How can winegrowers adapt to climate change? A participatory modeling approach in southern France

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1 Introduction

Mediterranean wine-growers have already faced rapid climate change as seen in the observed increase in air temperature of 0.19-0.25°C per decade over the 1960-2005 period (Mariotti et al., 2015). Their challenges will only increase with projections indicating a rise of annual temperatures (+1.6°C by 2050) and a decrease in annual rainfall (-10% by 2050), especially during spring and summer (Ferrise et al., 2016). The higher temperatures have already advanced berry ripening and harvest dates by 2 weeks over the past 35 years, and the increase in water stress alters yield and berry attributes (van Leeuwen and Darriet, 2016). There is an urgent need for effective and localized adaptation measures in response to climate change (Cradock-Henry and Frame, 2021).

Adaptation in this case is defined as "the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm, or exploit beneficial opportunities" (IPCC, 2015, p. 76). From a biophysical perspective, many adaptation measures are possible (Haasnoot et al., 2020). In viticulture for example, irrigation and water saving techniques, varietal selection, and even vineyard relocation can contribute to the adaptation to climate change (Santos et al., 2020). However, the potential of those adaptation measures, alone or in combination, has not been fully investigated (Naulleau et al., 2021). Moreover, the spatial diversity of viticultural landscapes has been integrated into adaptation studies mainly through biophysical spatial factors such as soil and climate (Daccache et al., 2015; Liles and Verdon-Kidd, 2020), but only rare studies, Terribile et al. (2017) for example, has considered multiple socio-technical factors such as variety diversity, planting density, PDO regulations, water access, or farm organization. These spatially complex factors affect potential levers and barriers to the implementation of adaptations measures and their performances at several scales (Neethling et al., 2019). There is a need to design and assess adaptation strategies, here defined as combinations of adaptation measures fitted in time and space to heterogeneous local conditions within a landscape.

In viticulture, adaptation strategies have already been proposed and assessed by researchers, either alone, or interacting with stakeholders. In the first case, researchers have developed and used dynamic crop models at national scales to explore strategies based on a single adaptation, such as irrigation (Fraga et al., 2018) or mulching (Fraga and Santos, 2018). Other strategies based on vineyard migration at European (Malheiro et al., 2010) and worldwide scales (Hannah et al., 2013) have been designed and evaluated using probabilistic models. While those strategies benefit from a quantitative evaluation, their main drawback is insufficient consideration of local context and stakeholders' capacity to implement multi-measure adaptation strategies (van Leeuwen et al., 2013). In the second case, studies have involved stakeholders in the design of adaptation strategies. The stakeholders have been engaged through in-depth interviews (e.g., Lereboullet et al., 2013; Neethling et al., 2017; Nicholas and Durham, 2012), online surveys (e.g., Dunn et al., 2015), and collective workshops (e.g., Aigrain et al., 2016), where they share perceptions on climate change issues, adaptation possibilities, and the constraints they face. Participatory approaches can embrace various scales such as field, farm, and regional scales. Resulting strategies can combine short and long-term adaptations, also called tactical or strategic options (e.g., Dunn et al., 2015; Lereboullet et al., 2013), and reactive or anticipatory options (e.g., Neethling et al., 2017; Nicholas and Durham, 2012). Although those co-designed adaptation strategies benefit from shared knowledge among stakeholders, further work is needed to numerically evaluate their potential, and thus help decision making at different scales (Mosedale et al., 2016; Nicholas and Durham, 2012). No previous study has developed approaches that combine participatory design of strategies with a crop model-based evaluation, in a context of climate change (Naulleau et al., 2021).

Participatory modeling offers a wide range of tools and methods to engage stakeholders in the modeling processes (Voinov et al., 2018). Among them, process-based models are particularly suitable to visualize and analyze complex systems that are confronted with a combination of climatic factors (e.g., temperature, evaporative demand, rainfall) and management options (e.g., variety, canopy management, water management) (Knowling et al., 2021). However, the use of process-based models in participatory approaches remains difficult because of model complexity that makes it difficult to perform realistic parameterization (data requirement), describe the model (assumptions, simplifications), and transmit its results (large number of variables and data) (Passioura, 1996). Nevertheless, finding the balance between complexity and communication of information about climate change is crucial to reach a shared understanding of its local impacts and the potential of adaptation strategies.

In this study, we worked together with stakeholders to design and numerically evaluate climate change adaptation strategies at field, farm, and watershed scales. We hypothesized that the involvement of stakeholders to explore spatial and temporal combinations of adaptation measures would help determine their viability in grapevine systems under future climatic conditions. The case study was located in the Rieutort watershed, a typical Mediterranean vineyard watershed of 45 km², for which a spatially-explicit numerical model was previously developed with local and regional stakeholders (Naulleau et al., 2022). In this paper, we used this model with the same stakeholders to (i) design adaptation strategies that could be modeled, (ii) discuss simulation results, and (iii) expand the discussion to other potential adaptations.

2 Material and methods

2.1 A participatory modeling process in a viticultural watershed

The Rieutort watershed (45 km²) is representative of the Languedoc vineyard region. The watershed encompasses 1,400 ha of heterogeneous vineyards grown in alluvial, clay-limestone and shale soils. Its Mediterranean climate is characterized by a gradient from the northern mountainous areas (705 mm mean annual rainfall, data Cabrerolles weather station 2000–2019) to the southern coastal plain (581 mm mean annual rainfall, data Puisserguier weather station 2000–2019). The northern area is dedicated to traditional farming under the guidelines for Protected Denomination of Origin (PDO) certification and the southern area under Protected Geographical Indication (PGI) conditions, which are more similar to "New World type viticulture". Ten percent of vineyard surfaces are irrigated. At least 59 winegrowers have one or more vineyard plots in the watershed and are registered in the French Land Parcel identification system (RPG 2017). They are grouped either in cooperative cellars or in PDO syndicates with various environmental labels such as high environmental value, organic, or biodynamic. In a previous participatory mapping exercise with local stakeholders, the watershed was divided into eight production sectors (Fig. 1A) according to climate, soils, production modes (i.e., low yield objective in Protected Designation of Origin (PDO) areas, high yield objective in Protected Geographical Indication (PGI) areas), and irrigation use (Naulleau et al., 2022).

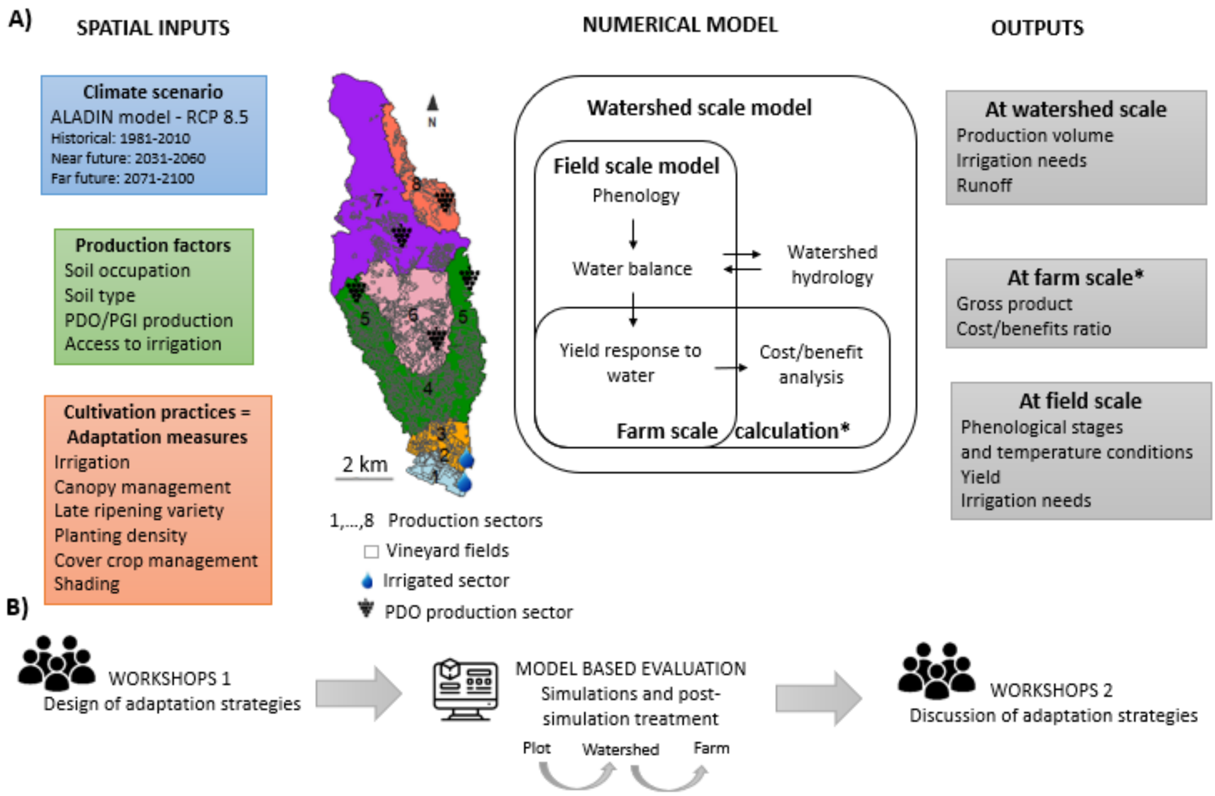

Figure 1. Description of the Rieutort watershed with a numerical model (A) and a summary of the workflow (B) of stakeholders designing and assessing climate change adaptation strategies. *For eight selected farms. The eight production sectors are described in Supp Table 1. PDO: Protected Designation of Origin. PGI: Protected Geographical Indication. RCP: Representative Concentration Pathways.

