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Abstract

Among the multiple adaptations that exist to face climate change, irrigation is one straightforward option for wine growing. Yet, widespread development of irrigation may strengthen water scarcity and further increase farmers' vulnerability to water stress. In this context, understanding the conditions of the adoption of irrigation is of outmost importance to characterize the process, the risks and the policy implications of climate change adaptation. This paper presents an empirical approach for understanding the factors driving current and envisioned irrigation at farm level, by combining Internet-survey data and *terroir* data (precipitation, temperature, and soil water holding capacity) characterizing wine growers and farms in southeastern France (Languedoc-Roussillon). Survey data include current and future practices, the perceptions of past changes, and wine growers' main objectives. The sample gathers 28% of growers that are already irrigating their vines, 39% that are considering this option for the future. Results of different econometric models show that both *terroir* and socio-economic factors such as perceptions and objectives play significant roles in the adoption of irrigation. Specifically, perceptions of water scarcity seem to drive future irrigation projects much more than real water scarcity. These results carry important policy implications for water-demand forecasting and water-supply planning.

Key-words: adaptation, climate change, irrigation, wine, global change, perceptions

1. Introduction

As most agricultural sectors (Fischer et al., 2005), grape and wine production are likely to be heavily affected by climate changes (Hannah et al., 2013). Many North European vineyards are not irrigated, and the relative drought experienced by vines in summer is key for wine quality (Van Leeuwen, Destrac-Irvine, 2017). However, climate change might threaten the quality and the volume of wine production (Lerebouillet et al., 2014). Thus climate change calls for a wide range of production, organizational or marketing adaptation options such as the use of irrigation, tillage strategies, changes in pruning, planting new grape varieties, shifts in planted areas, enological adaptations or new marketing strategies (Nicholas and Durham, 2012; Ashenfelter and Storchman, 2016 ; Ollat et al., 2016).

In regions with both dry summers and available water resources, irrigation will play a dominating role in agriculture's response to climate change (Elliott et al., 2014). However, irrigation is not a marginal adaptation as it requires substantial investments and changes in practices. It will also lead to additional pressures on water resources already harmed by climate change because of lower recharge rates and increased evapotranspiration. In the long-run, irrigation may even turn out to be a maladaptation[1] (Barnett and O'Neill, 2010 ; Viguier et al., 2014) which is a situation in which the actions of individuals' triggers new vulnerabilities for either another group (future generation, other users) or another source of vulnerability within the group. At farm level, the choice for irrigation is such that it might potentially make the production model more vulnerable when facing specific external constraints, such as the prohibition of water withdrawals if growers have not introduced other drought coping measures. At higher scales, in the absence of an effective mechanism for regulating withdrawals, a growth in water demand caused by the increase in irrigated areas may lead to a decrease in water availability, strengthening thereby the vulnerability of other users of the resource and ecosystems. Niles and Mueller (2016) also highlighted that growers with irrigation infrastructures have a reduced perception of climate change, and

[1] He suggests 5 criteria for maladaptation: increase emissions of greenhouse gases, disproportionately burden the most vulnerable, have high opportunity costs, reduce incentives to adapt, and set paths that limit the choices available to future generations.

therefore, are less willing to participate in greenhouse gas emission mitigation efforts. Furthermore, irrigation alone cannot tackle all the effects of climate change: for instance, Fraga et al. (2018) predict that irrigation will compensate only for a small share of yield drop in hotter Portuguese regions.

In this context, understanding the motivation and factors underlying the choices of growers regarding irrigation and alternative drought coping strategies may help better anticipate future water demand and lay the foundations for a larger public debate. Both because irrigation is costly and potentially risky, it appears of absolute importance to anticipate the potential economic and environmental consequences of this adaptation for individuals and the society in general. This would allow a collective debate to take place based on sound information. Understanding the future water demand is also a challenge for robust water-conveyance infrastructure planning. There are as yet relatively few published empirical studies that are looking at how and why irrigation was adopted by farmers in response to climate change, particularly in industrial countries and still fewer on viticulture. Although recently, Merloni et al. (2018) investigated the adaptive capacity of Italian wine growers faced with climatic change and Willey and Marling (2019) explored water security perception and irrigation practices of Australian wine growers.

