2020) to forecast budburst, flowering, and veraison dates (maturity being fixed 35 days after veraison). We used parameters from three varieties (Chardonnay, Syrah, and Cabernet Sauvignon) that have different phenologies and are grown in the Rieutort watershed. Calculated phenological stages were inputs for the daily water balance model. We chose the WaLIS model (Celette et al., 2010) for the simulation of water balance because it has been frequently used in the Mediterranean area (Delpuech and Metay, 2018; Gaudin et al., 2014), and was familiar to a number of the stakeholders. The WaLIS model allowed the consideration of three adaptation levers cited by stakeholders: cover crop management, grapevine canopy management, and irrigation. We implemented an automatic irrigation schedule which was activated when the calculated Fraction of Transpirable Soil Water (FTSW, also converted into predawn water potential according to Lebon et al., (2003)) decreased under thresholds that vary according to the phenological stages and production objectives. We used the thresholds proposed by Ojeda (2007) to maintain a low to moderate constraint: FTSW of 0.21 (-0.3 MPa) between budburst and flowering, 0.12 (-0.4 MPa) between flowering and mid-flowering-veraison, 0.07 (-0.5 MPa) between mid-flowering-veraison and veraison, and 0.04 (-0.6 MPa) between veraison and maturity). WaLIS includes the calculation of runoff based on the curve number method (CN) which is determined from given empirical values, according to land cover, soil hydrological group, and soil state surfaces (Romero et al., 2007; USDA, 1993). It has the advantage working on a daily time-step which is consistent with the climatic projection data. Stakeholders noted total runoff in the watershed as an issue under future climate conditions (decreasing river flow, flood risk, and lower rainfall efficiency). Therefore, we added a hydrological module derived from the MHYDAS model (Moussa et al., 2002) which instantaneously distributes water into the downstream plots, or into streams. The connectivity rules between plots, and between plots and streams, were derived from the Geo-MHYDAS model (Lagacherie et al., 2010). Finally, stakeholders highlighted decreasing yield as one of the major sources of concern when dealing with climate change issues. However, we determined that the existing grape models (Knowling et al., 2021; Moriondo et al., 2015) did not fit our specifications in terms of data availability and consistency with the other chosen models. Consequently, we tailored an *ad hoc* model (Affholder et al., 2012) that coupled the WaLIS model with a Grape Yield response to water model (GraY) derived from Guilpart et al. (2014) (detailed in Section 3.1.2).

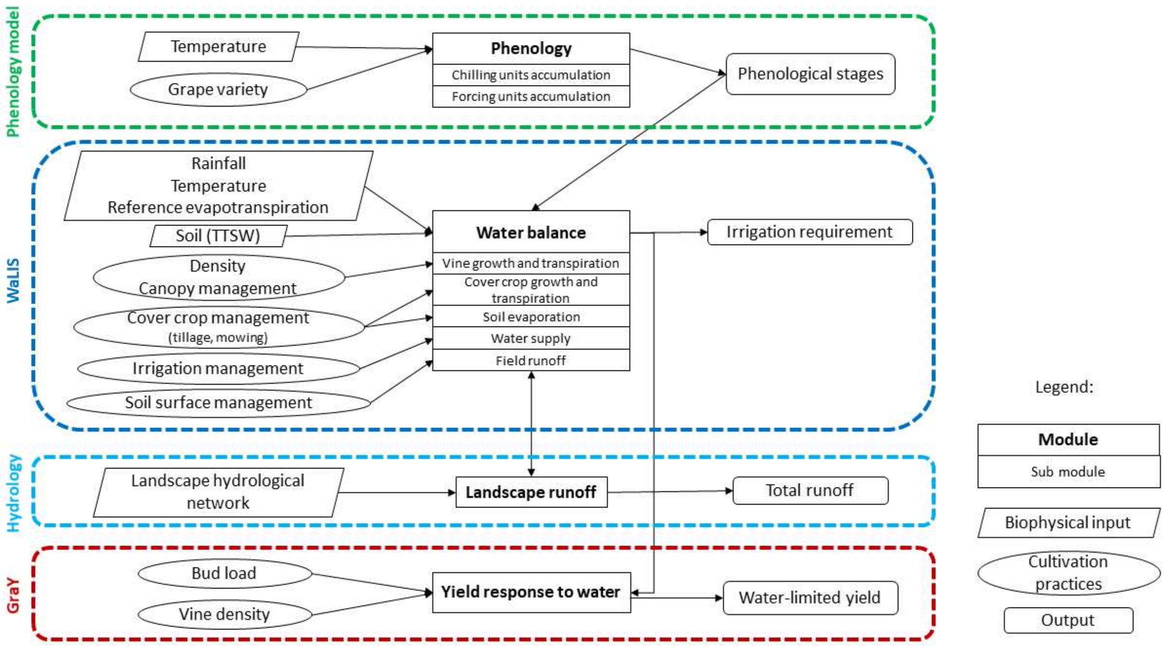

Figure 3: Numerical simulation model composed of 4 modules: phenology (Morales-Castilla et al., 2020), water balance (Celette et al., 2010), a yield response to water module adapted from Guilpart et al. (2014) and a hydrological module derived from Moussa et al. (2002) and Lagacherie et al. 2010. TTSW: Total transpirable soil water. The spatial and temporal model coupling is implemented in OpenFLUID environment at daily time-step.

2.2.2 Step 2: model parameterization and testing

2.2.2.1 Definition of the baseline situation

The second workshop was dedicated to the description of the current grapevine production system, the objective being to implement the watershed model in the baseline situation. First, researchers presented the model together with the conceptual scheme, highlighting the processes included in or excluded from the simulation model. After a discussion about model components, stakeholders described the current situation in order to obtain spatially explicit input parameters. Researchers presented the available maps on land use, irrigated areas, PDO delimitation and soils. Existing information was reviewed by stakeholders and corrected during a participatory mapping exercise. The stakeholders also described practices of irrigation (supply, frequency, restrictions), canopy management (rows spacing, canopy height and bud load), and cover crop management (sowing dates, covered surfaces, tillage or mowing dates) for the different types of grapevine production systems. They then localized those practices on the map. Some information was difficult to collect during the workshop. Therefore, additional information (e.g., varietal distribution in space) was provided later by local participating institutions.

After the workshop, the researchers transformed the collected information into model inputs to simulate the baseline situation. Since we did not have spatialized data for the varieties, we calculated the portion of early, mid, and late ripening varieties by type of production, using the data provided by the stakeholders. Then we attributed a variety type (early, mid, late ripening) to each vineyard plot according to its type of production and with respect to the calculated ratios. We only simulated the yield response to water (GraY model) for the Syrah variety (constituting 50% of the Rieutort vineyard area), because we did not have sufficient data nor the local expertise for calibrating other varieties.