To design and assess adaptation strategies, we organized two sets of participatory workshops (4 hours each) in January and July 2021. The two sets were separated by a 6-month modeling phase performed by researchers (Fig. 1B). Participants were selected after a preliminary series of individual interviews organized to assemble a representation of the different types of production in the watershed (Naulleau et al., 2022). Each set of workshops included two workshops, one with 15 invited local stakeholders (eight winegrowers, one representative from the cooperative winery, two representatives from PDO syndicates, two technical advisors, one local policy maker, and one agri-environmental coordinator) and one with 5 invited regional stakeholders (three representatives from extension and advisory services, one agri-environmental coordinator and one regional policy maker) (Supp Table 2). Workshop agendas were planned with the participants to maximize participation and to ensure at least one representative for each type of stakeholder (more details in Supp Table 2). We hypothesized that regional stakeholders might propose bolder strategies, while local stakeholders would gravitate towards more restrictive but locally adapted strategies that account for the diversity of local conditions and constraints, as argued in March et al. (2012). Five regional stakeholders participated in both of the regional workshops. Nine, and then six, local stakeholders participated in the two local workshops. The first set of workshops (WS1) was aimed at designing the adaptation strategies, including the spatial distribution of adaptation measures in the watershed. Intermediary meetings and interviews with participants were held during the modeling step to refine modelers' choices and share information. The second set of workshops (WS2) consisted in the presentation and discussion of simulation results.

2.2 The design of adaptation strategies

In an earlier step of the participatory approach, the stakeholders listed potential adaptation measures (Naulleau et al., 2022, p. 6). Among those adaptation measures, six could be simulated (late ripening varieties, irrigation, reducing canopy size, adjusting cover cropping, reducing density, and shading). Seven of the listed measures could not be integrated in the model: drought-tolerant varieties, high quality rootstocks (according to drought tolerance and grafting techniques), water-efficient training systems, soil quality improvement (in terms of water holding capacity, nutrient availability and sanitary conditions), east-west row orientations, and the introduction of hedges).

Following the discussion of climate change impacts in the Rieutort watershed (see details in Naulleau et al., 2022), a participatory mapping exercise was devoted to the design of adaptation strategies (Caron and Cheylan, 2005). The first set of workshops (WS1) were conducted in three steps to help define the adaptation strategies. First, stakeholders indicated on a map where they would position adaptation measures—regardless of whether or not they could be simulated—among the eight production sectors (Figure 1). Second, researchers sought more precisions on the six simulated adaptations: (i) their possible combinations within a production sector, (ii) their location (e.g., percent of surface, which variety), and (iii) their exact modalities (i.e., extent of canopy reduction, timing of cover crop destruction, surfaces with cover crop, shade time and effects). Third, researchers and stakeholders agreed on the agenda for the following step: the simulation of adaptation strategies.

1.1 The modelling phases

The model used to simulate the co-designed adaptation strategies was developed in participation with the same stakeholders (Naulleau et al., 2022, Supp. Fig. 1). It combines a phenological (Morales-Castilla et al., 2020), a water balance (WaLIS, Celette et al., 2010), a yield formation (GrAY, Naulleau et al., 2022), and a hydrological module (Lagacherie et al., 2010) (Fig. 1A), and is implemented in the landscape modeling platform OpenFLUID (Fabre et al., 2013). It simulates the daily spatiotemporal dynamics of water fluxes and grapevine production at field scale within the landscape while considering (i) the spatial variability of soils and climate and (ii) the diversity of cropping systems (i.e., grapevine varieties, planting density, bud load, etc.). The model is able to simulate the impacts of six adaptation measures: irrigation, reduced canopy, late ripening varieties, reduced density, cover crop management, and shading.

After the first set of workshops (WS1), researchers started by conducting simulations at field scale (Section 2.3.1) in order to explore a large range of options proposed by stakeholders. They then combined adaptation measures to design several plausible strategies at the watershed scale (Section 2.3.2), selecting only options leading to efficient adaptation. The model provided output indicators at field and watershed scales that were co-designed with stakeholders (see Naulleau et al., 2022 for more details). The indicator at farm scale was co-designed with stakeholders and based on model outputs (Section 2.3.3).

1.1.1 Simulations of adaptation measures at field scale

The simulations at field scale consisted in exploring the performance of simulated adaptation measures on phenology, water balance, and yield under different options (shade time and effects, intensity of canopy reduction, timing of cover crop destruction, surfaces with cover crop). The evaluation indicators were harvest dates, air temperature during berry ripening (proxy for berry quality), irrigation requirements, and yield.

We created a typical case sampling of fields in the watershed for the simulations at field scale. We used a criterion-based sampling (Ritchie et al., 2003) to select one representative field per production sector (Fig 1). Each adaptation was simulated individually for each considered field according to the rules presented in Table 1 (location, value ranges). Some of these rules were fully described by stakeholders (e.g., reduced density), other were partially described and had to be supplemented by information from scientific and grey literature (e.g., shading, cover crop management). Stakeholders identified the watershed's seven major varieties as belonging to three phenological groups characterized by their budburst precocity, according to Pl@ntGrape (2020): early (merlot), mid-late (syrah, grenache), and late varieties (carignan, cinsault, cabernet sauvignon and mourvedre). In the model, we used available parameters for merlot, syrah, and cabernet sauvignon to represent each category respectively (Morales-Castilla et al., 2020). For each field, simulations were conducted for the three types of varieties (early, mid, and late), and the results were expressed as their weighted average, using the proportions of the varieties observed in the corresponding production sector (Supp Table 1).

Results were expressed as the difference in harvest date, temperature during ripening, irrigation supply, and yield, when compared to the reference situation of the historical period (1981-2010). We also evaluated the level of confidence in the model's results by estimating their similarities and divergences with scientific and grey literature. A low level of confidence was attributed when we did not find literature that corroborated the model's results. A medium level was attributed when the model's results were consistent with the literature but at a different magnitude. A high level of confidence meant that the model's results were similar to those in the literature.