This paper intends to improve the knowledge on the factors, including individual perceptions and objectives, that drive farmers' irrigation adoption to contribute to the understanding on the processes of adaptation. To do so, an empirical case study of wine-growing farms in Languedoc-Roussillon (LR) (Occitanie, South of France), examines the factors that explain the adoption of irrigation by current irrigators and by those who intend to irrigate in the future. We distinguish a set of physical variables that characterize the *terroir* – precipitation, temperature, and soil water holding capacity – from the individual socio-economic variables that characterize either the farmer or the farm, such as the age, the level of education, the objectives pursued by wine growers and their perceptions of the hydric stress and previous changes. This is realized by analyzing, with econometrics, data collected through an Internet based survey coupled with terroir data.

LR is particularly suited to study the process of irrigation adoption as the vineyard is currently facing a transitional phase with new opportunities to adopt irrigation (extension of the water conveyance infrastructure and recent favorable changes in regulation). Vine covers 244 698 ha in LR and makes it the first wine growing region with about 30% of the French vineyard even though this area dropped by 43% from 1975 until 2015 (DRAAF, 2015).

The contribution of this article to the literature is to address and analyze the socio-economic determinants of irrigation adoption. It is also, as far as we know, the first study concerning adaptation to climate change that combine data obtained from a custom-designed Internet questionnaire with georeferenced soil and climate –*terroir*- data.

After this introduction, the second section presents the state of the art on adaptation and the factors affecting adaptation; the third section – material & method – presents viticulture in Languedoc-Roussillon and the issues raised by climate change as well as the method. The fourth section presents the results of the descriptive analysis and the econometric models for past and future irrigation choices. The fifth section offers a discussion of the results, leading to the conclusion.

2. Background on adaptation and adaptation factors in agriculture

Adaptations are "demonstrations" of the ability to adapt and represent ways of reducing vulnerability (Smit and Wandel, 2006, Nicholas and Durham, 2012). Smit and Skinner (2002) propose a typology that distinguishes (i) technologic developments/innovations; (ii) public programs and insurance; (iii) farm-level production practices; and (iv) financial management of the farm.

2.1 Empirical economic approaches for examining technology adoption

Few studies have examined the factors that lead to or facilitate the adoption of adaptive measures to address climate change, e.g., Nicholas and Durham (2012), Deressa et al. (2009) and Thomas et al. (2007) in the southern hemisphere. There is a more extensive literature on the adoption of new technologies (e.g. Feder and Umali, 1993), which is one type of possible adaptation to climate change. Marra et al. (2003) have proposed a review of literature on technology adoption through economic and sociologic approaches, and raise the role of uncertainty, risk, and learning in the theoretical models. These studies often develop empirical approaches for understanding these processes. They apply both qualitative approaches (detailed interviews) and quantitative ones. Among quantitative approaches, two strands in the literature on technology adoption in agriculture contrast sharply.

The first is based on classical models of production economics and development that rely on profit maximization and the incorporation of the alternative technology into the model. They then derive the conditions under which technology adoption proves worthwhile and should be pursued. Empirical studies then test these models against observations. Koundouri et al. (2006) is one of the typical studies in this strand. Notably, the authors incorporate uncertainty into the problem, arguing that profits after technology adoption are unknown. They test their theoretical model against empirical survey data from Crete, where farmers were given the opportunity to adopt a new irrigation technology. The seminal paper by Caswell and Zilbermann (1985) examines alternative irrigation technologies (drip, gravity, and sprinkler) in the United States. Another example is Di Falco and Veronesi (2013) who develop a two-stage multinomial model in which, after determining the factors of adaptation, the effects of various adaptations on net revenues are characterized.

The second strand in this literature examines the adoption of technologies by modeling with econometrics the probability of adoption rather than imposing any explicit form of profit maximization. The rationale can be both that the *apriori* profit can be difficult to infer when the technology's effects on revenues are not straightforward, or that analysts want to assess other drivers than profit maximization such as those recognized by behavioral economics, e.g., attitudes, values, and motivations (Burton, 2004) included in the decision process. Moreno and Sunding (2005) suggest an elaborate nested logit model to allow for a simultaneous technology/crop-selection model, focusing on various irrigation technologies in the USA. Deressa et al. (2009) develop a multinomial logit model to analyze the determinants of farmers' choices of several adaptation strategies in the Nile basin of Ethiopia. Below et al. (2012) test a multiple regression of an adaptation score (activity-based adaptation index) using latent variables constructed by weighting various adaptation options. Trinh et al. (2018) explore the determinants of agriculture's adaptation to climate change in Vietnam. Because individual farm strategies are varied (maximization of yields, improvement of wine quality, preservation of land, etc.) and adaptation measures have no unique and straightforward effects on revenues, we build on a pragmatic approach in line with this second strand.