The third workshops (WS3a and WS3b, four hours each) were dedicated to the discussion of the simulation results for the baseline situation at the field scale and for historical climate (1981-2010). This included graphical representation of model outputs for 10 representative situations (e.g., yield, phenological date, daily runoff, vine water status). During the presentation, stakeholders were asked to share their analysis of the simulation results, their agreement or disagreement, as well as their suggestions to improve the model. This step allowed the adjustment of some model inputs and parameters before presenting the results at the watershed scale.

The adjustments suggested by stakeholders during the parametrization step led us to conduct on-farm monitoring. This was (i) helpful in building trust in the model with a quantitative comparison of observed and simulated data, and (ii) it allowed us to estimate soil parameters (TTSW: total transpirable soil water) that could not be estimated by stakeholders during workshop.

2.2.2.2 Field monitoring network

The quantitative evaluation of the WaLIS-GraY model (i.e., coupling of WaLIS and GraY models) was based on on-farm data collected in the Rieutort watershed. We monitored the grape water status and yield components of 10 contrasting plots (soil type, production type, cover crop management, and irrigation access) on the basis of the production systems described by stakeholders in WS2 (Figure 1 and full description in appendix A – Table A.1). For each plot, 30 plants were monitored from March to September 2020. The grapevine water status was monitored during summer (three measurements from June to August) by measuring the predawn leaf water potential with a pressure chamber (Soil Moisture Equipment Corp., Santa Barbara, USA), on 12 fully expanded leaves per plot. The yield, shoot, and bunch numbers were measured on the 30 vine plants. On each of these plants, one bunch was randomly selected to obtain the number of berries per bunch and the averaged berry weight from a sample of 200 berries.

To simulate the grapevine yield with the WaLIS-GraY model, we first parameterized the WaLIS model (Celette et al., 2010) that simulates the time course of FTSW (Fraction of Transpirable Soil Water) at a daily time step. Simulations were conducted for the 10 plots, from September 2018 to September 2020. We used the weather data recorded at the weather station of Murviel-les-Beziers (Figure 1). Maximum crop coefficient (Kmax) was calculated with the model of Riou (Riou et al., 1989) using measurements of the average canopy size (height, wide, porosity) of the 30 vine plants in each plot. Parameters describing spontaneous cover crops (e.g., LAI growth rate, leaf life span) were taken from Andrieux et al. (2015). Total transpirable soil water was estimated by inversion of the WaLIS model (Pellegrino et al., 2006). Parameter values for all the simulations are given in Appendix A (Table A.2). The quality of the simulations was assessed against observed values of predawn water potential converted into FTSW (Lebon et al., 2003), observed yield, and yield components. Four statistical criteria were calculated to assess the model performance: the model efficiency (EF), the coefficient of determination (R^2), the normalized average error (NAE), and the normalized root mean square error (NRMSE) (Janssen and Heuberger, 1995).

2.2.2.3 Choice of output representations

The third workshops were also tasked with choosing the evaluation indicators (i.e., the model outputs representations) that would be presented at watershed scale during the following workshops. After discussing the outputs of the model at the field scale, stakeholders selected those of interest. For each selected output, researchers asked stakeholders to define the relevant temporal aggregation (e.g., seasonal variability, annual mean), spatial aggregation (e.g., mean by soil type, by production type), and type of representation (map, bar plot, table).

2.2.3 Step 3: model simulations at watershed scale

Future climate data were obtained from the regional climate model CNRM-ALADIN version 5.2 (http://www.umr-cnrm.fr/spip.php?article125&lang=en). Projections were bias corrected using the cumulative distribution functions (CDF) transformation proposed by Michelangeli et al. (2009).

We used the daily meteorological data from Murviel-les-Beziers weather station (Figure 1) between 1990 and 2005, to correct the projections on the central climatic area of the watershed (Table 2). The same correction was then applied to the northern and southern climatic areas (Appendix A – Table A.3). We simulated the baseline situation described by stakeholders for the historical period (1981-2010), two time horizons (2039-2060 and 2069-2100), and two Representative Concentration Pathways (RCP 4.5 and 8.5). The reference evapotranspiration ET_0 was calculated according to Penman-Monteith equation (Allen et al., 1998).

Table 2: Simulated average and standard deviation of climatic characteristics for the central area of the Rieutort watershed (Data Meteo-France – CNRM-ALADIN). Annual values were calculated from September to August; growing season values from April to September. RCP: Representative Concentration Pathway

	1981-2010	2031-2060		2071-2100	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Annual precipitation	692 mm (±257)	-1.2 %	-8.5 %	-1.9 %	-12 %
Growing season precipitation	229 mm (±119)	+3.9%	-3.5 %	+12.8%	-10.9 %
Annual mean temperature	14.4°C (±0.5)	+1.2°C	+1.6°C	+2.1°C	+3.9°C
Growing season mean temperature	19.2°C (±0.9)	+1.5 °C	+1.9°C	+2.4°C	+4.6°C
Annual cumulated ET_0	986 mm (±148)	+7.5 %	+9.5 %	+12.0 %	+ 21.0%

In the near future (2031-2060), the increase in temperature and reference evapotranspiration are similar for RCP 4.5 and 8.5. Conversely, growing season precipitation is predicted to increase in RCP 4.5, while it is predicted to decrease in RCP 8.5. Changes in the far future (2071-2100) are accentuated in RCP 8.5, with an increase of 4°C in temperature, and a decrease of 12% in rainfall. It is worthy to note that the growing season rainfall is projected to increase (+12%) in RCP 4.5. Similar trends are observed for the northern and southern climatic areas. By the end of the century, in RCP 8.5, temperature increase will be more pronounced in the northern areas (+5°C) and annual rainfall will decrease below a critical threshold for grapevine growth in the southern areas, with an average annual precipitation of 520 mm (Appendix A – Table A.3).

Finally, we ran the watershed model of the baseline situation, with the five climate scenarios. The results of the simulations were presented to the two groups of stakeholders in WS4a and WS4b (4 hours each). After a brief reminder of model characteristics and climate change scenarios, the simulations results were presented using the indicators collectively built in WS3. After the presentation, stakeholders were asked to share their analyses of the scenario simulations.

2.3 Modeling software and representations

The spatial and temporal model coupling was developed using the OpenFLUID software platform for spatial modelling in landscapes (http://www.openfluid-project.org) (Fabre et al., 2013). The open source software framework and user environment of OpenFLUID was chosen for its original features that are relevant for this work:

- representation of simple and complex landscapes, such as agricultural landscapes, made of spatial objects with associated attributes and spatial connections,
- easy integration of existing modules or development of new modules,
- spatio-temporal model coupling at various scales,
- adaptable input and output data formats for easier pre- and post-processing.