Table 1. Detailed simulations of adaptation measures at field scale, followed by information sources. If parameters existed in the reference situation, the value is indicated by an asterisk

Adaptation measures	Parameters changed	Production sectors	Values	Sources
Irrigation	Irrigation dose	1, 2, 4, 5, 6, 7	10 mm (20 mm first volume applied)	Stakeholders
	Soil water content thresholds	1, 2, 4 (PGI)	21% between budburst and flowering 12% between flowering and mid-flowering-veraison, 7% between mid-flowering-veraison and veraison 4% between veraison and maturity	Ojeda, 2007
		5, 6, 7 (PDO)	12% between budburst and flowering 7% between flowering and mid-flowering-veraison, 4% between mid-flowering-veraison and veraison 3% between veraison and maturity	Ojeda, 2007
	Maximum annual volume of irrigation	1, 2 (Current irrigation network)	Unlimited	Stakeholders
		4,5 (Collective network extension)	80 mm	
		6,7 (Hill reservoir creation)	50 mm	
Late ripening variety Late ripening composite[1]	Chilling and forcing units requirement	All the sectors All the sectors	Supp Table 3	Morales-Castilla et al., 2020; Parker et al., 2013, 2020, 2011
Reduced canopy	Crop coefficient (* between 0.40 to 0.62)	All the sectors	-10 cm height: 0.36 to 0.58 -20 cm height: 0.33 to 0.53	Riou et al., 1989
Reduced density	Plant density	1, 2, 3, 4, 5, 6 (* 4500 plants.ha^{-1})	4000 plants.ha^{-1}	Stakeholders + van Leeuwen et al., 2019
		7,8 (* 4000 plants.ha^{-1})	3300 plants.ha^{-1}	
Shading	Shading time ET_0	All the sectors All the sectors	From veraison to maturity - 60% global radiation - 2°C on daily maximal temperature superior to 35°C	Stakeholders + Caravia et al., 2016
Cover crop management	Destruction date (* fixed date between 15th February to 15th March)	All the sectors	at budburst at flowering	Stakeholders + Celette et al., 2008; Fernández-Mena et al., 2021
	Surface covered during summer	All the sectors	1 inter-row out of 4 1 inter-row out of 2 All inter-rows All rows and inter-rows	

[1] hypothetical extremely late variety, built by combining information on several late ripening varieties (Morales-Castilla et al., 2020)

1.1.2 Simulations of adaptation strategies at watershed scale

The simulations at watershed scale consisted in testing co-designed spatial and temporal combinations of adaptation measures within the watershed. For each of these strategies, we simulated the impacts of one or several combinations of adaptations measures on the spatially-explicit irrigation supplies and grape production in the watershed. The adaptation measures requiring high investment costs (irrigation, shading nets) or replantation (late variety, density reduction) were applied to a limited surface of the production sectors. Irrigation was limited to the planned irrigated areas, shading nets were introduced to the early-ripening varieties (considered as more vulnerable), and reduced density was applied to the late ripening varieties (considered as more adapted to traditional low-density systems). Changes in land use was also considered as another adaptation measure at watershed scale. The relocation of vineyards was based on the examination of agricultural areas depicted in earlier (1974) black-and-white images. These images were taken from the IGN database and processed to obtain orthophotos at sub-meter resolution following Vinatier and Arnaiz (2018). Homogeneous areas visible on orthophotos were then classified as arable lands, orchards, vineyards, forests, or moors. This was accomplished with a deep learning algorithm trained on a sample covering approximately 600 fields, with an accuracy of 0.8 (Kappa Index).

1.1.3 Post-simulation calculation at farm scale

In WS1, some stakeholders felt that the consideration of the farm scale was critical, even though difficult to model due to the high diversity of farms in the watershed. They focused on the economic valuation of the adaptation measures. We therefore included these stakeholders (one PDO representative and one agro-environmental coordinator) in the process of identifying representative farms and developing a farm-scale indicator that could be calculated from the modeling results, mainly in terms of production gains and losses.

First, we selected farms whose vineyards were primarily located in the watershed. Among the 59 farms registered in the French Land Parcel identification system (RPG 2017) with at least one field in the watershed, we selected an initial sample of 18 farms with more than 85% of their surface in the watershed. We verified that the distribution of farm size in this sample was similar to that of the 59 registered farms (Supp Fig. 2). Within this sample, we selected eight farms to represent farm diversity in the watershed.

Stakeholders designed an indicator (NecPrice) representing the market price for wine that would compensate for climate change impacts on yield and adaptation costs (i.e., maintain the historical gross profit—$GP_{historical}$). As suggested by the stakeholders, we used an operation-based costing approach, which allowed us to limit consideration to the changing operations between initial and adaptation strategy at plot scale. Note that Georgopoulou et al. (2017) also used an operation-based costing approach in their cost-benefit analysis of adaptation in Greek vineyard. We assumed that production costs were fixed over time. The 2020 average bulk market price was proposed by the stakeholders as a pertinent reference, to which each winegrower could adapt ($P_{historical}$— communicated by the joint trade council of Languedoc wines).

$$NecPrice = \frac{GP_{historical}}{GP} * P_{historical}$$

Where $GP = \sum_f \left[\left(Y_f * S_f - C_f \right) * P_f \right]$

NecPrice: necessary market price for wine in order to compensate for climate change impacts on yield and the costs of adaptation (in €/hl)
GP: gross profit (in €)
With for each field of the farm f,
Y_f: yield (in hl/ha),
S_f: surfaces (in ha),
C_f: sum of adaptation costs for the field f (in €/ha),
P_f : prices (in €/hl) varying according to production type.

Adaptation costs (Table 2) include material and labor for annual operations (trimming, tillage, irrigation maintenance) and investment costs (irrigation infrastructure and material, shade nets). We also considered cost savings from density reduction. We did not look at costs linked to the planting of new vines, because we considered this to be a normal farm operating expense not specifically linked to the adaptation. Adaptation costs for material and labor were taken from Roby et al. (2008) and increased by 15 % to account for inflation over the 2008-2019 period, as proposed by Van Leeuwen et al. (2019). Infrastructure costs were communicated by the regional stakeholders. The total costs of adaptation over the 30-year simulation periods were divided by 30 to obtain an annualized cost per hectare. All costs were presented and validated by the stakeholders.

Adaptation benefits were calculated by multiplying yield gains by the production prices (Table 2). Three values of bulk market prices were used for the different production sectors.

Table 2. Adaptation costs and benefits per hectare and per year. Benefits are indicated for three different bulk market prices. The range of costs and benefits for each adaptation measure corresponds to the eight different production sectors (see Fig 1 and Supp table 1).

				Benefit (€ .ha^{-1} .year^{-1})		
Adaptation measures	Infrastructure life time (years)	Cost (€ .ha^{-1} .year^{-1})	Source	Sector 1 to 4 (90 €/hl)	Sector 5 to 7 (159 €/hl)	Sector 8 (190 €/hl)
Irrigation – Actual network	30	350	Regional stakeholders	920 to 1200	-	-
Irrigation – Network extension	30	500 to 600	Regional stakeholders	1473	-	-
Irrigation – Hill reservoir	30	600 to 850	Regional stakeholders	-	960 to 1600	-
Shading nets	10	500 to 700	Regional stakeholders	270 to 550	440 to 860	180
Reduced density	-	-700 to – 1000	(Roby et al., 2008)	1000 to 2000	1200 to 3000	830
Tillage cost (cover crop management)	-	50 to 60	(Roby et al., 2008)	- 1000 to -1200	-	-
Trimming cost (reduced canopy)	-	50 to 70	(Roby et al., 2008)	900 to 1000	-	-
Late ripening variety	-	0		-	-	-

2.3 The discussions of the adaptation strategies with stakeholders

The study ended with a second set of workshops conducted with local and regional stakeholders. The aim was to present and discuss the numerical evaluation of adaptation strategies at field, watershed, and farm scales. After a brief review of climate change impacts and the model's ability to simulate adaptations measures, researchers presented model outputs at field scale for the 2031-2060 and 2071-2100 periods.

Stakeholders were then asked to complete the evaluation by estimating separately the feasibility and desirability of the six simulated adaptation measures and the non-simulated measures mentioned earlier (Naulleau et al., 2022). The latter included drought-tolerant varieties, high quality rootstocks (according to drought tolerance and grafting techniques), water-efficient training systems, soil quality and water holding capacity improvement (organic fertilization, mulching, fallow length, decompaction by deep rooting crop species, decompacting by soil ripping), east-west row orientations, and the introduction of hedges. Stakeholders had seven green stickers to designate the most feasible or desirable measures, and seven red stickers to designate the least feasible or undesirable measures. There was no obligation to use all the stickers. Stakeholders were asked to explain their choice during a recorded collective discussion. After the workshops, we calculated a score (S) for each adaptation (a) and group of stakeholders (g). For each criteria c (feasible/unfeasible, desirable/undesirable):

$$S_{c,g,a} = \frac{N_{i=c,j=g,k=a}}{\max\limits_{\substack{i=c \\ j=g}}\left(N_{i,j,k}\right)} * \max_{j=g}\left(N_{i,j,k}\right)$$

where $N_{i,j,k}$ is the number of stickers for the criteria c, the group g and the adaptation a. $\max_{j=g}(N_{i,j,k})$ was 5 in both groups.

The researchers then presented the designed adaptation strategies at watershed scale and the simulation results under the RCP 8.5 climate scenario for the periods 2031-2060 and 2071-2100. Finally, the researchers presented the range of evolution in *NecPrice* indicators by the mid-century time horizon at farm scale. At each stage of the presentation, stakeholders were asked to share their perception of the simulations and suggest other strategies they could further imagine.