2.2 Adoption factors of adaptations to climate change

Two types of factors explaining the adoption of adaptation actions can be distinguished. The first type includes physical variables or *terroir* variables, such as temperature, precipitation and soil; they characterize the water demand of the crop. The second type covers individual characteristics of the farm and of the farm owner.

The factors contributing to the adoption of adaptations in agriculture identified in the literature are numerous. However, it is difficult to identify adaptation factors specific to irrigation in the literature: in general, other adaptations to climate change are considered. Deressa et al. (2009) consider soil conservation, crop changes, planting trees and changing planting dates. The adoption of various irrigation technologies (drip, gravity, and sprinkler) is examined in numerous publications but without being viewed as adaptations to climate change (e.g. Negri and Brooks, 1990).

Farm characteristics such as its size, land use and access to the property, and farmer's characteristics such as the age, education, perception of risk, experience or participation to specific capacity building events are factors affecting the choice of adaptation (e.g. Thomas et al. (2007), Deressa et al. (2009), Wheeler et al. (2013), Trinh et al. (2018)). The choice of adaptations also rests on considerations of goals, attitudes and values (Adger et al., 2009, Marshall et al., 2012). The importance of perceptions of climate change and beliefs on adaptation choices has been highlighted by Wheeler et al. (2013). Nicholas and Durham (2012) examined the influences of various information sources on farm-management decisions and also show that experience and the history of the farm are crucial. They further suggest that the greater the profit margins, the more farms are able to experiment and adopt new practices. Boyer and Touzard (2017) investigate the role of networks in the elaboration of climate change adoption strategy.

3. Material & Method

3.1. Grape growing in Languedoc-Roussillon, impact of climate change and irrigation

Located along the Mediterranean coastline, Languedoc-Roussillon (LR) is the largest wine-producing region of France (see Figure 1). The wine industry accounts for 54% of the economic worth of the region's agriculture, about 30% of national production by volume, and contributes strongly to the regional image as regards tourism (DRAAF, 2015). LR is characterized by a Mediterranean climate and is thus hotter and dryer than major north European vineyards. As a consequence, climate change is a threat more than an opportunity for the vineyard. In addition, wine-growing in the region is facing international competition and globalization of the wine market (Anderson and Pinilla, 2018), the decline in wine consumption and the specific difficulty of maintaining wine prices, especially for bulk wine purchases (Touzard, 2011). The threat of climate change is illustrated for instance with a change in regulation: since 2006, regulation regarding vine irrigation no longer takes places for wines except for some wine with “protected designation of origin” wines. Together with the 2008 reform of the EU Common Market Organization for Wine, which deregulates the yield maximum for vines with no geographic identification, these regulatory changes are likely to entail a potential increase in the yield targets for wines that could locally increase water demand of viticulture. This makes a study of recent developments in wine-producing practices particularly interesting for the region.

For the French Mediterranean area, current climate projections indicate lower precipitation during the summer, but also much more frequent violent storms in the fall (Terray and Boé, 2013). A lowering of rainfall in late spring, a key moment in the plant cycle (flowering and setting) could cause a decline in the quality of the wine. More frequent periods of drought in summer could impact the grapes during the maturation phase and lead to reductions in the yields and to high concentrations of sugar and so ultimately to an increase in alcohol content. As regards crop pests, climate change would have a moderate effect, given that interannual variations in the current climate are very large (the "vintage effect") in comparison to expected trends of climate change. Thus, if no adaptation of wine-growing or wine-making practices is undertaken, climate change could affect the quality and quantity of the wines produced, as well as the areas where they can be produced (Ollat et al., 2016).

Among agricultural practices, irrigation can be considered as the most straightforward adaptation option in the face of climatic change. Irrigation is not traditional in the LR vineyard. It is only in the last decade that irrigation has started to be practiced in the plains where a surface water network is available and because irrigation was authorized for most areas. Recently, the extension of a long distance channel conveying water from the Rhone river to the south-eastern areas of the basin, the *Aquadomitia* channel (financed by EU) has offered water access to new areas. In this case, since it is enabled by a large publicly funded water-conveyance infrastructure, irrigation lies in between collective and individual adaptations. Furthermore, irrigation can prove to be expensive, both for the farmer and for the taxpayer (between 8,000 and 10,000 €/ha of investment costs excluding the water-main for one hectare with drip irrigation from a surface system[2]) and its cost-benefit ratio is debated. Yet, alternative water-management strategies exist such as tillage, green cover or canopy management. Changes in the organization of the farm may also be relevant, including adaptation of rootstocks and changes in the grape variety or even, relocation of the vines. Wine making practices like the reduction of alcohol content, e.g., dilution and filtration by reverse osmosis or the addition of acid (Nicholas and Durham, 2012) are however restricted by regulations in France.

