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

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16 1 Introduction

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

26 Adaptation in this case is defined as “the process of adjustment to actual or expected climate
27 and its effects. In human systems, adaptation seeks to moderate or avoid harm, or exploit
28 beneficial opportunities” (IPCC, 2015, p. 76). From a biophysical perspective, many adaptation
29 measures are possible (Haasnoot et al., 2020). In viticulture for example, irrigation and water
30 saving techniques, varietal selection, and even vineyard relocation can contribute to the
31 adaptation to climate change (Santos et al., 2020). However, the potential of those adaptation
32 measures, alone or in combination, has not been fully investigated (Naulleau et al., 2021).
33 Moreover, the spatial diversity of viticultural landscapes has been integrated into adaptation
34 studies mainly through biophysical spatial factors such as soil and climate (Daccache et al.,
35 2015; Liles and Verdon-Kidd, 2020), but only rare studies, Terribile et al. (2017) for example,
36 has considered multiple socio-technical factors such as variety diversity, planting density, PDO
37 regulations, water access, or farm organization. These spatially complex factors affect
38 potential levers and barriers to the implementation of adaptations measures and their
39 performances at several scales (Neethling et al., 2019). There is a need to design and assess
40 adaptation strategies, here defined as combinations of adaptation measures fitted in time and
41 space to heterogeneous local conditions within a landscape.

42 In viticulture, adaptation strategies have already been proposed and assessed by researchers,
43 either alone, or interacting with stakeholders. In the first case, researchers have developed
44 and used dynamic crop models at national scales to explore strategies based on a single
45 adaptation, such as irrigation (Fraga et al., 2018) or mulching (Fraga and Santos, 2018). Other

46 strategies based on vineyard migration at European (Malheiro et al., 2010) and worldwide
47 scales (Hannah et al., 2013) have been designed and evaluated using probabilistic models.
48 While those strategies benefit from a quantitative evaluation, their main drawback is
49 insufficient consideration of local context and stakeholders' capacity to implement multi-
50 measure adaptation strategies (van Leeuwen et al., 2013). In the second case, studies have
51 involved stakeholders in the design of adaptation strategies. The stakeholders have been
52 engaged through in-depth interviews (e.g., Lereboullet et al., 2013; Neethling et al., 2017;
53 Nicholas and Durham, 2012), online surveys (e.g., Dunn et al., 2015), and collective workshops
54 (e.g., Aigrain et al., 2016), where they share perceptions on climate change issues, adaptation
55 possibilities, and the constraints they face. Participatory approaches can embrace various
56 scales such as field, farm, and regional scales. Resulting strategies can combine short and long-
57 term adaptations, also called tactical or strategic options (e.g., Dunn et al., 2015; Lereboullet
58 et al., 2013), and reactive or anticipatory options (e.g., Neethling et al., 2017; Nicholas and
59 Durham, 2012). Although those co-designed adaptation strategies benefit from shared
60 knowledge among stakeholders, further work is needed to numerically evaluate their
61 potential, and thus help decision making at different scales (Mosedale et al., 2016; Nicholas
62 and Durham, 2012). No previous study has developed approaches that combine participatory
63 design of strategies with a crop model-based evaluation, in a context of climate change
64 (Naulleau et al., 2021).

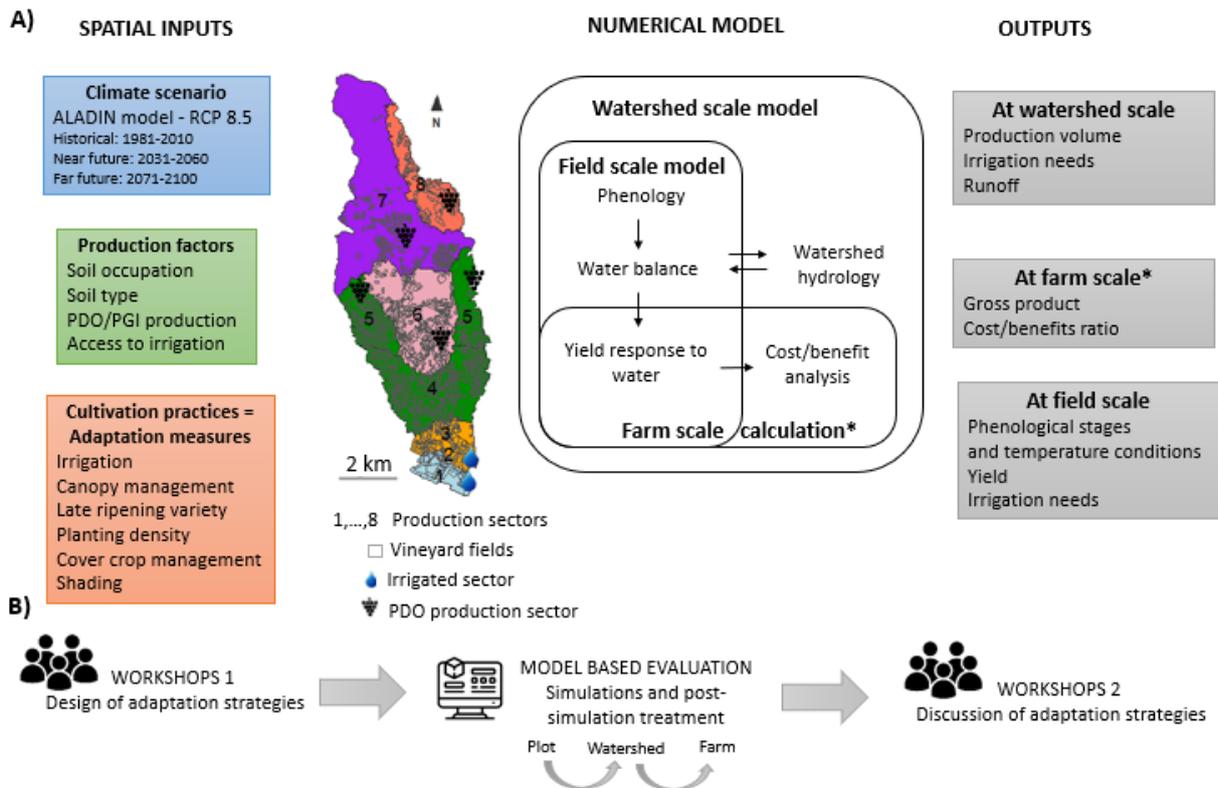
65 Participatory modeling offers a wide range of tools and methods to engage stakeholders in
66 the modeling processes (Voinov et al., 2018). Among them, process-based models are
67 particularly suitable to visualize and analyze complex systems that are confronted with a
68 combination of climatic factors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