The complete coupled model (Figure 3) was implemented as plugged modules in the OpenFLUID platform, using C++ language and embedded R code (Eddelbuettel et al., 2020). Simulations were defined as parameterized OpenFLUID projects, and results were post-processed using the R software (R Core Team, 2018) with "ggplot" (Wickham, 2016) and "cartography" packages (Giraud et al., 2020).

3 Results

3.1 From the conceptual scheme to the simulation model (step 1)

3.1.1 Conceptualization with stakeholders

The first workshop (WS1) completed two tasks: (a) a list of climate change impacts and corresponding adaptation levers that were collectively discussed, and (b) a conceptual scheme constructed by researchers and based on the workshop discussions. During the workshop, a consensus around preoccupying climatic events was reached, with a particular focus on the water and temperature regimes (e.g., increase in intra-annual rainfall variability, frequency of heavy rains, heat waves, strong winds). The participants identified a large range of impacted processes following such events: agronomic (yield, plant mortality, phenology, pest pressure), environmental (streamflow, irrigation water consumption), and economic (regional economy, irrigation costs). They considered various adaptation levers which they were asked to classify according to spatial and time scales. Two groups of adaptation levers were discussed: long-term adaptations at planting (row orientation, drought tolerant varieties, training system, rootstocks, etc.), and seasonal adaptations (canopy management, organic fertilization, irrigation, etc.). The opportunity or challenge to implement these adaptations levers depend on various aspects of the landscape (water access, PDO delimitation), the farm (adaptive capacity, equipment, investment capacity, yield objective, winery, etc.), and the field (soil type, vine age, slope, PDO regulations).

Researchers designed a conceptual scheme based on the elements collected during WS1 (Figure 4) and presented it to stakeholders for validation in WS2. The comparison between the conceptual scheme and existing simulation models led to the modeling choices described in Section 2.2.1. The absence of non-simulated processes and adaptation levers could be explained by the lack of data in the watershed (e.g., farm data, soil analyses), the absence of modeling tools (e.g. farm-decision model, pest pressure), or the lack of certain information (rootstock effect, yield response to water for different training systems and varieties). Yield quality and heat damage were not directly modeled because the discussion primarily focused on the relationship between yield quantity and water availability. However, agro-climatic indicators that give information on climatic risk on yield and its quality were designed with the stakeholders later in the process (see section 3.2.3).

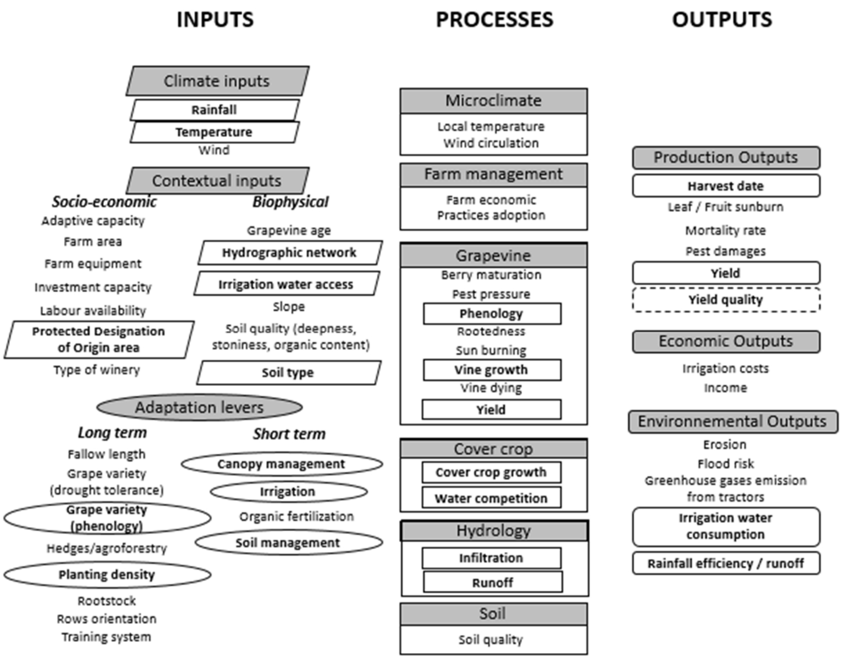

Figure 4: Conceptual scheme derived from WS1 discussion. Inputs are indicated on the left, model components with associated processes in the middle, and outputs on the right. Only the framed and bold items are included in the watershed simulation model. Dotted frames indicate an item deduced from model simulation outputs.

3.1.2 Development of the grape yield model GraY

The complete numerical model is presented in Section 2.2.1. Here, we detail the Grape Yield model (GraY) which was developed after recognizing the importance that participants gave to the evaluation of grapevine yield evolution under future climatic conditions.

The grapevine yield was decomposed as in Guilpart et al. (2014):

$$Yield = nShoot * fBud * nBerry * wBerry * 10^{-3}$$

where *Yield* is the fresh yield (in kg/plant), *nShoot* is the number of shoots per plant (fixed by pruning operation), *fBud*, *nBerry*, are *wBerry* are bud fertility (i.e., number of bunches per shoot), the number of berries per bunch and the mean berry weight (in g), respectively.

Each of these yield components was calculated as a function of the soil water availability simulated by the WaLIS model (FTSW), at critical phenological phases. These response functions were parameterized with data sets from Guilpart et al. (2014) and Gaudin et al. (2014) (complete dataset description in Appendix B – Table B.1). Daily simulated FTSW were averaged for thermal time periods of 100°Cd (cumulative thermal degree in base 10) from budburst to harvest. For each period the Pearson coefficient between each yield component and mean FTSW was calculated, and its significance was tested. By this means, we identified four critical periods – consistent with Guilpart et al. (2014) – during which yield component values are highly and significantly correlated with mean FTSW: between 500 and 600°Cd in year n-1 for bud fertility, between 700 and 800°Cd in year n-1 for berry number per bunch, between 800 and 900°Cd, and between 1400 and 1500°Cd in year n for berry weight (detailed in Appendix B – Fig. B.1).

The response curve of yield components to mean FTSW during critical period ($\overline{FTSW_{crit}}$) was derived from these statistical analyses (Figure 5 A, B, C). Each yield component remained at maximum between $\overline{FTSW_{crit}} = 1$ and a threshold value $FTSW_{th}$, and decreased linearly between $FTSW_{th}$ and $\overline{FTSW_{crit}} = 0$. Yield component maximum, minimum, and threshold values were obtained using the Nelder-Mead minimization algorithm (Nelder and Mead, 1965). Bud fertility varied between a minimum of 0.2 bunches/shoot and a maximum of 2 bunches/shoot. Number of berries per bunch varied between a minimum of 65 berries/bunch and a maximum of 200 berries/bunch. Berry weight varied between a minimum of 1 g and a maximum of 2 g. Threshold values $FTSW_{th}$ were 0.7, 0.6 and 0.22, respectively.