3 Results

3.1 Adaptation measures at field scale

3.1.1 Model-based evaluation and discussion with stakeholders

Among the 13 adaptation measures mentioned during the first set of workshops, six could be simulated and were presented to stakeholders during WS2 (Table 3). Irrigation compensated for yield losses due to climate change in most of the cases, with a high level of confidence in model results. The yield losses in irrigated PGI production were probably overestimated due to the presence of a shallow water table that was not considered in the model but could provide water to grapevine roots. The historical average volume of irrigation water applied (21 mm/year) to PGI vineyards was multiplied by 1.85 for the mid-century horizon and by 2.33 for the end-century horizon (38 mm/year at mid-century to 49 mm/year at end-century). Currently, PDO vineyards are not irrigated in the studied areas, but the model estimation suggests that 27 mm/year would enable the yield objective to be reached. The level of irrigation remained relatively stable under future climatic conditions (reaching 34 mm/year at end-century). Regional stakeholders confirmed that there is currently a deficit in the water balance in PDO vineyards, and they noted that the "*positive effect of irrigation in reducing mortality in superficial soils*" was not modeled. Local stakeholders noted that the volume of irrigation required is particularly important during dry years when the water reservoirs are difficult to replenish.

The use of late ripening varieties would limit the delay of harvest dates to one week, which is only a modest improvement compared to the three-week advancement expected from climate change by the end of the century. Furthermore, limiting the delay of the harvest date had little impact on the mean temperature during ripening (decreasing 0.4°C for the 1971-2100 period). Adversely, it delayed the flowering period, pushing it towards warmer and dryer conditions that could reduce yield. The simulations with the hypothetical late ripening composite variety did compensate for the three-week delay of harvest, even though temperatures during ripening remained higher than those of the historical period. This variety corresponds to a non-existing variety whose budburst would occur at end of April and reach maturity in October (under historical climate conditions). Local stakeholders were skeptical about the consequences: "*That would mean that we would need to prune the whole vineyard from mid-March to mid-April, which would be impossible to schedule in that short period.*" Regional stakeholders were more motivated to seek similar characteristics among ancient or foreign varieties.

The three water-saving adaptation measures (shading, reduced canopy, and reduced density) showed positive effects on yield and irrigation levels (Table 3). The reduction of canopy height and plant density compensated for the effects of climate change, limiting water stress by reducing surface transpiration rates. However, regional stakeholders were concerned that it could lead to an unbalance between vegetative and generative growth. The results on shading systems seemed realistic to the regional stakeholders and offered a slight offset of climate change impacts on yield. Local stakeholders recognized the positive effects of those three adaptation measures on yield and irrigation supplies but emphasized that they would also have impacts on berry attributes at harvest (alcohol degree, acidity) that should be estimated.

They also mentioned that density reduction and shading nets would require changes in the PDO specifications.

The model only considered the effects of cover crops in terms of water budget (soil infiltration and competition for water). Simulations showed that, on average, keeping soil cover during summer decreased yield. However, the yield losses remained low (<5%) for sectors 1 and 2 which have the highest available soil water capacity (data not shown). Local stakeholders noticed that grapevine systems would benefit from other services provided by cover crops (e.g., physical soil properties, microclimate) that were not evaluated in this study. Both groups promoted the "*development of a more flexible date for cover crop destruction*" in order to maximize beneficial effects of a cover crop while minimizing its impacts on yield.

Table 3: Simulated effects of adaptation measures on harvest dates, mean temperature during ripening, irrigation supplies and yields, as compared to historical values. Results were averaged for the 8 representative fields of the Rieutort watershed for RCP 8.5 and two time periods: 2031-2060 and 2071-2100. Colors indicate the magnitude of the effects. Bullets indicate the level of confidence in model results (●: low, ●●: medium and ●●●: high). PDO: Protected designation of Origin, PGI: Protected geographical indication production.

3.1.2 Feasibility and desirability of adaptation measures

Among the 13 adaptation measures mentioned during the first workshops, the most desirable (score > 4) according to local stakeholders were the reduced canopy and improved soil quality (maximal score in Figure 2A). They also highlighted a large number of other desirable measures (score between 2 and 3): water-efficient training systems, reduced density, and drought tolerant varieties and rootstocks. In total, they identified ten measures as desirable (score > 1). Regional stakeholders identified two desirable adaptation measures, among which reduced canopy did not appear, but the adaptive management of cover crop was mentioned. The desirability of some adaptation measures (shading nets, hedges, and irrigation) was subject to significant debate, particularly among the local stakeholders.

The most feasible adaptation measures differed between the two groups (Figure 2B). Local stakeholders identified reduced canopy as the most feasible adaptation, especially in the southern portion of the watershed, while regional stakeholders identified the adaptive management of cover crop as most feasible. Both groups detailed feasible adaptation measures to improve soil quality (increase fallow length, avoid compacting, increase organic fertilization) and to incorporate water-efficient training systems. Planting drought tolerant varieties was considered as unfeasible by both groups because they have not yet been developed.

The comparison between desirability and feasibility showed interesting results. Drought tolerant varieties and rootstock were not considered feasible, but they were seen as desirable, and both appeared as a priority for further research. Irrigation and late ripening varieties were seen as feasible, but their desirability was questionable. Irrigation was feasible in some areas, depending on economic investment, but it incurred a risk of dependence on water resources. The limited ability of late ripening varieties to delay harvest, as well as the labor constraints involved, reduced the desirability of this adaptation measure for both groups. Hedges and shading nets appeared neither feasible nor desirable. Although stakeholders recognized their beneficial effects, hedges were described as difficult to implement, and shading nets were both expensive and detrimental to the appearance of the landscape. Finally, reduced canopy, improved soil quality, row orientation, training systems, and reduced density were identified as promising because they are both feasible and desirable.

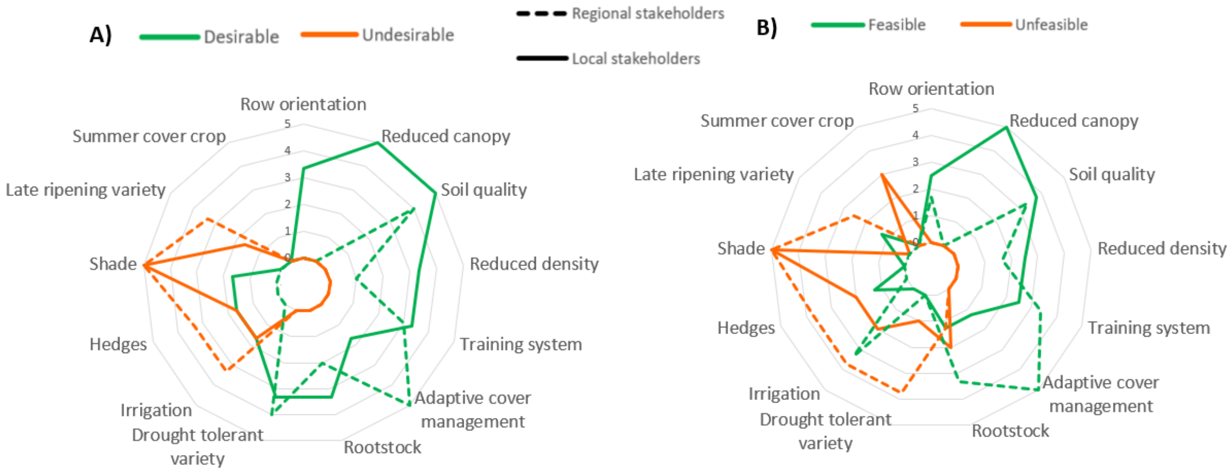

Figure 2: (A) Desirability and undesirability scores and (B) feasibility and unfeasibility of adaptation measures, according to local and regional stakeholders.

3.2 Adaptation strategies at watershed scale

3.2.1 Overview of the co-designed adaptation strategies

The *baseline strategy* reflected the current production systems, without management changes to adapt to climate change. The following list describes the measures that compose each adaptation strategy designed in the first workshops (Table 4) and their implementation in the model:

- *Delayed harvest strategy*: The whole surface of the watershed is replanted with late ripening variety to prevent berry ripening from occurring during the warmest period. No simulation at watershed scale was performed because the results at plot scale showed little impact on temperatures during ripening (see section 3.1.1).
- *Water stress limitation strategy (WSS)*: Water-saving practices are implemented with the aim of maintaining production volume, while enhancing water use efficiency. In the simulations, the strategy followed three gradual steps according to the adaptation measures implemented (Table 4). The irrigated areas were extended as currently planned in the watershed (WSS_irri). Short term adaptation measures (reduced canopy, and cover crop in one of every four inter-rows) were implemented in the Southern sectors of the watershed (WSS_ST) where local stakeholders pointed out their relevance during WS1 (Table 5). Long-term adaptation measures were only considered for limited surfaces (WSS_LT) because they require replanting or high

investments (Table 5). Shading systems were simulated in all production sectors, and primarily on early ripening variety, while density reduction was indicated for the late ripening varieties of the northern areas.