[2]Figures often cited for current irrigation projects under Aquadomitia

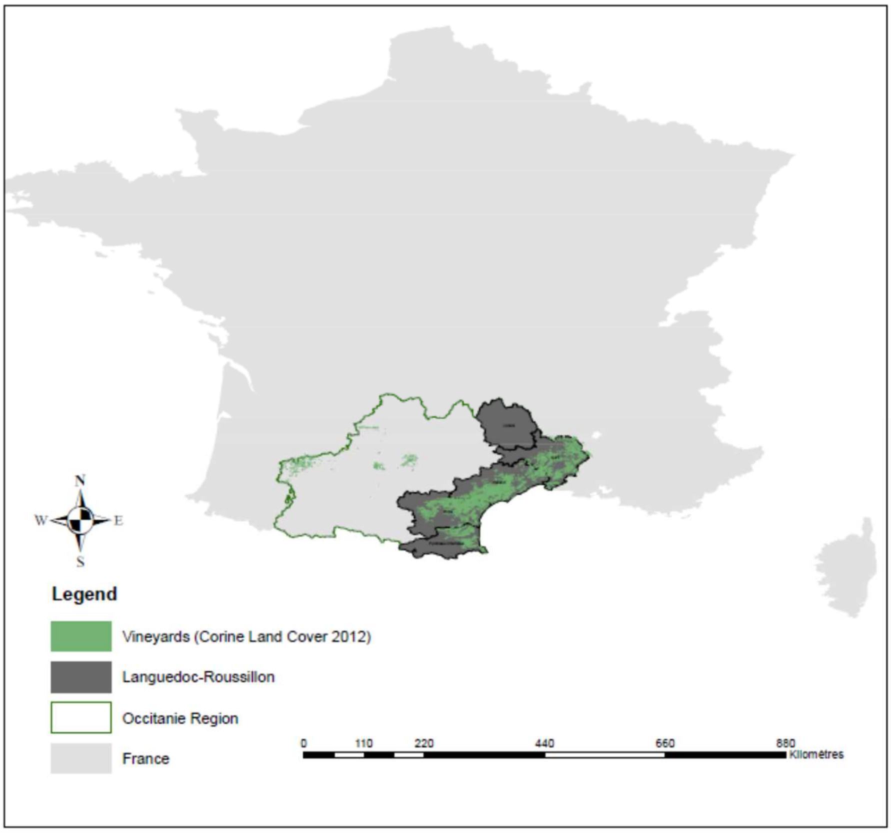

Figure 1 Siuation map : Languedoc-Roussillon (ex-administrative region) is located in Occitanie, South of France

3.2. Method

3.2.1. Survey data collection

Data were collected via a survey, during the summer of 2014, among growers in the LR region. The design of an Internet questionnaire was based on a first qualitative analysis of semi-directive interviews conducted with 44 wine growers from the Hérault département (French county included in LR) focusing on the adaptation actions implemented. The internet questionnaire was developed using LimeSurvey® and distributed by email through several professional organizations (about 3000 vinegrowers received the survey). The principal advantage of an Internet questionnaire is its cost when compared with a traditional face-to-face survey with selective sampling. Based on the widespread distribution by email of the questionnaire, the sampling method can be described as "non-selective".

This survey mainly addressed (i) the wine growers' perceptions of past regulatory, economic and climatic changes, (ii) the structurally-oriented production practices or choices that they have implemented or that they consider to adopt in the future, (iii) the socio-economic factors likely to explain these adaptation choices, including the goals pursued, which incorporate their individual attitudes and values.

Two scenarios were suggested: a baseline scenario that represents continuity and consists in an extension of the changes or developments perceived in the past by the respondents, and a climate-change scenario characterized for Languedoc-Roussillon in the year 2050 (IPCC SRES Scenario A1B[3] (IPCC, 2007) by (a) an increase in average temperatures (of up to 2.8°C) and in the number of days when the temperature is at least 35°C (up to 19 days in summer); (b) a drop in average precipitation of some 180 mm per year and an increase in the duration of periods of drought, which would extend to almost five months of the year; and (c) an increase in the intensity of severe rainstorms, especially in the fall.