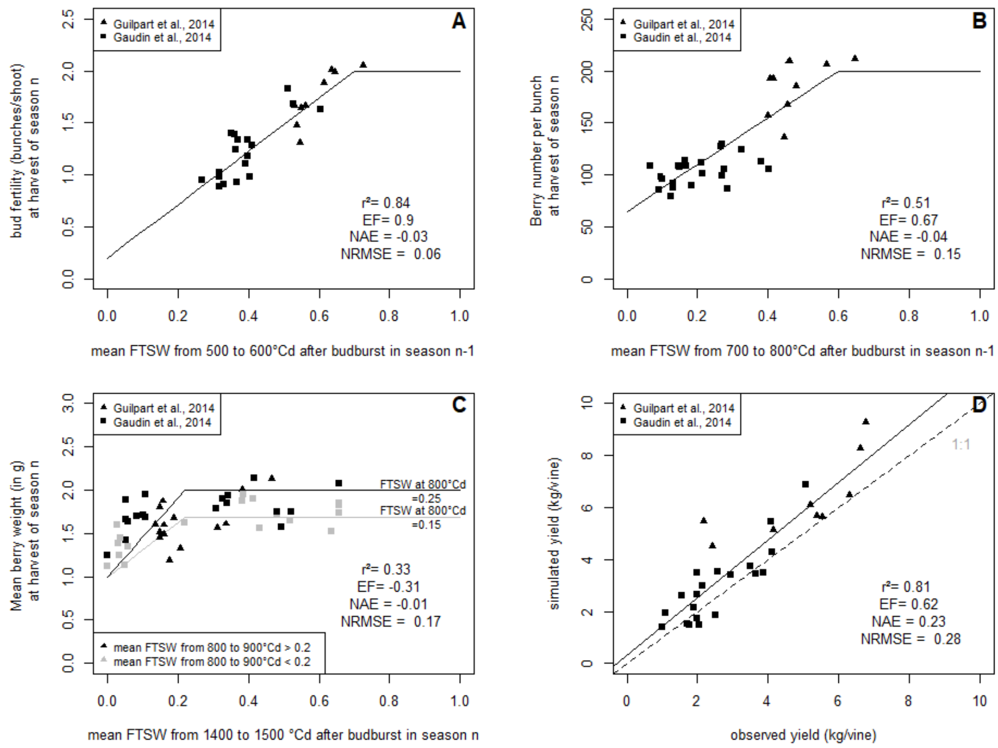

Figure 5: Grape Yield model (GraY) calibration for Syrah variety: A) bud fertility, B) number of berries per bunch and C) berry weight as a function of the mean fraction of transpirable soil water during the corresponding critical period ($\overline{FTSW_{crit}}$). D) Simulated and observed yield (supplementary figures in Appendix B – Fig B.2). r²: coefficient of determination; EF: model efficiency; NAE: Normalized average error; NRMSE: Normalized root mean square error.

Simulated and measured yields were compared for the two data sets together (Figure 5D). The overall correlation was significant (R^2=0.79, $p<0.05$) and proved the capability of the WaLIS-GraY model to catch the major sources of variability found in the experimental yield data. The values of NRMSE (29%) and model efficiency (0.6) attest to the ability of the modeling solution to reproduce measured yields. Simulated yields tended to be higher than the observed ones, especially for high yields (NAE = 0.16). A possible reason is the lack of consideration for other limiting factors, such as nitrogen, as evidenced by Guilpart et al. (2014).

3.2 Model testing (step 2)

3.2.1 Description of the baseline situation

The second workshop started with the identification of the key location factors that determine the spatial distribution of grapevine production systems. Stakeholders first considered soil type as the main factor. They modified the soil map to delimit five main units. Alluvial and fersiallitic areas were unchanged, but the "clay-limestone" area was divided into two areas that identify the soils from the central part of the watershed as more shallow and stonier. They also divided the "shale" area into two areas, indicating more soil heterogeneity in mountainous areas, although those areas were difficult to delimit precisely. Cover crop management was identified as closely linked to soil type due to different levels of weed competition and soil water availability. Three characteristics of cover crop management were described: a destruction date of spontaneous winter cover (from the 15th of February for alluvial, fersiallitic, and non-stony clay limestone soils to the 1st of March for other soils), a date of mechanical tillage after harvest (15th of October—for southern sector only), and a number of inter-rows kept covered during summer (1 inter-row in 4 for 33 ha in the watershed).

The second factor that stakeholders highlighted as a key determinant of spatial distribution of grapevine production systems was the type of wine production (PDO or PGI) directly linked with yield objectives. The location of PDO production areas was provided by PDO syndicate representatives; PGI areas were deducted from all the remaining areas. For each type of production, stakeholders reported the planting density (from 4000 vines/ha in PDO area on shale soil to 4500 vines/ha for other areas), the canopy height (from 1.1 m to 1.4 m), the bud load (from 9 to 15 buds/vine), and the grapevine varieties. We found no early ripening varieties in PDO production sectors, which averaged 80% mid-ripening varieties and 20% late-ripening varieties. By contrast, the variety distribution in PGI sectors averaged 30% early-ripening, 40% mid-ripening and 30% late-ripening varieties.

The last factor was the access to water irrigation for PGI production in the southern part of the watershed. Opinions on the irrigation management to implement in the model varied among the local and regional stakeholders, but finally, irrigation supplies were fixed at 20 mm for the first supply and 10 mm afterwards, with unlimited annual supply from budburst to harvest.

These factors led to eight production sectors which are presented in Figure 6. Each sector corresponds to a block of similar grape growing systems (soil, type of production, irrigation practices). Sectors 1 to 3 are in the southern climatic area, sectors 4 to 6 are in the central climatic area, and sectors 7 and 8 are in the northern climatic area.

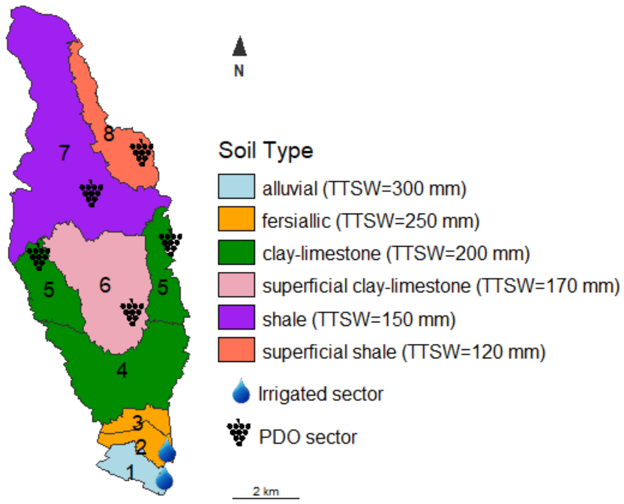

Figure 6: Presentation of the baseline situation according to the eight production sectors defined during the second workshop. TTSW = Total transpirable soil availability determined by the WaLIS model inversion. PDO: Protected designation of origin.