- *Soil improvement strategy*: The combination of soil management practices with high-quality rootstock are implemented in order to improve available water capacity in the soil and favor deep grapevine roots. The lack of knowledge about soil heterogeneity in the watershed along with the related physical and biological processes in the soil did not allow us to evaluate quantitatively the performance of this soil improvement strategy.
- *Relocation strategy (RelocS)*: The vineyards are relocated northward, given the aptitude of northern vine systems to withstand climate change (Naulleau et al., 2022). The main limitation in evaluating this strategy is the lack of data on soil characterization, especially for the northern shale soils. Therefore, we hypothesized that the northern areas where vines had been previously cultivated (1974) could be re-converted into vineyards to compensate production losses from climate change.

Table 4: Combination of adaptation measures in the four co-designed strategies (irri: irrigation, ST: short-term, LT: long-term). X: simulated and ●: non-simulated

	Adaptation strategies					
	Delayed harvest strategy	Water stress limitation strategy			Soil improvement strategy	Relocation strategy
Adaptation measures		*IRRI*	*ST*	*LT*		
Late ripening variety	X					
Irrigation		X	X	X		X
Reduced canopy			X	X		
Summer cover crop			X	X		
Reduced density				X		
Shading	●			X		
Hedges	●					
East-west row orientation	●					
Drought tolerant variety				●		
High quality rootstock					●	
Water efficient training system				●		
Improved soil quality*					●	
Relocation						X

* Longer fallow period, good soil preparation before planting, organic fertilization, mycorrhiza, and limiting irrigation in the first years after planting

Table 5: Percentage of the sector's surface area engaged in each adaptation measure for the three options of the water stress limitation strategy *(WSS)*: irrigation where it is possible (irri), short term adaptation measures (ST) and long-term adaptation measures (LT). * 1 inter row out of 4.

Sector (vineyard surface)	WSS_irri	WSS_ST		WSS_LT	
	Irrigation	Reduced canopy	Summer cover crop*	Reduced density	Shading nets
1 (94 ha)	100%	100%	100%		20%
2 (77 ha)	100%	100%	100%		11%
3 (108 ha)		100%	6%		17%
4 (400 ha)	8%	100%	2%		20%
5 (173 ha)	32%		1%		39%
6 (278 ha)	46%		6%		46 %
7 (205 ha)	30%			31%	40%
8 (84 ha)				61%	29%
Watershed (1418 ha)	**31%**	**48 %**	**14 %**	**8%**	**31%**

3.2.2 Impact of the water stress limitation strategy (WSS) to enhance water use efficiency

The water stress limitation strategy was applied to portions of four vineyard sectors (4,5,6,7) that are not currently irrigated. The resulting mean irrigation levels in these newly irrigated sectors were lower than for the two sectors (1,2) that are currently irrigated (Figure 3A). This difference can be traced to a combination of the maximum annual irrigation allowed by the collective management of water resources and the lower water requirement of PDO production as compared to PGI production. In sector 6, where the limestone soils are superficial and the planting density is 4,500 plants ha-1, the maximum volume of irrigation water was required 1 year in 4 during the period 2071-2100, which implies frequent difficulty in satisfying grapevine water demand. In the period 2031-2060, the irrigated surface (*WSS_irri*) was almost tripled, and the irrigation water requirement at watershed scale doubled from 68,000 m^3 to 134,000 m^3 (Fig 3B). The short-term (*WSS_ST*) and long-term (*WSS_LT*) measures did not significantly reduce the level of irrigation at field or watershed scales.

The mean yields in the newly irrigated surfaces were maintained, and even increased compared to the historical period (Fig 4A). The short-term adaptation strategy (*WSS_ST*) showed a positive effect on yield in the two non-irrigated sectors located in the southern part of the watershed (sector 3 and 4), allowing them to reach the objective of 12 t/ha. In both future time periods, the long-term adaptation strategy (*WSS_LT*) of shading nets and reduced density restored the northern sector's yield to the historical level. Shading nets also limited yield decrease in the central sectors, but this effect was visible only for the 2031-2060 period. At watershed scale, compensation for yield loss due to climate change was only achieved through the mobilization of irrigation in the short and long-term adaptation measures, and this only at the near future horizon (Fig 4B). Production losses at the end of the century in the WSS_LT strategy were estimated at 6%, compared to 14% in the baseline. PGI production suffered the highest yield loss. However, the mean yield in PGI production sectors (sectors 1 to 4) remained higher than the 12 t/ha authorized for PGI certification. By contrast, the mean yield in sector 8 remained below the authorized 6 t/ha for PDO production.

Local stakeholders suggested going further in the long-term adaptation strategy, by simulating an extreme strategy where all vineyard surfaces would be shaded and reduced in density. In terms of the reduction of production losses presented in Figure 4B, the regional stakeholders stressed that the water-saving strategy, based on conservative development of irrigation, remained unequal among winegrowers. Indeed, although production was sometimes maintained with few winegrowers having access to irrigation, especially in PDO sectors, for the others, the lack of irrigation would still imply production and revenue losses due to climate change.

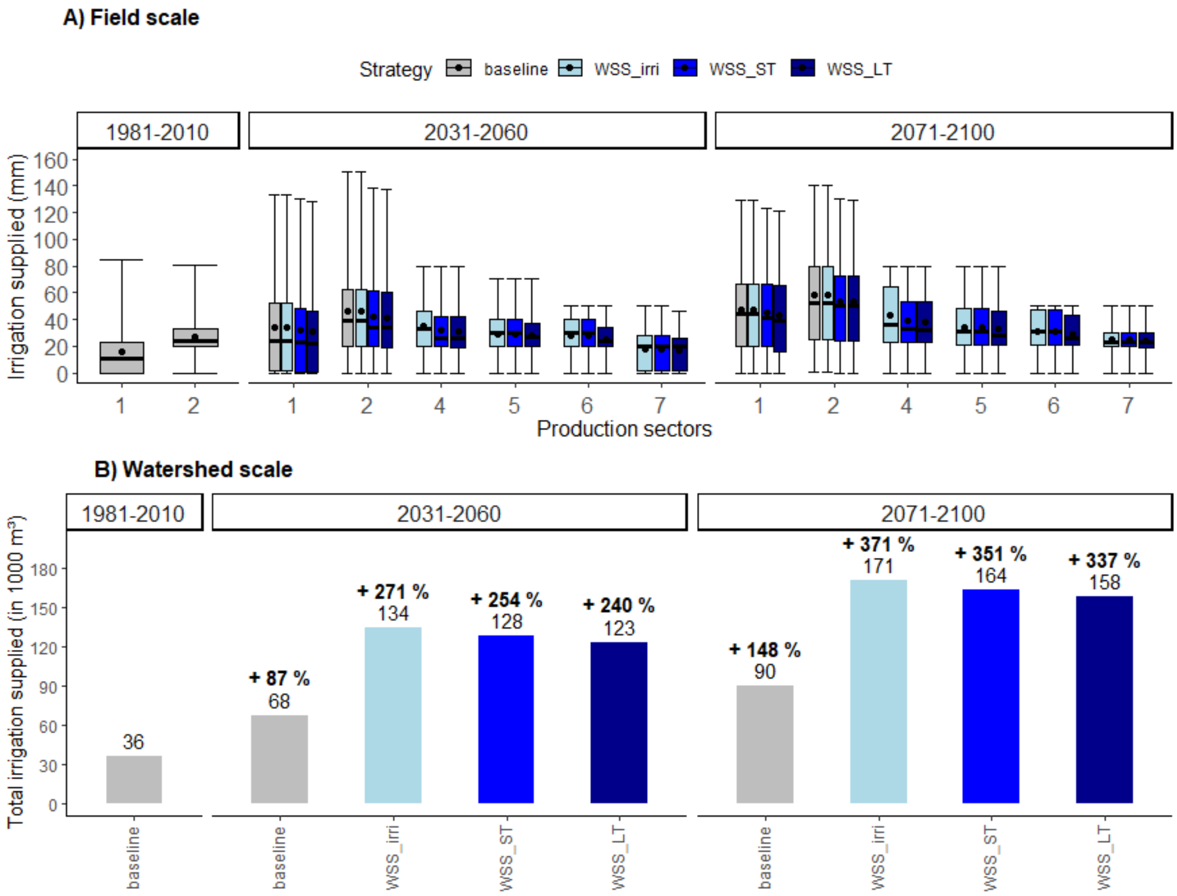

Figure 3: Annual irrigation supplied at (A) field and (B) watershed scale, according to the three water stress limitation strategies (WSS) in RCP 8.5. Boxplots correspond to the 30 years of simulation (mean indicated by a point). Barplots correspond to the mean irrigation supplied and the percentage of difference when compared to the baseline of the historical period. Sectors 3 and 8 had no plans for irrigation.