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

87 2 Material and methods

88 2.1 A participatory modeling process in a viticultural watershed

89 The Rieutort watershed (45 km²) is representative of the Languedoc vineyard region. The
90 watershed encompasses 1,400 ha of heterogeneous vineyards grown in alluvial, clay-
91 limestone and shale soils. Its Mediterranean climate is characterized by a gradient from the
92 northern mountainous areas (705 mm mean annual rainfall, data Cabrerolles weather station
93 2000–2019) to the southern coastal plain (581 mm mean annual rainfall, data Puisserguier
94 weather station 2000–2019). The northern area is dedicated to traditional farming under the
95 guidelines for Protected Denomination of Origin (PDO) certification and the southern area
96 under Protected Geographical Indication (PGI) conditions, which are more similar to "New
97 World type viticulture". Ten percent of vineyard surfaces are irrigated. At least 59
98 winegrowers have one or more vineyard plots in the watershed and are registered in the
99 French Land Parcel identification system (RPG 2017). They are grouped either in cooperative
100 cellars or in PDO syndicates with various environmental labels such as high environmental
101 value, organic, or biodynamic. In a previous participatory mapping exercise with local
102 stakeholders, the watershed was divided into eight production sectors (Fig. 1A) according to
103 climate, soils, production modes (i.e., low yield objective in Protected Designation of Origin
104 (PDO) areas, high yield objective in Protected Geographical Indication (PGI) areas), and
105 irrigation use (Naulleau et al., 2022).



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

112

113 To design and assess adaptation strategies, we organized two sets of participatory workshops
 114 (4 hours each) in January and July 2021. The two sets were separated by a 6-month modeling
 115 phase performed by researchers (Fig. 1B). Participants were selected after a preliminary series
 116 of individual interviews organized to assemble a representation of the different types of
 117 production in the watershed (Naulleau et al., 2022). Each set of workshops included two
 118 workshops, one with 15 invited local stakeholders (eight winegrowers, one representative
 119 from the cooperative winery, two representatives from PDO syndicates, two technical
 120 advisors, one local policy maker, and one agri-environmental coordinator) and one with 5
 121 invited regional stakeholders (three representatives from extension and advisory services, one
 122 agri-environmental coordinator and one regional policy maker) (Supp Table 2). Workshop
 123 agendas were planned with the participants to maximize participation and to ensure at least

124 one representative for each type of stakeholder (more details in Supp Table 2). We
125 hypothesized that regional stakeholders might propose bolder strategies, while local
126 stakeholders would gravitate towards more restrictive but locally adapted strategies that
127 account for the diversity of local conditions and constraints, as argued in March et al. (2012).
128 Five regional stakeholders participated in both of the regional workshops. Nine, and then six,
129 local stakeholders participated in the two local workshops. The first set of workshops (WS1)
130 was aimed at designing the adaptation strategies, including the spatial distribution of
131 adaptation measures in the watershed. Intermediary meetings and interviews with
132 participants were held during the modeling step to refine modelers' choices and share
133 information. The second set of workshops (WS2) consisted in the presentation and discussion
134 of simulation results.

135 2.2 The design of adaptation strategies

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

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

155 1.1 The modelling phases

156 The model used to simulate the co-designed adaptation strategies was developed in
157 participation with the same stakeholders (Naulleau et al., 2022, Supp. Fig. 1). It combines a
158 phenological (Morales-Castilla et al., 2020), a water balance (WaLIS, Celette et al., 2010), a
159 yield formation (GrAY, Naulleau et al., 2022), and a hydrological module (Lagacherie et al.,
160 2010) (Fig. 1A), and is implemented in the landscape modeling platform OpenFLUID (Fabre et
161 al., 2013). It simulates the daily spatiotemporal dynamics of water fluxes and grapevine
162 production at field scale within the landscape while considering (i) the spatial variability of
163 soils and climate and (ii) the diversity of cropping systems (i.e., grapevine varieties, planting
164 density, bud load, etc.). The model is able to simulate the impacts of six adaptation measures:
165 irrigation, reduced canopy, late ripening varieties, reduced density, cover crop management,
166 and shading.

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

174 1.1.1 Simulations of adaptation measures at field scale

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

180 We created a typical case sampling of fields in the watershed for the simulations at field scale.
181 We used a criterion-based sampling (Ritchie et al., 2003) to select one representative field per
182 production sector (Fig 1). Each adaptation was simulated individually for each considered field
183 according to the rules presented in Table 1 (location, value ranges). Some of these rules were
184 fully described by stakeholders (e.g., reduced density), other were partially described and had
185 to be supplemented by information from scientific and grey literature (e.g., shading, cover

186 crop management). Stakeholders identified the watershed's seven major varieties as
187 belonging to three phenological groups characterized by their budburst precocity, according
188 to Pl@ntGrape (2020): early (merlot), mid-late (syrah, grenache), and late varieties (carignan,
189 cinsault, cabernet sauvignon and mourvedre). In the model, we used available parameters for
190 merlot, syrah, and cabernet sauvignon to represent each category respectively (Morales-
191 Castilla et al., 2020). For each field, simulations were conducted for the three types of varieties
192 (early, mid, and late), and the results were expressed as their weighted average, using the
193 proportions of the varieties observed in the corresponding production sector (Supp Table 1).

194 Results were expressed as the difference in harvest date, temperature during ripening,
195 irrigation supply, and yield, when compared to the reference situation of the historical period
196 (1981-2010). We also evaluated the level of confidence in the model's results by estimating
197 their similarities and divergences with scientific and grey literature. A low level of confidence
198 was attributed when we did not find literature that corroborated the model's results. A
199 medium level was attributed when the model's results were consistent with the literature but
200 at a different magnitude. A high level of confidence meant that the model's results were
201 similar to those in the literature.