3.2.2 Quantitative evaluation of the WaLIS-GraY model with on-farm measurements

The 10 monitored plots, located in the eight production sectors, produced yields ranging from 1.03 to 7.73 kg/vine. Water status varied significantly during the 2020 season which was characterized by a wet spring (244 mm from March to May) and a dry summer (81 mm from June to August), thus allowing soil water recharge at the beginning of the season followed by a progressively important water constraint. Measured predawn water potential in mid-August ranged from -0.4 to -0.9 MPa. Table 3 shows the evaluation indicators of the WaLIS-GraY model, including soil water availability (FTSW) and yield components. The simulated FTSW was in agreement with measured predawn water potential for eight of the 10 plots (EF > 0.57). The differences between simulated and observed FTSW could partly be explained by the low ability of the WaLIS model to simulate a goblet training system in plot 8 and by the lack of consideration for leaf damage caused by disease that was observed in plot 4. The normalized average error was between 5 and 35% and was negative for seven plots. Simulated data tended to slightly overestimate soil water availability.

The GraY model was quite proficient at simulating grapevine yield. The R^2 and EF values were 0.86 and 0.71, respectively. The normalized average error was negative (-0.21%, i.e., -0.58 kg/vine) showing a yield underestimation, with variation among fields. While simulated bud fertility – a major determinant of grapevine yield – showed a positive model efficiency (EF = 0.27), the simulated number of berries and berry weight exhibited a negative model efficiency. Those components may compensate for each other and result in good predictions of yield. We presume that the prediction of the number of berries could be further improved by considering the current season's climatic conditions, primarily air temperature and rainfall (Zhu et al., 2020). Nevertheless, R^2 and NRMSE were satisfactory and significant (R^2 = 0.53 and 0.49, NRMSE = 0.27 and 0. 19, resp.).

Table 3: Goodness-of-fit indicators of the simulations performed with the WaLIS-GraY model for the 10 experimental plots (supplementary figures in Appendix A – Figure A.1). FTSW: Fraction of soil transpirable water, fBud: bud fertility, nBerry: number of berries per bunch, wBerry: berry weight in g. N: Number of observations; R^2: coefficient of determination (p<0.1, ** p-value < 0.05); EF: model efficiency; NAE: Normalized average error; NRMSE: Normalized root mean square error.*

	FTSW										Yield component			
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	fBud	nBerry	wBerry	Yield
N	3	3	3	3	3	3	3	3	3	3	10	10	10	10
R^2	0.85	0.98*	0.96	0.41	0.99*	0.87	0.96	0.97*	1**	0.98*	0.44**	0.53**	0.49**	0.86**
EF	0.61	0.89	0.95	-5.8	0.70	0.57	0.53	-1.37	0.86	0.98	0.27	-0.32	-0.67	0.71
NAE	0.20	0.15	-0.06	-0.26	-0.32	-0.30	-0.35	1.21	-0.31	-0.05	0.09	-0.22	-0.15	-0.21
NRMSE	0.34	0.34	0.16	0.60	0.37	0.42	0.39	1.30	0.32	0.14	0.36	0.27	0.19	0.37

3.2.3 Evaluation indicators for watershed simulation

The second part of the third workshop produced a list of indicators aimed at representing the impacts of climate change at watershed scale (Table 4). The group of regional stakeholders (WS3a) selected mainly field-scale indicators to represent the level of grape production and water use (irrigation and runoff). They also designed indicators to estimate the climatic risks on grape production, in terms of both quantity and quality. Those indicators consisted of identifying the temperatures that are detrimental to the vine production (frost, scalding, berry maturation conditions). Researchers added some indicators which relate to the entire watershed, because up to this point the watershed scale had not been fully represented. The added indicators relate to climate change impacts highlighted in WS1 (Table 4).

Table 4: List of co-designed indicators, along with their description, scale and source (S: stakeholders, R: researchers)

Indicator	Description	Scale	Source
Production			
Yield	30-years yield average (t/ha)	Sector	S
Total grape production	30-years average of the total amount of grapevine production (in 1000 hl)	Watershed	R
Risk to production			
R_frost	Number of years out of 30 with Tmin < 0°C between budburst and flowering dates	Climate area	S
R_heat	Number of years out of 30 with Tmax > 40°C between flowering and veraison dates	Climate area	S + (Crespy, 1992)
R_Tmax_mat	Number of years out of 30 with Tmax > 37°C between veraison and maturity dates	Climate area	S + (Bergqvist et al., 2001)
R_Tmin_mat	Average Tmin between veraison and maturity dates (°C)	Climate area	S + (Tonietto and Carbonneau, 2004)
Ampli_T	Average Tmax – Tmin between veraison and maturity dates (°C)	Climate area	S + (Neethling et al., 2012)
Water			
Irrigation needs	30-years average of the annual amount of irrigation water requirement (mm)	Field	S
Seasonal irrigation needs	30-years average of monthly amount of irrigation water requirement (mm)	Field	R
Total irrigation needs	30-years average of annual amount of irrigation water (m^3)	Watershed	R
Total run-off	30-years average of the annual sum of runoff reaching the hydrological network (m^3)	Watershed	S

3.3 Simulations under current and future climatic conditions (step 3)

3.3.1 Phenological dates and associated climatic risks

In the historical period (1981-2010), phenological stages (budburst, flowering, veraison and maturity) occur earlier in southern areas than in northern areas (Figure 7A). This 13-day difference between harvest dates was confirmed by stakeholders in WS4 and is mainly due to milder temperatures and late-ripening varieties in the northern areas. At the horizon 2050, the two climate scenarios show similar predictions with harvest dates being 10 days earlier, on average, than historical dates. At the horizon 2100, phenological advance is more pronounced for RCP 8.5, with a more important advance in the northern areas, where budburst occurs 13 days earlier, and harvest occurs 23 days earlier. Projected phenological dates show a shortening of the grapevine cycle ranging from 2 (RCP45_2100) to 10 days (RCP85_2100).