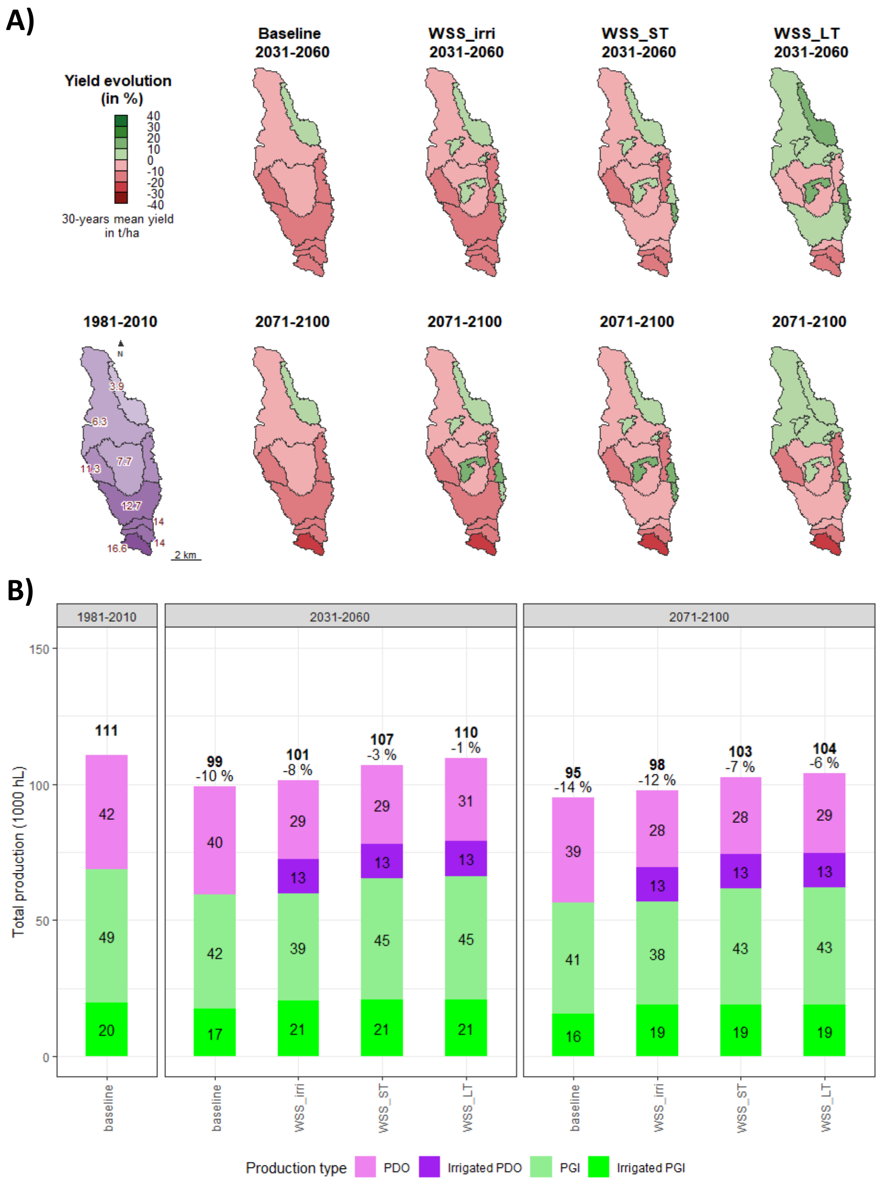

Figure 4: Evolution of grapevine production in RCP 8.5 for the period 2031-2060 and 2071-2100 in comparison to the historical period (1981-2010): (A) variation of mean yield by sector and (B) mean annual volume of production according to type (PGI: Protected Geographical Indication, PDO: Protected Designation of Origin).

3.2.3 Relocation strategy to compensate for production losses

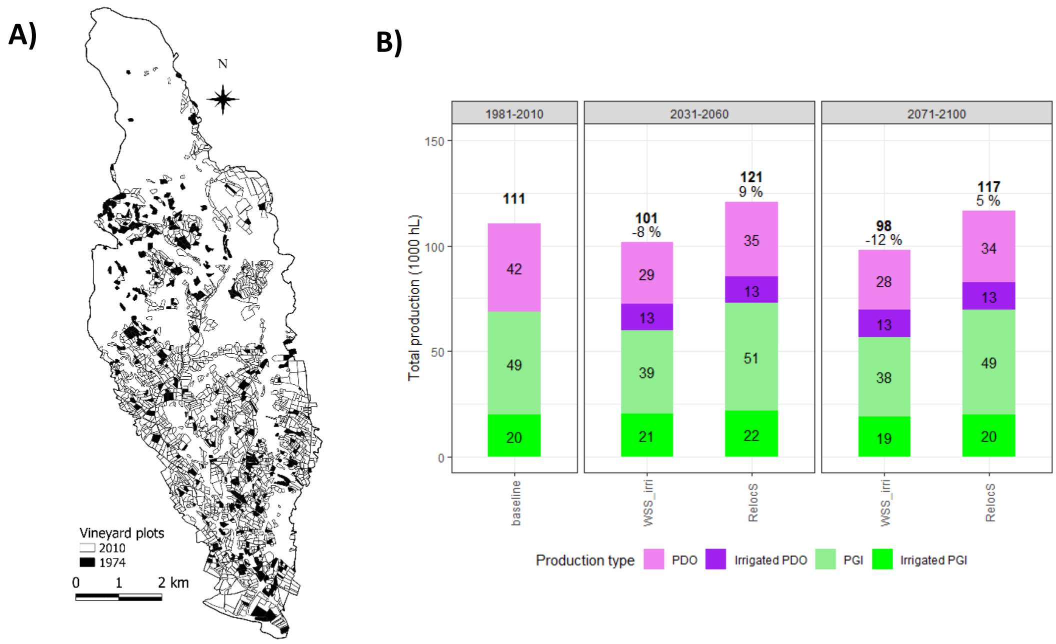

Figure 5: A) Map of the vineyard baseline (white) and relocation strategies (white + black); B) Effects of the relocation strategy (RelocS) on the total production volume under the RCP 8.5. PDO: Protected Designation of Origin. PGI: Protected Geographical Indication production.

During the timespan between the aerial images of 1974 and 2010, 330 ha of vineyard were converted into forests (173 ha), fallows (61 ha), cereals (38 ha), pastures (37 ha) and other crops (21 ha). Among those surfaces, 160 ha are located in PDO sectors, mainly in the northern areas, and 170 ha in PGI sectors in the south (Fig 5A). The reconversion of those surfaces into vineyard, without considering fallow time, compensated for or increased the volume of watershed production compared to the historical period (+9% by the period 2031-2060, +5% by the period 2071-2100) (Fig 5B). On average, the mean yield in these new areas reached 40 hl/ha for PDO production by the end of each time periods, and 70 hl/ha for PGI production by 2060 and 64 hl/ha by 2100. Local stakeholders confirmed the historical move southward. Generally, vineyards were abandoned because of difficult terrains in the more mountainous region and lower yields compared to other fields in the same sector. Local stakeholders estimated that the reconversion of those fields could be feasible if winegrowers managed to produce a quality wine, with historical varieties. But issues related to access, labor, and related costs would remain. A detailed analysis of soil properties in these areas would be necessary to precisely identify areas suited to relocation.