202 Table 1. Detailed simulations of adaptation measures at field scale, followed by information
203 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 Ojeda, 2007
		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	
	Soil water content thresholds	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) 4,5 (Collective network extension) 6,7 (Hill reservoir creation)	Unlimited 80 mm 50 mm
Late ripening variety	Chilling and forcing units requirement	All the sectors	Supp Table 3	Morales-Castilla et al., 2020; Parker et al., 2013, 2020, 2011
Late ripening composite ¹		All the sectors		
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	From veraison to maturity	Stakeholders + Caravia et al., 2016
		All the sectors	- 60% global radiation - 2°C on daily maximal temperature superior to 35°C	
Cover crop management	Destruction date (* fixed date between 15 th February to 15 th 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 hypothetical extremely late variety, built by combining information on several late ripening varieties (Morales-Castilla et al., 2020)

204 1.1.2 Simulations of adaptation strategies at watershed scale

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

221 1.1.3 Post-simulation calculation at farm scale

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

228 First, we selected farms whose vineyards were primarily located in the watershed. Among the
229 59 farms registered in the French Land Parcel identification system (RPG 2017) with at least
230 one field in the watershed, we selected an initial sample of 18 farms with more than 85% of
231 their surface in the watershed. We verified that the distribution of farm size in this sample
232 was similar to that of the 59 registered farms (Supp Fig. 2). Within this sample, we selected
233 eight farms to represent farm diversity in the watershed.

234 Stakeholders designed an indicator (NecPrice) representing the market price for wine that
 235 would compensate for climate change impacts on yield and adaptation costs (i.e., maintain
 236 the historical gross profit— $GP_{\text{historical}}$). As suggested by the stakeholders, we used an
 237 operation-based costing approach, which allowed us to limit consideration to the changing
 238 operations between initial and adaptation strategy at plot scale. Note that Georgopoulou et
 239 al. (2017) also used an operation-based costing approach in their cost-benefit analysis of
 240 adaptation in Greek vineyard. We assumed that production costs were fixed over time. The
 241 2020 average bulk market price was proposed by the stakeholders as a pertinent reference,
 242 to which each winegrower could adapt ($P_{\text{historical}}$ — communicated by the joint trade council of
 243 Languedoc wines).

$$244 \quad \text{NecPrice} = \frac{GP_{\text{historical}}}{GP} * P_{\text{historical}}$$

$$245 \quad \text{Where } GP = \sum_f [(Y_f * S_f - C_f) * P_f]$$

246 NecPrice: necessary market price for wine in order to compensate for climate change impacts
 247 on yield and the costs of adaptation (in €/hl)

248 GP: gross profit (in €)

249 With for each field of the farm f,

250 Y_f : yield (in hl/ha),

251 S_f : surfaces (in ha),

252 C_f : sum of adaptation costs for the field f (in €/ha),

253 P_f : prices (in €/hl) varying according to production type.

254

255 Adaptation costs (Table 2) include material and labor for annual operations (trimming, tillage,
 256 irrigation maintenance) and investment costs (irrigation infrastructure and material, shade
 257 nets). We also considered cost savings from density reduction. We did not look at costs linked
 258 to the planting of new vines, because we considered this to be a normal farm operating
 259 expense not specifically linked to the adaptation. Adaptation costs for material and labor were
 260 taken from Roby et al. (2008) and increased by 15 % to account for inflation over the 2008-
 261 2019 period, as proposed by Van Leeuwen et al. (2019). Infrastructure costs were
 262 communicated by the regional stakeholders. The total costs of adaptation over the 30-year
 263 simulation periods were divided by 30 to obtain an annualized cost per hectare. All costs were
 264 presented and validated by the stakeholders.

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

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

Adaptation measures	Infrastructure life time (years)	Cost (€ .ha ⁻¹ .year ⁻¹)	Source	Benefit (€ .ha ⁻¹ .year ⁻¹)		
				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		-	-	-

270 2.3 The discussions of the adaptation strategies with stakeholders

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

276 Stakeholders were then asked to complete the evaluation by estimating separately the
 277 feasibility and desirability of the six simulated adaptation measures and the non-simulated
 278 measures mentioned earlier (Naulleau et al., 2022). The latter included drought-tolerant
 279 varieties, high quality rootstocks (according to drought tolerance and grafting techniques),
 280 water-efficient training systems, soil quality and water holding capacity improvement (organic
 281 fertilization, mulching, fallow length, decompaction by deep rooting crop species,

282 decompacting by soil ripping), east-west row orientations, and the introduction of hedges.
 283 Stakeholders had seven green stickers to designate the most feasible or desirable measures,
 284 and seven red stickers to designate the least feasible or undesirable measures. There was no
 285 obligation to use all the stickers. Stakeholders were asked to explain their choice during a
 286 recorded collective discussion. After the workshops, we calculated a score (S) for each
 287 adaptation (a) and group of stakeholders (g). For each criteria c (feasible/unfeasible,
 288 desirable/undesirable):

$$289 \quad S_{c,g,a} = \frac{N_{i=c,j=g,k=a}}{\max_{\substack{i=c \\ j=g}}(N_{i,j,k})} * \max_{j=g}(N_{i,j,k})$$

290 where $N_{i,j,k}$ is the number of stickers for the criteria c, the group g and the adaptation a.
 291 $\max_{i=g}(N_{i,j,k})$ was 5 in both groups.

292
 293 The researchers then presented the designed adaptation strategies at watershed scale and
 294 the simulation results under the RCP 8.5 climate scenario for the periods 2031-2060 and 2071-
 295 2100. Finally, the researchers presented the range of evolution in *NecPrice* indicators by the
 296 mid-century time horizon at farm scale. At each stage of the presentation, stakeholders were
 297 asked to share their perception of the simulations and suggest other strategies they could
 298 further imagine.