Details are given in Appendix A.

3.2.2. Adjusting the sample

The choice of an Internet questionnaire involves self-selection: people who respond are likely not to have been selected at random from all of the population studied, because it is the surveyed themselves who decide whether or not to participate. In order to control and limit this bias, an adjustment by weighting was carried out. We assigned a weight to each observation in the sample, determined according to its probability of being in the target population (Cameron and Trivedi, 2010). This probability was assessed on the basis of pre-identified criteria, so as to correct for the bias introduced by the respondents' self-selection. In our sample, this bias can mainly be explained by a higher probability of response from farmers that are currently irrigating and are therefore directly involved in the issue of

[3] In 2014 (date of the survey) this was the reference set of climatic scenarios, now this could be compared to the RCP 8,5 scenario (worse case scenarios in each set)

irrigation, and growers who make their wine in private cellars, both because they are more frequent in the distribution lists of professional organizations and because their room for maneuver in terms of technical adaptations is relatively greater than that of farmers supplying their vine in cooperative cellars. We have therefore made an adjustment by weighting on these two criteria: irrigated areas and wine-making type (own cellar versus cooperative). Details concerning the representativeness of the sample are presented in the Appendix B.

3.2.3. Characterization by "*terroir*" data

In order to control for weather variables and soil, the farmers were asked to geographically localize their largest parcel. This georeferenced data enabled to characterize the *terroir* for each farm. The following data were extracted for each observation:

- The cumulative monthly precipitation from April to September, in mm (monthly mean over 1981 to 2010);
- The sum of monthly temperatures above 10° C between April and September (monthly mean over 1981 to 2010);
- The soil water holding capacity , which represents the capacity of a soil to hold water, in mm.

They were obtained from the INRA Soil Database (for the water storage capacity) and the results of Méteo-France's AURHELY® interpolation model. The two databases (survey and *terroir*) were then matched. A water-stress coefficient was calculated as the ratio between the temperature and the precipitation indicator (scarcity index). This index is simple but it has a significant power to explain irrigation. The model behavior encouraged to keep the other “terroir” data separate (and not to integrate them in an index, suggesting that they are acting differently). More information on this data is given in Appendix C.

3.2.4. Modeling choices

Using the database, we then examine with econometric models the factors that might determine the decision to irrigate or to envisage this practice in the future, either in the context of a baseline scenario (extension of perceptions), or under a climate-change scenario. We develop binary logit regression models which infer the effect of the variation of a unit of the independent variable on the probability that the event will occur (irrigate/consider irrigation). Their cumulative standard normal distribution allows to keep the distribution of independent variable values between 0 and 1. This is particularly suitable for studying irrigation, which constitutes a binomial variable whose probability of adoption by respondents is either 0 (non-irrigators) or 1 (irrigators). Our econometric approach distinguishes control variables, which in this case are limited to the parameters of the *terroirs* (precipitation, temperature, available capacity) and interest variables related to the characteristics of the farm and the farmer. The results of collinearity tests performed on these variables (correlation on all variables followed by collinearity tests on the models[4]) fall within acceptable limits. The transformations of variables were also explored, as related to theory and intuition.

4. Results

4.1. The sample's descriptive statistics

The sample comprises 352 farmers accounting for 4% of the region's utilized agricultural area for wine-producing vines and 2% of the wine-farms. Table 1 shows the descriptive statistics of main variables before and after adjustment of the sample. Table 2 presents the correlations (before adjustment). Overall, the sample appears representative of the general population of wine-growers in the region (see details in Appendix B).

[4] With STATA's Collin package, checking that the VIF (variance inflation factor), an indicator of how much of the inflation of the standard error could be caused by collinearity, remains close to 1.