1.2 Cost-benefits analysis at farm scale

We calculated the bulk-wine price increase necessary to compensate for production losses and adaptation costs for eight representative farms in the watershed and for the different water-saving strategies (*WSS_irri*, *WSS_ST*, *WSS_LT*) (Table 5). The studied farms differed in their structure (cooperative winery or independent), type of production (PDO, PGI or mixed), and location among the eight production sectors. Average bulk-wine price received by the eight farms ranged from 90 €/hl to 190 €/hl in 2020. In the case where no adaptation measure is taken (the *baseline*), the NecPrice must increase between 1 and 18 €/hl (excluding inflation). The most impacted farms would be members of cooperative wineries producing more than half of their production as PGI wine, without irrigation (Table 6).

The expansion of irrigation in the watershed (*WSS_irri*) involved four farms, all with PDO production and water supplies in hill reservoirs. The extent of the conversion to irrigation on these farms varied from 18% to 75% of their cultivated surfaces (Table 6). The gain in yield from irrigation would cover the irrigation costs, as seen in the lower necessary price increase with the irrigation strategy compared to the baseline strategy. The regional stakeholders agreed with this analysis with the understanding that the winegrowers would have to respect the yield limitation set by the PDO syndicates (6 t/ha) in order to benefit from the higher price of a PDO wine. They also noted that the adaptation costs of irrigation infrastructure for hill reservoirs are highly variable and depend on factors such as location, water sources, and topography. We might have underestimated the costs, but one stakeholder argued that 800€/ha/year is the "*maximum acceptable cost*." If costs rose above that amount, he believed that the infrastructure would not be built. Local stakeholders believed that the investment required would entail significant costs to local government agencies, and they raised the question of the necessity of such spending. Moreover, the availability of the water supply is not guaranteed, creating an additional risk that was not considered here (i.e., the evaluation assumes that reservoirs are recharged each year).

Short term adaptations (WSS_ST strategy) were primarily associated with the farm in the southern part of the watershed. The additional costs related to reduced canopy (trimming) were low, and the yield gain simulated in the model covered the adaptation costs. This balance between cost and benefit was maintained even for the farm that also adopted the practice of a cover crop on one inter-row in four during summer. Nevertheless, local stakeholders suggested that the positive effect of severe trimming on yield, as well of its impact on wine quality still need further verifications.

Long-term adaptations (WSS_LT strategy) were chosen for the independent farms with vineyards in the northern part of the watershed. The costs of shading nets were covered by the yield gain. The reduced planting density resulted in economic benefits from reduced production costs, which supports the results of Van Leeuwen et al. (2019).

To sum up, no adaptation measure at watershed scale would cost more than the benefits in yield. However, only two of them (irrigation and reduced density) resulted in benefits that fully compensated for the effects of climate change, and these two only did that in particular cases. These results reflect the sentiment that stakeholders often repeated: "*There is no miracle solution.*" The range of increase in the bulk-wine price (from 1€/hL to 18€/hL) needed in order to compensate for climate change consequences, albeit uncertain, did not allow for price variations between years. The local stakeholders concluded that "*the market price itself is a real lever*" and may avoid investment in expensive infrastructures. A debate took place on the ability of the PDO syndicate and PGI organizations to increase their prices to compensate for yield losses.

Table 6: Evolution in the Necessary bulk-wine price (€/hl) according to farm characteristics and water stress limitation strategies (WSS), for the RCP 8.5 during the period 2031-2060. Blue bars represent the percentage of farm surfaces where the adaptation is implemented. The evolution in the Necessary bulk-wine price is null (0) if the benefit of adaptation is equal to the adaptation cost. That evolution is a decrease (↘) if the benefit of the adaptation strategy is superior to the adaptation cost, and it is a strong decrease (↘↘) if the benefit of the adaptation strategy compensated for negative effects of climate change (in terms of necessary price). Grey cases indicate the farm is not concerned by that strategy. PDO: Protected Designation of Origin, PGI: Protected Geographical Indication (certified labelling).

Farm Description				Mean production	Adaptation (% farm surfaces)					Necessary price evolution for the period 2031-2060 (in €/hl)			
					WSS_irri	WSS_ST		WSS_LT					
Winery	Production	Production sector	Surface (ha)	Reference	Irrigation	Cover crop	Canopy man.	Density	Shade	Baseline strategy	WSS_irri	WSS_ST	WSS_LT
Independant	High premium PDO	7,8	26	190 €/hl						+1 €/hl			↘↘
	PDO	7,8	17	158 €/hl						+6 €/hl	↘↘		↘↘
	PDO	5,6,7,8	17	158 €/hl						+12 €/hl	↘		↘
	PDO / PGI	5,6	30	107 €/hl						+14 €/hl		↘↘	↘↘
Cooperative	mostly PDO	5,6	30	144 €/hl						+13 €/hl	↘	↘	↘
	PDO / PGI	4,5,6	17	125 €/hl						+18 €/hl	0	↘	↘
	mostly PGI	3,4	30	103 €/hl						+17 €/hl		↘	↘
	Irrigated PGI	1,2	17	90 €/hl						+12 €/hl		0	

4 Discussion

4.1 Co-designed adaptation strategies

The four co-designed adaptation strategies were defined according to specific concerns: harvest date, water efficiency, soil quality, and soil occupation. One strategy does not exclude another; so these strategies can be combined together in an operational perspective. The potential of these adaptation strategies, and the measures they involve, have been partially evaluated by a model and by local expertise; however, the relevance of these strategies can be debated with respect to the scientific literature.

Exploiting the genetic diversity among grapevine cultivars to limit the effects of climate change on phenology was demonstrated by Morales-Castilla et al. (2020) as successful at a worldwide scale but insufficient in some regions like southern Europe. Our results at the scale of a medium-size watershed in Mediterranean vineyards confirmed only a limited effect from late ripening varieties for reducing the temperature during berry ripening. Nevertheless, further scenarios should be explored by (i) more precisely considering the diversity of existing varieties in the watershed and (ii) running simulations with other very late ripening Mediterranean varieties, such as those cultivated in Cyprus or Greece. The effectiveness of the late harvest strategy would depend primarily on the global decisions taken to reduce future emissions and minimize the rise in global temperature. In any case, varietal diversity is crucial to manage labor during the year (winter pruning, harvest), to limit bioclimatic risks (frost, drought, pest disease), and to contribute to the blending process during wine-making (Nicholas and Durham, 2012).

Genetic diversity should also be explored according to the drought-tolerance of varieties and rootstocks. Today 110 Richter is the most widely used rootstock in Languedoc, but the even more drought tolerant 140 Ruggeri could be included in the adaptation strategies even though its effect on water balance is difficult to evaluate quantitatively (Ollat et al., 2015). Similar options do exist through the use of drought-tolerant varieties (Duchene, 2016).

The water stress limitation strategy encompasses a large range of adaptation measures. In our study, the development of irrigation systems corresponds to the current local policy measures, which plan to increase irrigated vineyard surfaces from 16% to 30% by 2030 (Département Hérault, 2019). However, this policy does not guarantee the economic investment necessary for the infrastructure. Moreover, the irrigation systems' sustainability is debated among stakeholders and scientists (Grantham et al., 2010). Our participatory design showed that winegrowers producing PGI wine in areas with water constraints were more likely to adopt tactical adaptations, while winegrowers producing PDO wine in dryer or drought-prone areas, were more likely to adopt strategic adaptations. The model's results showed that the tactical adaptations proposed in PGI production systems are insufficient in the long term to counterbalance the effects of climate change. Thus, winegrowers in these areas would eventually need to engage in more disruptive adaptations (planting density, market positioning, etc.). The traditional Mediterranean goblet training system, which can still be found in some of the drought-prone areas (Deloire et al., 2022), could be an interesting adaptation but needs more documentation in the literature. For PDO production systems, it is worth noting that the proposed strategic adaptations could appear unrealistic under current regulations (i.e., reduced planting density) and local customs (i.e., shading nets).

The soil improvement strategy is an important lever to promote deep rooting and soil water storage. A recent review by Marín et al. (2020) recognized the complexity of root-soil interactions, as well as the importance of understanding that complexity in climate change adaptations. But the current state of knowledge on rootstocks and root/soil processes did not allow us to introduce this complexity into our simple process-based model. We can hypothesize that an increase of either rooting depth or soil porosity would lead to an increase of Total Transpirable Soil Water (TTSW). This would have a positive effect on the water balance and thus increase drought resilience (Gaudin and Gary, 2012). The difficulty is how to measure the extent that different types of soil management (fallow length, decompacting by soil ripping, organic fertilization, biochar, mulching, cover crop, etc.) would increase the TTSW. Regional stakeholders suggested using the model to evaluate the available soil water capacity needed to maintain historical yield. The goal would be to evaluate the ability of changes in soil management to fill the gap between the current and future soil water capacity needed.