299 3 Results

300 3.1 Adaptation measures at field scale

301 3.1.1 Model-based evaluation and discussion with stakeholders

302 Among the 13 adaptation measures mentioned during the first set of workshops, six could be
 303 simulated and were presented to stakeholders during WS2 (Table 3). Irrigation compensated
 304 for yield losses due to climate change in most of the cases, with a high level of confidence in
 305 model results. The yield losses in irrigated PGI production were probably overestimated due
 306 to the presence of a shallow water table that was not considered in the model but could
 307 provide water to grapevine roots. The historical average volume of irrigation water applied
 308 (21 mm/year) to PGI vineyards was multiplied by 1.85 for the mid-century horizon and by 2.33
 309 for the end-century horizon (38 mm/year at mid-century to 49 mm/year at end-century).
 310 Currently, PDO vineyards are not irrigated in the studied areas, but the model estimation

311 suggests that 27 mm/year would enable the yield objective to be reached. The level of
312 irrigation remained relatively stable under future climatic conditions (reaching 34 mm/year at
313 end-century). Regional stakeholders confirmed that there is currently a deficit in the water
314 balance in PDO vineyards, and they noted that the *“positive effect of irrigation in reducing*
315 *mortality in superficial soils”* was not modeled. Local stakeholders noted that the volume of
316 irrigation required is particularly important during dry years when the water reservoirs are
317 difficult to replenish.

318 The use of late ripening varieties would limit the delay of harvest dates to one week, which is
319 only a modest improvement compared to the three-week advancement expected from
320 climate change by the end of the century. Furthermore, limiting the delay of the harvest date
321 had little impact on the mean temperature during ripening (decreasing 0.4°C for the 1971-
322 2100 period). Adversely, it delayed the flowering period, pushing it towards warmer and dryer
323 conditions that could reduce yield. The simulations with the hypothetical late ripening
324 composite variety did compensate for the three-week delay of harvest, even though
325 temperatures during ripening remained higher than those of the historical period. This variety
326 corresponds to a non-existing variety whose budburst would occur at end of April and reach
327 maturity in October (under historical climate conditions). Local stakeholders were skeptical
328 about the consequences: *“That would mean that we would need to prune the whole vineyard*
329 *from mid-March to mid-April, which would be impossible to schedule in that short period.”*
330 Regional stakeholders were more motivated to seek similar characteristics among ancient or
331 foreign varieties.

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

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

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

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

		2031-2060				2071-2100			
		Harvest date	Ripening temperatures	Irrigation needs	Yield	Harvest date	Ripening temperatures	Irrigation needs	Yield
Mean historical values (1981-2010)		11-sept	22.4 °C	—	10.5 t/ha	11-sept	22.4 °C	—	10.5 t/ha
∅	Mean climate change impacts	●●●	●●●	●●	●●	●●●	●●●	●●	●●
Irrigation	Irrigation PGI (current network)	—	—	●●	●●	—	—	●●	●●
	Irrigation PGI (network extension)	—	—	●●	●●	—	—	●●	●●
	Irrigation PDO (network extension)	—	—	●●	●●●	—	—	●●	●●●
	Irrigation PDO (hill reservoir)	—	—	●●	●●●	—	—	●●	●●●
Late ripening variety	Late ripening varieties	●●●	●●●	●	●●	●●●	●●●	●	●●
	Late ripening composite	●	●	●	●	●	●	●	●
Canopy management	10 cm height reduction	+	—	●●	●	+	—	●●	●
	20 cm height reduction	+	—	●●	●	+	—	●●	●
Shade	Shading nets	+	●●	●●	●●	+	●●	●●	●●
Density	Reduced density	—	—	●●	●●	—	—	●●	●●
Cover crop dest.	At budburst	—	—	●●	●●	—	—	●●	●●
	At flowering	—	—	●●	●●	—	—	●●	●●
Cover crop surfaces	1 inter-row out of 4	—	—	●●	●●	—	—	●●	●●
	1 inter-row out of 2	—	—	●●	●●	—	—	●●	●●
	All interrows	—	—	●●	●●	—	—	●●	●●
	All rows and inter-rows	—	—	●	●●	—	—	●	●●

	Harvest date (days)	Mean temperature during ripening (°C)	Irrigation need (mm)	Mean yield (%)
Favorable effects ↑	+ 14 d	- 6 °C	- 60 mm	+ 25 %
	+ 7 à 14 d	- 3 à - 6 °C	- 40 à - 60 mm	+ 15 à + 25 %
	+ 3 à 7 d	- 1 à -3 °C	- 20 à - 40 mm	+ 5 à + 15 %
Unfavorable effects ↓	- 3 à + 3 d	- 1 à + 1 °C	- 20 à + 20 mm	-5% à - 5%
	- 3 à - 7 d	+ 1 à + 3 °C	+ 20 à + 40 mm	- 5 à -15 %
	- 7 à - 14 d	+ 3 à + 6 °C	+ 40 à + 60 mm	- 15 à -25%
—	Not modeled			
- / 0 / +	Unfavorable / neutral / favorable effects (qualitative data)			

Level of confidence
 ●●● High
 ●● Medium
 ● Low

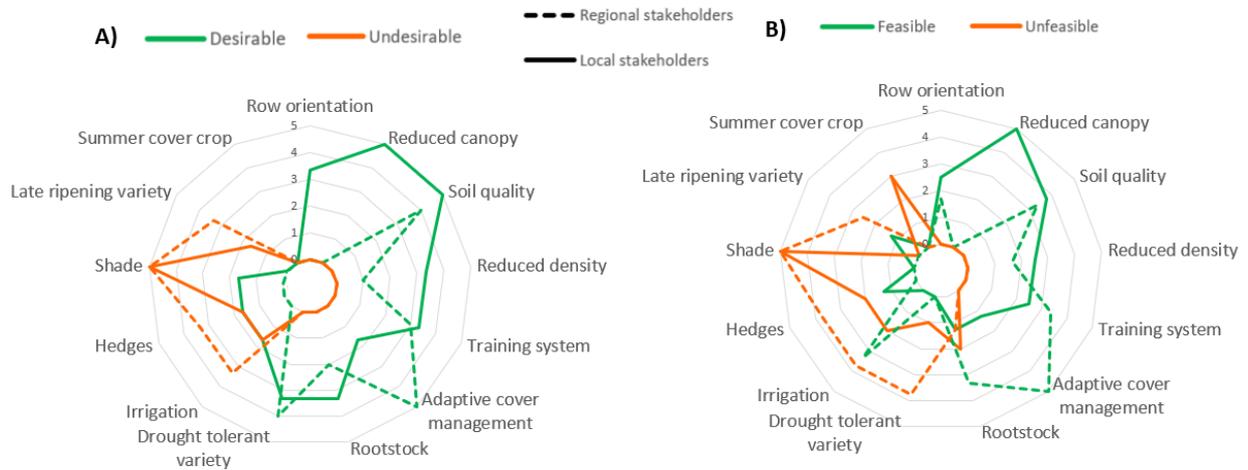
359 3.1.2 Feasibility and desirability of adaptation measures

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

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

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

389



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

393 3.2 Adaptation strategies at watershed scale

394 3.2.1 Overview of the co-designed adaptation strategies

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

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

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

415 • *Soil improvement strategy*: The combination of soil management practices with high-
 416 quality rootstock are implemented in order to improve available water capacity in the
 417 soil and favor deep grapevine roots. The lack of knowledge about soil heterogeneity in
 418 the watershed along with the related physical and biological processes in the soil did
 419 not allow us to evaluate quantitatively the performance of this soil improvement
 420 strategy.