Earlier budburst does not lead to an increased risk of frost because the date of the last frost in climate projection also advanced (Figure 7B). However, stakeholders professed: *"despite the lesser occurrence of frosts, we are still afraid of a late frost"*. The combined effects of advanced phenology and increased temperatures lead to an increased risk of heat damage between flowering and veraison by the horizon 2100. Berry maturation conditions change faster. For the time horizon 2050, night temperatures increase by 3.5°C and maximal night temperatures exceed 37°C more than two years in three, which could alter berry maturation processes. For the time horizon 2100, as highlighted by a participant of WS4b: *"a nighttime temperature of 23°C during maturation, that's hot"*.

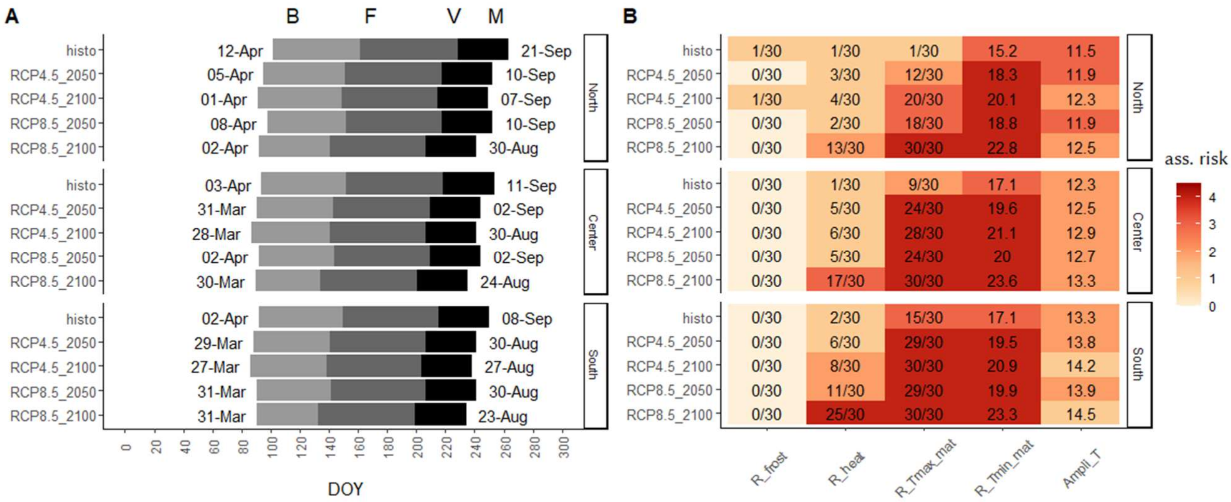

Figure 7: A) Simulated phenological stages (B: budburst, F: flowering, V: veraison, M: maturity) and B) associated risk indicators (R_) for yield quantity (frost, heat) and quality (ripening inhibition, fresh night, thermal amplitude), same units as in Table 4. Data are presented according to the three climatic areas (top: north, middle: center, bottom: south) in the historical period (1981-2010), and for two time horizons (2031-2060 and 2071-2100), according to two representative concentration pathways (RCP).

3.3.2 Irrigation needs and total grape production

Mean simulated irrigation requirements for the historical period are 21 mm per year (Table 5), which seemed low to stakeholders with respect to current practices: "*these are the requirements, not the inputs. You'd be surprised by the difference; the reality is more than 100 mm*". There are several possible reasons for the difference between model outputs and stakeholder statements. First, the irrigation needs were presented as a 30-year average, including many years that do not require irrigation. Second, stakeholders mentioned that the actual irrigation amounts are greater than real needs. Nonetheless, they highlighted the need for efforts to reduce the gap between grapevine water requirement and inputs. In future climate scenarios, irrigation requirements increase by 62 to 85% at the horizon 2050 and are predicted to more than double by the end of the century in the RCP 8.5. The largest increases in water requirements occur during spring, although historical spring irrigation is almost nil. These predicted requirements, however, remain lower than the current practices estimated by local stakeholders.

Total grapevine production at watershed scale is expected to decrease from -5% to -11% by mid-century (Table 5). The decrease in production is relatively similar in RCP 4.5 for both time horizons (-5 to -7%), whereas the predicted decrease reaches -14% in RCP 8.5 for 2100. The type of production that undergoes the most important decrease is the PGI irrigated production, despite the increase in irrigation water supply. An explanation could be the irrigation thresholds that might be too low to maintain high yield under future climatic conditions. We expect that yield losses could be limited by higher irrigation levels. In any case, irrigated production represents a small part of the Rieutort grapevine production (< 20% in volume) and maintaining the production in those irrigated areas would not counteract the global drop of production at watershed scale. Stakeholders argued for "*a better sharing of water resources*" and defended the idea to "*consider other irrigation practices for high-quality production"* in order to reach the objective of limiting irrigation, while securing production.

Table 5: Irrigation requirements and grape production under future climatic conditions. PGI: protected geographic indication. PDO: protected designation of origin. RCP: Representative concentration pathway.

Indicators	1981-2010	2031-2060		2071-2100	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
At field scale					
Irrigation requirements (mm)	21	34 (+ 62%)	38 (+85%)	37 (+76%)	49 (+133%)
-Spring irrigation requirements (March to May)	3	11 (+ 267%)	10 (+ 233%)	10 (+ 233%)	14 (+ 367%)
-Summer irrigation requirements (June to Sept)	18	23 (+ 28%)	28 (+ 56%)	27 (+ 50%)	35 (+ 94%)
At watershed scale					
Total production (1000 hl)	111	105 (-5%)	99 (-11%)	103 (-7%)	95 (-14%)
- PGI irrigated	20	17 (- 15%)	17 (- 15%)	16 (- 20%)	16 (- 20%)
- PGI non-irrigated	49	44 (- 10%)	42 (- 14%)	44 (- 10%)	41 (- 16%)
- PDO	42	43 (+ 2%)	40 (- 5%)	43 (+ 2%)	39 (- 7%)

3.3.3 Grapevine yield

During the historical period (1981-2010), lower yields (<5 t/ha) are found in the northern area with PDO production on superficial soil, while the highest productivity sectors (> 14 t/ha) are located in the southern and irrigated areas (Figure 8). These patterns showed a general agreement with stakeholders' perceptions. Projections show contrasted yield evolution according to the two RCPs. In RCP 4.5, modeled yields slightly increase in the northern sectors. This could be explained by two factors: the more pronounced advance in phenology that avoids drought periods after flowering period (critical period for bud fertility and berry number determination), and the higher summer rainfall amounts predicted in RCP 4.5 (Table 2) that refill soil water reserve more efficiently in superficial soils. In the other sectors, yields decrease by 10% in 2050 and 20% in 2100. In RCP 8.5, the yields in all sectors were predicted to decrease by 10 to 20 % in 2050 and as much as 30% for the southern sectors in 2100. The important yield decrease in the southern irrigated area could be explained by the particularly low annual rainfall amounts predicted with the RCP 8.5 scenario (< 530 mm). It is worth noting that the model could overestimate the yield decrease in the southernmost sector because it does not consider the presence of a groundwater table that could mitigate the vineyard water stress.