The vineyard relocation strategy has often been studied at large scales (e.g., de C. Teixeira et al., 2014; Hannah et al., 2013; Malheiro et al., 2010), and our results confirm the advantages of moving to higher altitudes to adapt to climate change. But the limitations of such studies, including ours, is the lack of attention to conservationist conflicts over land use (Hannah et al., 2013), the low resolution of the input data (soil, climate, practices, etc.), and the technical feasibility of cultivating those areas. Further research could focus on this strategy and expand knowledge about the choices to buy or rent (or not) new land, as studied in Delay et al. (2015).

4.2 An original method to design and assess adaptation strategies

The method proposed here is original in that it combines tools used independently in previous studies: the participatory design of adaptation strategies and process-based model simulations under future climatic conditions. We had some difficulty involving stakeholders in a complex design process, so the resulting adaptation strategies included some choices made by the modelers. This could be due to several reasons. First, we dedicated only one set of workshops to strategy design. The first strategies could reflect a hesitancy on the part of stakeholders testing the model approach, as previously experienced in Hossard et al. (2013). Second, the design framework was constrained by the modeling tools. Our simulations considered a limited number of typical cropping systems in the watershed, a unique driver of change (climate change), and only six field scale technical changes to define adaptation strategies. The issue might have been avoided by using narrative scenarios to encourage creativity and consistency (e.g., Delmotte et al., 2017). However, as the timeline extends, the number of possible values of the variables explodes, and the narratives would become more difficult to translate into quantitative scenarios (Alcamo, 2009; Leenhardt et al., 2012).

The economic evaluation of the adaptation strategy was crucial for the two types of stakeholders. However, the co-designed economic indicator showed some limitations: (i) costs and benefits poorly consider plots and farms diversity, (ii) variable costs and benefits are not considered, (iii) costs are fixed and annualized over time. Concerning the first point, we had only two available levels of costs and benefits according to the type of production (PDO or PGI), intrinsically linked with vineyard design. However, the diversity of plots (soil, slope, etc.) and farms (material, spatial distribution of plots, labor force, etc.) imply a wider range of operation costs. The marketing strategies (e.g. bulk vs. bottled, direct sales vs. cooperatives, environmental labelling) may also affect the selling price and therefore the benefits of the adaptation. Therefore, further and updated data collection on the economic performances of the different types of farms are needed to proceed to a monetary assessment of adaptations measures. National database can be used such as census (e.g. Bernetti et al. 2012), farm accounting (e.g. Sacchelli et al., 2017) or data available at the ministry of Agriculture (e.g. Georgopoulou et al., 2017) for estimating the operation costs and benefits in the vineyard. While these databases may have some limitations, the complexity and the high territorial differentiation of vineyard systems often lead the authors to use complementary sources of information like consultation of farmers (e.g. Georgopoulou et al., 2017) or experts (e.g. Sacchelli et al., 2017). On the second point, we suggest to introduce variable costs, such as the irrigation water price, and variables benefits depending on wine quality and market variability, to better compute costs and benefits. This would allow the exploration of economic adaptation scenarios such as the creation of climate-smart agriculture labels, or an increase in the cost of irrigation water. On the third point, the United Nations Framework Convention on Climate Change reviewed a large panel of approaches to assess the costs and benefits of adaptation options (UNFCCC, 2011). Among them, the approach proposed by stakeholders has similarities with the cost-benefit analysis (CBA). However, unlike our method, a discount rate is used in CBA to determine the present value of future benefit and cost flows. The IPCC reminds that discount rate is a core question but opinions vary sharply on its value (Chambwera et al., 2014). This value can vary between 0.1 to 2.5% among studies (Chambwera et al., 2014), while in the Greek vineyard, Georgopoulou et al. (2017) took on a rate of 6%. The discount rate parameter, that could appear subjective, is not easy to implement in a participatory approach. A solution could be to test various values of discount rate, with the challenge to keep results clear enough with the stakeholders.

4.3 Enriching interactions within and between groups of stakeholders

The choice of the territory and the co-design approach had some consequences on the size of the participant sample. First, the territory had a small size (45 km²). Therefore, the diversity of systems, stakeholders, and their opinions could be represented by a limited number of participants, including farmers. Second, co-design approaches require a constant and organized dialogue between participants and researchers (Jeuffroy et al., 2022); keeping an active and stable participation is thus necessary to build a fruitful dialogue. However, recent works often cite the difficulties of maintaining actor's involvement during workshops (Della Rossa et al., 2022). In our case, the collective planning and the dialogue established between participants helped ensuring a constant number of participants to preserve the diversity of stakeholders (localization, types of production, professions and ways of actions). There is no consensus in literature on the right number of participants for participatory design workshop. While Alcamo (2009) suggests a number between 15 and 25 for World Scenario Exercise (p. 137), design workshops of the 12 case studies analyzed by Jeuffroy et al. (2022) included between 7 and 25 participants, which is similar to the participation observed in our study. Our workshops gathered, in addition to other stakeholders, 8 farmers, who represented all production sectors. Although this number is relatively low, it corresponds to what was observed on the case studies of design workshops, which included between 0 and 8 farmers (Jeuffroy et al., 2022). Nevertheless, a larger number of farmers would have been beneficial to (i) limit the risk to neglect some adaptation measures and to (ii) represent a wider range of different interests and experiences.

The two separated groups of stakeholders produced and discussed complementary but sometimes contradictory information. The local stakeholders appreciated the concrete and local information they acquired on climate change and its potential consequences on their vineyards. Many ideas were mentioned during the workshop, such as the wish to innovate within their farm, the importance of sharing experiences, and the need to combine multiple adaptations. Local stakeholders tended to look at traditional practices to find solutions, but they complained about the prohibition of some of those practices decided at regional or national level (e.g., restrictions on planting density, varieties). Regional stakeholders were more interested in sharing information on adaptation measures, for which they are most often solicited. They highlighted the need of information on goblet systems (training the vines upright and planting in a grid pattern without use of a trellis), historical varieties, and foreign varieties. As further step, a final meeting could be organized to inform a broader audience about the results of our study, as well as to engage them in discussion (Voinov and Bousquet, 2010).

The interactions between researchers and the two groups of stakeholders did not differ significantly. However, each group helped develop analyses outside of the model's limits. For example, regional stakeholders helped compare model results with different experiences in other areas. Local stakeholders were more likely to identify possible feedback loops in their production systems. For example, water ponds would increase the available irrigation water, but a particularly dry winter could jeopardize the replenishment of the water ponds, and consequently decrease the available irrigation water. Thus, the cost-benefits ratio of the water source infrastructure would be adversely affected. They also proposed to account for extreme climate events (frost, hail, heat waves) by introducing particularly low production years, for which the probability could vary among climate scenarios. The relevance of stakeholder's knowledge about local conditions, constraints and feedback loops was demonstrated by Schaap et al. (2013) in their study evaluating the impacts of extreme events on Dutch farms. The next stage of the study should focus on deepening the participatory approach to include qualitative information on feedback effects into a (semi-) quantitative evaluation.

5 Conclusion

Most of the design and evaluation of adaptation strategies rely on either crop models that take little account of local diversity or participatory approaches that are not designed to meet quantitative information needs. In those cases, it can be difficult for stakeholders (winegrowers, technical advisors, policy makers) to fully understand the adaptation potential in a given context. In this study, we combined a participatory approach with the use of process-based models, thus making it possible to include local knowledge in the model-based exploration of adaptation strategies. This approach yielded insight into the heterogeneity of vulnerability and adaptive capacity of vineyards in a Mediterranean watershed. Although estimates of the potential and cost-effectiveness of adaptations are not absolute or definitive, our work with stakeholders identified effective combinations of adaptation measures that can be implemented in different grapevine systems.

Finally, we designed and assessed adaptation strategies that limit potential production losses due to climate change in the Rieutort watershed. The most productive areas showed the least leeway to adapt to climate change, even though they appear to be the most affected by the future climatic conditions. The systems with low yield production were better at withstanding climate change and were also more likely to adopt innovative adaptations. However, our study did not consider the effects of extreme events, nor the effects of socio-economic drivers of change. Reduced canopy, soil quality improvement, water-efficient training systems, and reduced density were identified as particularly promising adaptation measures and should be further investigated.

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