421 • *Relocation strategy (RelocS)*: The vineyards are relocated northward, given the
 422 aptitude of northern vine systems to withstand climate change (Naulleau et al., 2022).
 423 The main limitation in evaluating this strategy is the lack of data on soil
 424 characterization, especially for the northern shale soils. Therefore, we hypothesized
 425 that the northern areas where vines had been previously cultivated (1974) could be re-
 426 converted into vineyards to compensate production losses from climate change.

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

Adaptation measures	Adaptation strategies					
	Delayed harvest strategy	Water stress limitation strategy			Soil improvement strategy	Relocation strategy
		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	

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

431
 432

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

Sector (vineyard surface)	<i>WSS_irri</i>	<i>WSS_ST</i>		<i>WSS_LT</i>	
	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%

437

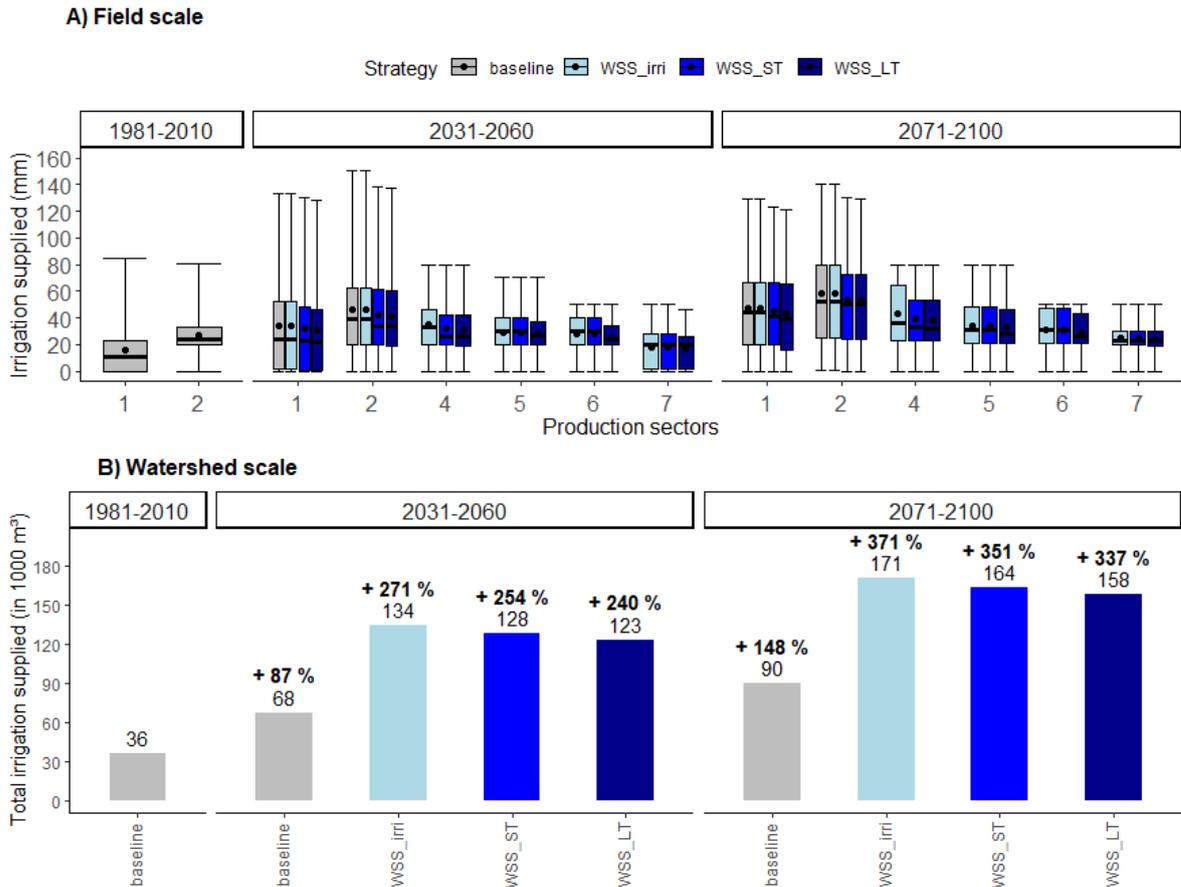
438 3.2.2 Impact of the water stress limitation strategy (*WSS*) to enhance water use efficiency

439 The water stress limitation strategy was applied to portions of four vineyard sectors (4,5,6,7)
 440 that are not currently irrigated. The resulting mean irrigation levels in these newly irrigated
 441 sectors were lower than for the two sectors (1,2) that are currently irrigated (Figure 3A). This
 442 difference can be traced to a combination of the maximum annual irrigation allowed by the
 443 collective management of water resources and the lower water requirement of PDO
 444 production as compared to PGI production. In sector 6, where the limestone soils are
 445 superficial and the planting density is 4,500 plants ha⁻¹, the maximum volume of irrigation
 446 water was required 1 year in 4 during the period 2071-2100, which implies frequent difficulty
 447 in satisfying grapevine water demand. In the period 2031-2060, the irrigated surface
 448 (*WSS_irri*) was almost tripled, and the irrigation water requirement at watershed scale
 449 doubled from 68,000 m³ to 134,000 m³ (Fig 3B). The short-term (*WSS_ST*) and long-term
 450 (*WSS_LT*) measures did not significantly reduce the level of irrigation at field or watershed
 451 scales.