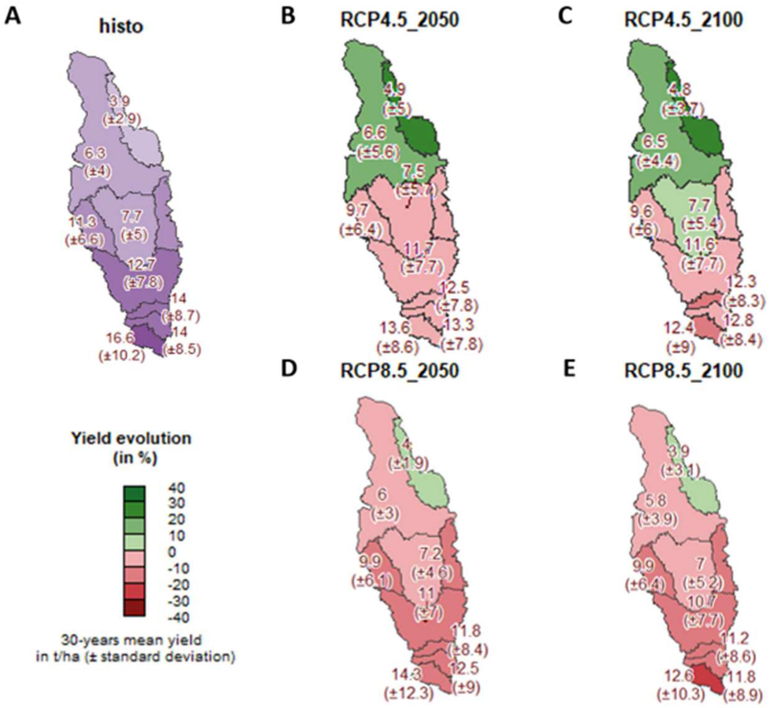

Figure 8: Mean yield evolution (and standard deviation) under two representative concentration pathways (RCP 4.5 in B and C, RCP 8.5 in D and E) scenario in historical period (1981-2010 in A), and two time horizons (2031-2060 in B and D and 2071-2100 in C and E).

In reaction to these results, participants first highlighted the importance of changes in management practices, particularly in the southern areas (as compared to northern areas). For example, they suggested that "*better vigor management could limit the water loss by transpiration.*" Stakeholders from the northern area interpreted the predicted low decrease in their yield as "*good news,*" but pointed out that they "*must maintain a high economic return for their wine.*" Finally, the participants suggested broadening the range of evaluation indicators with further details on berry sugar accumulation (in relationship with the leaf/fruit ratio), and economical aspects at farm scale.

4 Discussion

4.1 Model-based evaluation of climate change impacts

The sources of error in model predictions decrease when the number of simulated processes increases (i.e., the complexity of the model). By contrast, the uncertainties on the parameter values increase in parallel with model complexity (Passioura, 1996). In our study, the crop model (i.e., the coupling of phenological, WaLIS and GraY models) relies on fewer processes in an effort to find the best compromise between the number of processes and the number of parameters needed to estimate grape yield. Based on the results of Guilpart et al. (2014), we hypothesize that grape yield is limited by the number of sinks (clusters and berries) per plant, rather than by net assimilation. Consequently, our model does not include any effect of increasing CO_2 concentration in the atmosphere, omitting the positive effect it might have on photosynthesis, but this point needs to be further documented for perennial crops (Toreti et al., 2020). It should be noticed that until now, CO_2 enrichment of grapevines has been carried out with no limitation in water and nitrogen supplies, and only over the course of 2 to 3 years (Bindi et al., 2001; Moutinho-Pereira et al., 2009; Wohlfahrt et al., 2019). However, studies looking at other perennial systems (forests, grassland) and longer time periods showed that when soil resources are limited, the effect of elevated CO_2 on productivity may be less certain (Reich and Hobbie, 2013). Similarly, our model did not include variety-specific responses of yield to water deficit. It is likely that such variability exists among the current grapevine varieties (Duchene, 2016), but it is difficult to infer stable parameter values from the available data bases (Levin et al., 2020b). Despite these two simplifications, the WaLIS-GraY model was able to simulate grapevine yield with quality indicators similar to those in existing grapevine models found in the literature, such as UNIFI.GrapeML (Leolini et al., 2018) and STICS (Fraga et al., 2015). Moreover, our study emphasized on-farm situations, which is not the case in the majority of grapevine models (Knowling et al., 2021).

Other model limitations are related to the availability and quality of the input data. Stakeholders highlighted two main limitations in the data used. First, although we distinguished three climatic areas thanks to the medium-resolution climate projection data (8 x 8 km), we did not take into account microclimatic effects, which are determinant factors of vulnerability and adaptation in small-region studies (Le Roux et al., 2017; Quénol et al., 2017; Tissot et al., 2017). Second, the estimation of soil water availability was based on isolated estimations. Even if experimental fields were chosen with stakeholders to represent soil conditions in the watershed, it is difficult to capture small-scale variations. These estimations of spatial variations could be improved by using high spatial resolution satellite and crowdsourcing data (Pichon et al., 2021), which are promising tools to improve the quality of the spatial representation of the soil parameters.

Future development of the model could focus on three aspects. First, the structure of the model could be improved by including the effects of other climatic variables during different time periods, such as the effects of air temperature and rainfall during flowering (Zhu et al., 2020). Second, the validity of the model should be tested on other independent databases. In the recent literature, we have identified relevant databases that consider both grapevine water status and yield components during several years (Levin et al., 2020a; Zhu et al., 2020). This step should include a characterization of model uncertainties arising from model structure, parameters, and input data in order to address the confidence in our results in different contexts. Third, the model was developed initially for research purposes. Its current form lacks elements (e.g., an interface and simulation duration) that would allow an independent transfer to stakeholders. The model could also be made more accessible during workshops with stakeholders, for example, by facilitating the direct display of model results.