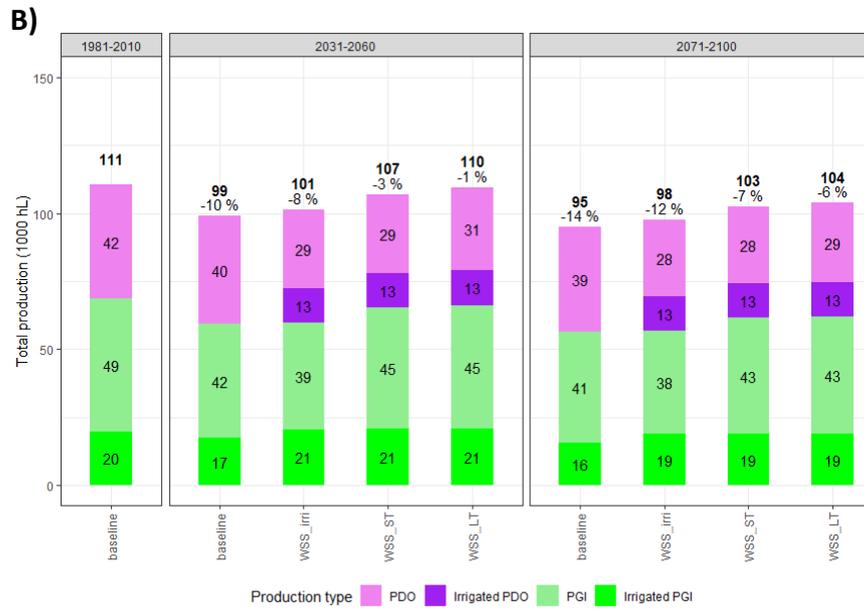
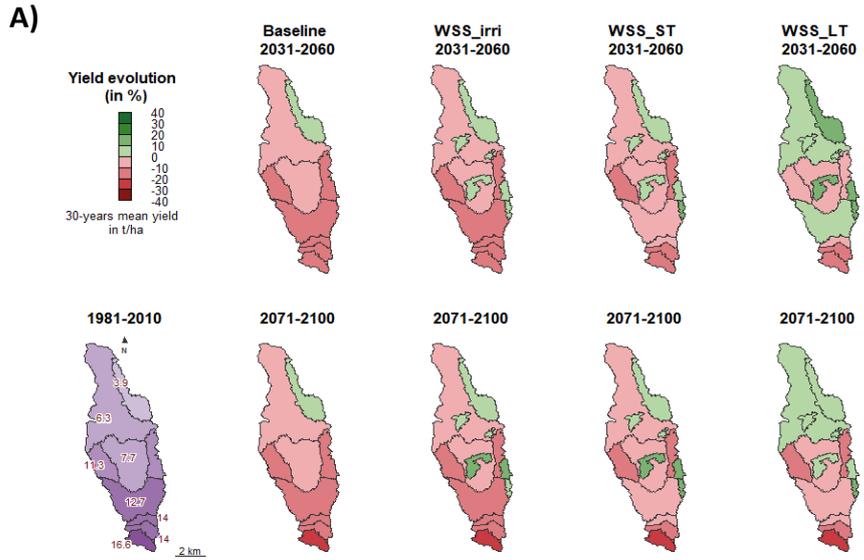
452 The mean yields in the newly irrigated surfaces were maintained, and even increased
 453 compared to the historical period (Fig 4A). The short-term adaptation strategy (*WSS_ST*)
 454 showed a positive effect on yield in the two non-irrigated sectors located in the southern part
 455 of the watershed (sector 3 and 4), allowing them to reach the objective of 12 t/ha. In both

456 future time periods, the long-term adaptation strategy (*WSS_LT*) of shading nets and reduced
457 density restored the northern sector's yield to the historical level. Shading nets also limited
458 yield decrease in the central sectors, but this effect was visible only for the 2031-2060 period.
459 At watershed scale, compensation for yield loss due to climate change was only achieved
460 through the mobilization of irrigation in the short and long-term adaptation measures, and
461 this only at the near future horizon (Fig 4B). Production losses at the end of the century in the
462 *WSS_LT* strategy were estimated at 6%, compared to 14% in the baseline. PGI production
463 suffered the highest yield loss. However, the mean yield in PGI production sectors (sectors 1
464 to 4) remained higher than the 12 t/ha authorized for PGI certification. By contrast, the mean
465 yield in sector 8 remained below the authorized 6 t/ha for PDO production.

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



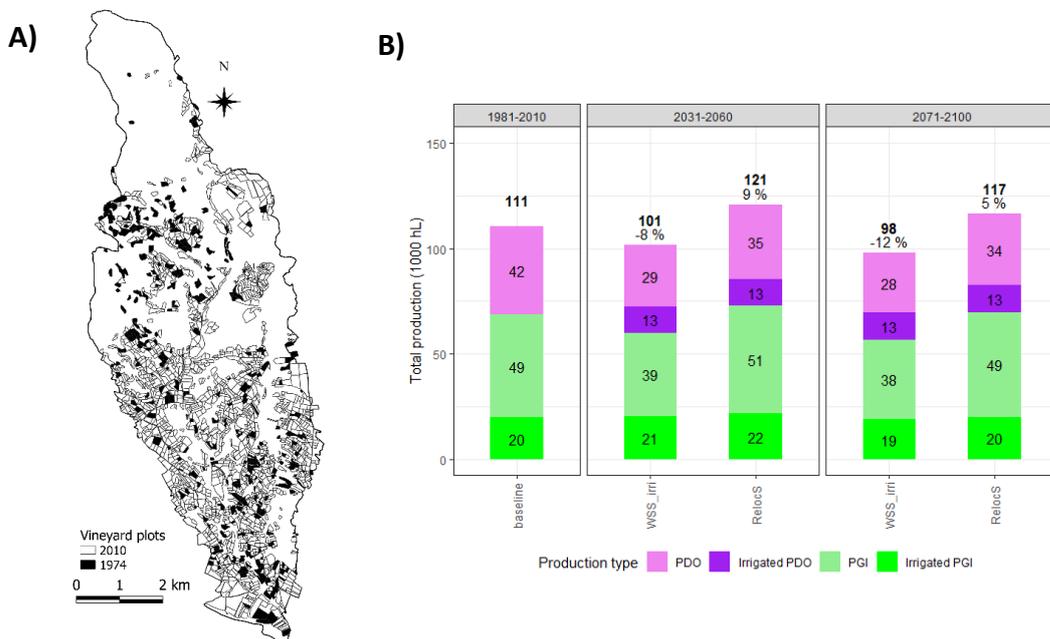
475 Figure 3: Annual irrigation supplied at (A) field and (B) watershed scale, according to the
 476 three water stress limitation strategies (WSS) in RCP 8.5. Boxplots correspond to the 30
 477 years of simulation (mean indicated by a point). Barplots correspond to the mean irrigation
 478 supplied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



482 Figure 4: Evolution of grapevine production in RCP 8.5 for the period 2031-2060 and 2071-
 483 2100 in comparison to the historical period (1981-2010): (A) variation of mean yield by sector
 484 and (B) mean annual volume of production according to type (PGI: Protected Geographical
 485 Indication, PDO: Protected Designation of Origin).

486 3.2.3 Relocation strategy to compensate for production losses

487



488

489 Figure 5: A) Map of the vineyard baseline (white) and relocation strategies (white + black); B)
 490 Effects of the relocation strategy (RelocS) on the total production volume under the RCP 8.5.
 491 PDO: Protected Designation of Origin. PGI: Protected Geographical Indication production.
 492

493 During the timespan between the aerial images of 1974 and 2010, 330 ha of vineyard were
 494 converted into forests (173 ha), fallows (61 ha), cereals (38 ha), pastures (37 ha) and other
 495 crops (21 ha). Among those surfaces, 160 ha are located in PDO sectors, mainly in the northern
 496 areas, and 170 ha in PGI sectors in the south (Fig 5A). The reconversion of those surfaces into
 497 vineyard, without considering fallow time, compensated for or increased the volume of
 498 watershed production compared to the historical period (+9% by the period 2031-2060, +5%
 499 by the period 2071-2100) (Fig 5B). On average, the mean yield in these new areas reached 40
 500 hl/ha for PDO production by the end of each time periods, and 70 hl/ha for PGI production by
 501 2060 and 64 hl/ha by 2100. Local stakeholders confirmed the historical move southward.
 502 Generally, vineyards were abandoned because of difficult terrains in the more mountainous
 503 region and lower yields compared to other fields in the same sector. Local stakeholders
 504 estimated that the reconversion of those fields could be feasible if winegrowers managed to
 505 produce a quality wine, with historical varieties. But issues related to access, labor, and related

506 costs would remain. A detailed analysis of soil properties in these areas would be necessary
507 to precisely identify areas suited to relocation.

508 1.2 Cost-benefits analysis at farm scale

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

518 The expansion of irrigation in the watershed (*WSS_irri*) involved four farms, all with PDO
519 production and water supplies in hill reservoirs. The extent of the conversion to irrigation on
520 these farms varied from 18% to 75% of their cultivated surfaces (Table 6). The gain in yield
521 from irrigation would cover the irrigation costs, as seen in the lower necessary price increase
522 with the irrigation strategy compared to the baseline strategy. The regional stakeholders
523 agreed with this analysis with the understanding that the winegrowers would have to respect
524 the yield limitation set by the PDO syndicates (6 t/ha) in order to benefit from the higher price
525 of a PDO wine. They also noted that the adaptation costs of irrigation infrastructure for hill
526 reservoirs are highly variable and depend on factors such as location, water sources, and
527 topography. We might have underestimated the costs, but one stakeholder argued that
528 800€/ha/year is the "*maximum acceptable cost.*" If costs rose above that amount, he believed
529 that the infrastructure would not be built. Local stakeholders believed that the investment
530 required would entail significant costs to local government agencies, and they raised the
531 question of the necessity of such spending. Moreover, the availability of the water supply is
532 not guaranteed, creating an additional risk that was not considered here (i.e., the evaluation
533 assumes that reservoirs are recharged each year).

534 Short term adaptations (*WSS_ST* strategy) were primarily associated with the farm in the
535 southern part of the watershed. The additional costs related to reduced canopy (trimming)
536 were low, and the yield gain simulated in the model covered the adaptation costs. This balance

537 between cost and benefit was maintained even for the farm that also adopted the practice of
538 a cover crop on one inter-row in four during summer. Nevertheless, local stakeholders
539 suggested that the positive effect of severe trimming on yield, as well of its impact on wine
540 quality still need further verifications.

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

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

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

Farm Description				Mean production Reference	Adaptation (% farm surfaces)					Necessary price evolution for the period 2031-2060 (in €/hl)			
Winery	Production	Production sector	Surface (ha)		WSS irri Irrigation	WSS ST Cover crop	WSS LT 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	

565 4 Discussion

566 4.1 Co-designed adaptation strategies

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

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

586 Genetic diversity should also be explored according to the drought-tolerance of varieties and
587 rootstocks. Today 110 Richter is the most widely used rootstock in Languedoc, but the even

588 more drought tolerant 140 Ruggeri could be included in the adaptation strategies even though
589 its effect on water balance is difficult to evaluate quantitatively (Ollat et al., 2015). Similar
590 options do exist through the use of drought-tolerant varieties (Duchene, 2016).

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

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

619 needed to maintain historical yield. The goal would be to evaluate the ability of changes in soil
620 management to fill the gap between the current and future soil water capacity needed.

621 The vineyard relocation strategy has often been studied at large scales (e.g., de C. Teixeira et
622 al., 2014; Hannah et al., 2013; Malheiro et al., 2010), and our results confirm the advantages
623 of moving to higher altitudes to adapt to climate change. But the limitations of such studies,
624 including ours, is the lack of attention to conservationist conflicts over land use (Hannah et al.,
625 2013), the low resolution of the input data (soil, climate, practices, etc.), and the technical
626 feasibility of cultivating those areas. Further research could focus on this strategy and expand
627 knowledge about the choices to buy or rent (or not) new land, as studied in Delay et al. (2015).