The present study quantitatively evaluates the impacts of climate change on grapevine phenology, irrigation needs, and grapevine yield. Regarding the phenology, our simulation shows clear advancement in the timing of each event, which is consistent with Fraga et al. (2016) in their study conducted at European scale. The more pronounced advancement at higher elevation corroborates the results of Caffarra and Eccel (2011). This may be related to a higher phenological sensitivity of mountain sites to climate change. Previous studies that simulated grapevine yields under future climatic conditions offer contradictory findings, in part because the model and data choices depend on the spatial scale. For example, our findings do not support previous research at the European scale that projected a yield increase in South of France for RCP 8.5 (STICS model in Fraga et al., 2016). But we see similarities with a medium-scale study led in the Tuscany region (61, 000 ha vineyard in Italy) that predicted yields decreasing from 15 to 30 % by the end of the century (Moriondo et al., 2011). The comparison of those two studies shows how spatial scale and model choice, linked to different climate and soil data sets, is crucial. Nevertheless, those studies involved invariant plant material and cultivation practices (variety, planting density, training system). Our study goes further by simulating different cropping systems according to their localization. Moreover, our findings suggest that the current diversity of practices is a way to limit grapevine vulnerability to climate change. The simulated irrigation water requirements are low compared to those reviewed by Naulleau et al. (2021). One reason for this could be that the irrigated areas are located in deep soils with a TTSW higher than 225 mm. In Mediterranean areas, grapevines are often cultivated in soils more prone to water stress (e.g., TTSW close to 100 mm in Gaudin and Gary, 2012). The main finding of this work is in agreement with Fraga et al. (2018); it suggests that the increased irrigation supply would not be sufficient to alleviate yield losses in irrigated areas.

4.2 Benefits and limitations of the participatory approach

While model-based evaluation of climate change impacts should be carried out with caution (due to various sources of uncertainty, Corbeels et al., 2018), they can be beneficial in a participatory approach to hybridize local and scientific knowledge and stimulate discussions. In this study, the early and frequent involvement of stakeholders was beneficial at multiple points in the modelling process: First, stakeholders actively helped at defining the representation of the baseline situation in the model. Information provided by generic datasets, commonly used by modelers (e.g., soil, cultivation practices) appeared too rough to represent the spatial variability in the studied landscape. As in Murgue et al. (2016), we found a compromise between case study spatial extent and level of details in the representation of cropping systems, although we reached a simpler representation than theirs. Nonetheless, the participatory mapping exercise significantly enhanced the representation of a common reference situation for grapevine landscape at pertinent scales and accomplished this relatively quickly. Second, as in Murgue et al. (2016), our participatory framework gave various occasions to explain and to update intermediary objects (conceptual scheme, baseline description, field-scale outputs, evaluation indicators) that evolved as the workshops progressed. Consequently, as in Leenhardt et al. (2012), the information and concepts shared between stakeholders and modelers were progressively assimilated and improved. These frequent interactions with stakeholders, together with the reciprocal sharing of data, could explain the higher level of trust in the model, and the stable participation rate.

This study impacted the stakeholders through their interactions with the researchers. They expressed the benefits they received from the study during a group discussion, and in an individual questionnaire at the end of the study. They initially identified the limits of current models in representing their systems and the impacts of climate change. But they appreciated the quantitative information they obtained from the researchers, especially in terms of climate evolution. The spatial representation helped clarify the diversity of their systems and constraints, and they particularly benefited from the extensive time dedicated to discussions and the sharing of experiences.

However, several limitations to the participatory approach should be acknowledged. First, the workshop participants were primarily drawn from the viticulture sector and were thus focused on "grape production" objectives (the agro-environmental facilitators were also close to this sector, and the regional policymaker acted primarily as an observer). Thus, we did not consider other important environmental and economic issues (e.g., other crop productions, water for human consumption, employment). We tried to enroll local and regional policy makers, with transversal skills (through interviews), but they decided to not participate in the workshops, although they "*remained interested in the study results.*" Indeed, the defined research problem was specific to the viticulture sector, and thus drew a specific audience. Second, modelers had difficulty taking account of certain processes that stakeholders highlighted as important. We can cite, among others, the effects of hedges and trees that can create a favorable microclimate for grapevines (Grimaldi, 2018), and processes linked to the evolution of pest pressure under a changing climate (Bois et al., 2017). Those two examples are difficult to include in a dynamic model because the underlying processes are complex and not well known. Processes to be considered are multi-factorial (climate, cultural practices, initial pest pressure, type of hedges, etc.); they require fine-scale data (topography, vegetation layers, humidity rate, etc.), and there are interactions between scales (from plant organs, grapevine canopy, field to landscape). Nonetheless, it is possible to include expert knowledge about these processes into other types of models (Voinov et al., 2018). Sacchelli et al. (2017) structured expert knowledge around climate change adaptation in Tuscany by using Cognitive Maps (semi-quantitative model) that allowed to detail all important concepts and the action/retroaction loops between them. Other model formalisms, such as the agent based models seen in Delay et al. (2015), are also based on expert knowledge to simulate dynamics at different spatial and temporal scales. However, such models are specific to the participants and the local conditions. Their uses and their results would probably be difficult to extrapolate to other areas. In our case, the watershed model remains generic and could be used to simulate other vineyards in the world, providing that necessary input data exist, and that grape yield is mainly limited by water. Our findings should certainly be able to be extrapolated to typical Mediterranean vineyards where coastal plains meet inland hills.

5 Conclusion

Combining modeling and participatory approaches remains challenging, especially in complex and uncertain contexts such as climate change issues. The present study was designed to implement a modeling approach that combines scientific and local knowledge to quantitatively evaluate the impacts of climate change in a Mediterranean vineyard watershed. We illustrate how the interactions between stakeholders and modelers led to an original watershed model whose inputs were spatially defined by local stakeholders. The integrated evaluation of climate change impacts reveals the heterogeneity of those impacts on the watershed, in terms of local conditions (soil and climate) and grapevine production systems. The entire territory would be impacted by high temperatures, increasing risks to production in both quantity and quality, but premium-wine production areas (PDO) would be less impacted than high-production areas (PGI). The stakeholders found the generated information on climate change impacts to be relevant, and in the next step, they will be involved in the design of local adaptation strategies.

Acknowledgement

This work was supported by the LACCAVE 2.21 project funded by the meta-program Adaptation of Agriculture and Forests to Climate Change (AAFCC) of the French National Research Institute for Agriculture, Food, and Environment (INRAE). This work is part of a PhD project funded by the Occitanie Regional Council and the INRAE AgroEcoSystem division. Authors would like to thank all study participants, as well as technical staff for their help in field data collection. We thank Iñaki Garcia de Cortazar (UE AgroClim) for providing phenological model and parameters, UE AgroClim for providing the climate data and Frederic Huard (UE AgroClim) for his advices on bias correction of climate projections data. We thank Guillaume Coulouma and Philippe Lagacherie (UMR LISAH) for Rieutort soil description, Thierry Lacombe (UMR AGAP) and Thierry Simonneau (UMR LEPSE) for their insights on grapevine physiology. Authors would like to thank Ben Boswell for English reviewing.

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