628 4.2 An original method to design and assess adaptation strategies

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

643 The economic evaluation of the adaptation strategy was crucial for the two types of
644 stakeholders. However, the co-designed economic indicator showed some limitations: (i) costs
645 and benefits poorly consider plots and farms diversity, (ii) variable costs and benefits are not
646 considered, (iii) costs are fixed and annualized over time. Concerning the first point, we had
647 only two available levels of costs and benefits according to the type of production (PDO or
648 PGI), intrinsically linked with vineyard design. However, the diversity of plots (soil, slope, etc.)
649 and farms (material, spatial distribution of plots, labor force, etc.) imply a wider range of

650 operation costs. The marketing strategies (e.g. bulk vs. bottled, direct sales vs. cooperatives,
651 environmental labelling) may also affect the selling price and therefore the benefits of the
652 adaptation. Therefore, further and updated data collection on the economic performances of
653 the different types of farms are needed to proceed to a monetary assessment of adaptations
654 measures. National database can be used such as census (e.g. Bernetti et al. 2012), farm
655 accounting (e.g. Sacchelli et al., 2017) or data available at the ministry of Agriculture (e.g.
656 Georgopoulou et al., 2017) for estimating the operation costs and benefits in the vineyard.
657 While these databases may have some limitations, the complexity and the high territorial
658 differentiation of vineyard systems often lead the authors to use complementary sources of
659 information like consultation of farmers (e.g. Georgopoulou et al., 2017) or experts (e.g.
660 Sacchelli et al., 2017). On the second point, we suggest to introduce variable costs, such as the
661 irrigation water price, and variables benefits depending on wine quality and market variability,
662 to better compute costs and benefits. This would allow the exploration of economic
663 adaptation scenarios such as the creation of climate-smart agriculture labels, or an increase
664 in the cost of irrigation water. On the third point, the United Nations Framework Convention
665 on Climate Change reviewed a large panel of approaches to assess the costs and benefits of
666 adaptation options (UNFCCC, 2011). Among them, the approach proposed by stakeholders
667 has similarities with the cost-benefit analysis (CBA). However, unlike our method, a discount
668 rate is used in CBA to determine the present value of future benefit and cost flows. The IPCC
669 reminds that discount rate is a core question but opinions vary sharply on its value
670 (Chambwera et al., 2014). This value can vary between 0.1 to 2.5% among studies (Chambwera
671 et al., 2014), while in the Greek vineyard, Georgopoulou et al. (2017) took on a rate of 6%. The
672 discount rate parameter, that could appear subjective, is not easy to implement in a
673 participatory approach. A solution could be to test various values of discount rate, with the
674 challenge to keep results clear enough with the stakeholders.

675 4.3 Enriching interactions within and between groups of stakeholders

676 The choice of the territory and the co-design approach had some consequences on the size of
677 the participant sample. First, the territory had a small size (45 km²). Therefore, the diversity
678 of systems, stakeholders, and their opinions could be represented by a limited number of
679 participants, including farmers. Second, co-design approaches require a constant and
680 organized dialogue between participants and researchers (Jeuffroy et al., 2022); keeping an

681 active and stable participation is thus necessary to build a fruitful dialogue. However, recent
682 works often cite the difficulties of maintaining actor's involvement during workshops (Della
683 Rossa et al., 2022). In our case, the collective planning and the dialogue established between
684 participants helped ensuring a constant number of participants to preserve the diversity of
685 stakeholders (localization, types of production, professions and ways of actions). There is no
686 consensus in literature on the right number of participants for participatory design workshop.
687 While Alcamo (2009) suggests a number between 15 and 25 for World Scenario Exercise (p.
688 137), design workshops of the 12 case studies analyzed by Jeuffroy et al. (2022) included
689 between 7 and 25 participants, which is similar to the participation observed in our study. Our
690 workshops gathered, in addition to other stakeholders, 8 farmers, who represented all
691 production sectors. Although this number is relatively low, it corresponds to what was
692 observed on the case studies of design workshops, which included between 0 and 8 farmers
693 (Jeuffroy et al., 2022). Nevertheless, a larger number of farmers would have been beneficial
694 to (i) limit the risk to neglect some adaptation measures and to (ii) represent a wider range of
695 different interests and experiences.

696 The two separated groups of stakeholders produced and discussed complementary but
697 sometimes contradictory information. The local stakeholders appreciated the concrete and
698 local information they acquired on climate change and its potential consequences on their
699 vineyards. Many ideas were mentioned during the workshop, such as the wish to innovate
700 within their farm, the importance of sharing experiences, and the need to combine multiple
701 adaptations. Local stakeholders tended to look at traditional practices to find solutions, but
702 they complained about the prohibition of some of those practices decided at regional or
703 national level (e.g., restrictions on planting density, varieties). Regional stakeholders were
704 more interested in sharing information on adaptation measures, for which they are most often
705 solicited. They highlighted the need of information on goblet systems (training the vines
706 upright and planting in a grid pattern without use of a trellis), historical varieties, and foreign
707 varieties. As further step, a final meeting could be organized to inform a broader audience
708 about the results of our study, as well as to engage them in discussion (Voinov and Bousquet,
709 2010).

710 The interactions between researchers and the two groups of stakeholders did not differ
711 significantly. However, each group helped develop analyses outside of the model's limits. For

712 example, regional stakeholders helped compare model results with different experiences in
713 other areas. Local stakeholders were more likely to identify possible feedback loops in their
714 production systems. For example, water ponds would increase the available irrigation water,
715 but a particularly dry winter could jeopardize the replenishment of the water ponds, and
716 consequently decrease the available irrigation water. Thus, the cost-benefits ratio of the water
717 source infrastructure would be adversely affected. They also proposed to account for extreme
718 climate events (frost, hail, heat waves) by introducing particularly low production years, for
719 which the probability could vary among climate scenarios. The relevance of stakeholder's
720 knowledge about local conditions, constraints and feedback loops was demonstrated by
721 Schaap et al. (2013) in their study evaluating the impacts of extreme events on Dutch farms.
722 The next stage of the study should focus on deepening the participatory approach to include
723 qualitative information on feedback effects into a (semi-) quantitative evaluation.

724 5 Conclusion

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

736 Finally, we designed and assessed adaptation strategies that limit potential production losses
737 due to climate change in the Rieutort watershed. The most productive areas showed the least
738 leeway to adapt to climate change, even though they appear to be the most affected by the
739 future climatic conditions. The systems with low yield production were better at withstanding
740 climate change and were also more likely to adopt innovative adaptations. However, our study
741 did not consider the effects of extreme events, nor the effects of socio-economic drivers of

742 change. Reduced canopy, soil quality improvement, water-efficient training systems, and
743 reduced density were identified as particularly promising adaptation measures and should be
744 further investigated.

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