			After weighting	Before weighting			
Variables	**Unit**	**Nb Obs.**	**Mean/ Frequency**	**Mean/ Frequency**	**Standard deviation**	**Min**	**Max**
Irrigation	Share	352	0,10	0,28	0,45	0	1
Envision irrigation (non irrigators)	Share	253	0,54	0,53	0,49	0	1
Envision irrigation with CC scenario	Share	253	0,56	0,56	0,50	0	1
Terroir							
Temperature	°C	301	1763	1 766	91	1355	2068
Precipitation	mm	297	225	224	47	142	380
Scarcity Index (Temp./Precipitation)	°C/mm	297	8,2	8,2	1,8	4.3	13.6
Soil water holding capacity	mm	297	91,3	93	42	7	255
Farmer characteristics							
Age	Year	351	50	50	10	24	76
Succession planned	Share	345	0,19	0,23	0,42	0	1
Higher education	Share	352	0,32	0,37	0,48	0	1
Professional groups	nb of memberships	352	1,57	1,67	0,96	0	5
Non risk-averse	Share	350	0,43	0,48	0,50	0	1
Farm & Wine characteristics							
Vineyard area*	ha	343	24	28	50	0,15	730
Diversification	Share	352	0,36	0,40	0,49	0	1
Winery	Share	352	0,16	0,38	0,48	0	1
AOC area > 50%	Share	225	0.55	0,54	0,50	0	1
Mean yield*	hL/ha	311	56,4	55	21	5	140
Mean wine price	€/hL	264	123	147	177	40	1330
Mechanical harvesting (% of total area)	%	349	70.5	69.6	36,2	0	95
No network water/Proxy for cost	Share	269	0.33	0.31	0,46	0	1
Organic farming*	Share	352	0,20	0,27	0,44	0	1
Main Objective of grower							
Produce quality wine	Share	352	0.76	0.79	0,26	0	1
Increase revenues	Share	352	0.77	0.77	0,29	0	1
Protect the environment	Share	352	0.67	0.68	0,28	0	1
Innovate	Share	352	0.47	0.48	0,30	0	1
Perceptions							
Share of parcels under water stress in summer	%	332	47	45	28	0	88
Perception of past changes							
Climatic	Share	352	0,74	0,73	0,44	0	1
Regulatory	Share	352	0,75	0,77	0,42	0	1

Economic*	Share	352	0,70	0,70	0,46	0	1
Technology*	Share	352	0,60	0,63	0,48	0	1

Table 1 Descriptive statistics of variables (*variable not included in the models; "AOC": "Appellation d'origine contrôlée" ~ Protected Designation of Origin (PDO)

Table 2 Correlations (the variables are the same as the one in table 1, but abbreviations are presented for layout issues) (*: p<0.05 ; in bold : correlation > 0,30)

Variables	Irrig	Fut irr.	F.irCC	T°	Rain	T°/R	Soil	Age	Succ.	Educ	Group	Risk	Area	Div	Winery	AOC	Yield	Price	Meca	W Cost	Organ.	O.Qual	O.Rev	O.Envi	O.Inno	Hyd.St	ClimC	RegulC	EcoC	TechC
Irrig	1.00																													
Fut. irr.	.	1.00																												
Fut.IrrCC	.	**0.68***	1.00																											
T°	0.16*	0.17*	0.12	1.00																										
Rain	-0.09	-0.12	-0.05	**-0.41***	1.00																									
T°/Rain	0.09	0.11	0.03	**0.62***	**-.94***	1.00																								
Soil	0.17*	0.01	-0.03	0.18*	-0.12*	0.18*	1.00																							
Age	0.05	-0.24*	-0.16*	0.09	0.05	-0.01	0.01	1.00																						
Succ.	0.02	0.12	0.12	0.04	0.04	-0.01	0.09	0.15*	1.00																					
Educ	-0.04	0.06	0.06	-0.08	0.02	-0.03	-0.02	-0.28*	0.09	1.00																				
Group	-0.00	0.05	0.14*	0.06	0.07	-0.04	-0.01	0.01	0.14*	0.11*	1.00																			
Risk	-0.01	-0.07	-0.08	-0.07	0.07	-0.08	-0.10	-0.07	-0.01	0.14*	0.14*	1.00																		
Area	0.03	0.12	0.04	0.20*	-0.04	0.08	0.02	-0.11*	0.08	0.19*	0.05	0.08	1.00																	
Div	0.17*	-0.06	-0.01	-0.06	0.12*	-0.12*	0.07	0.05	-0.04	0.10	0.11*	0.04	-0.04	1.00																
Winery	-0.01	-0.03	0.00	0.02	-0.02	0.01	-0.06	-0.05	0.16*	0.29*	**0.30***	0.21*	0.17*	0.03	1.00															
AOC	-0.23*	-0.21*	-0.21*	0.06	-0.04	0.05	-0.25*	0.04	-0.09	-0.08	-0.07	0.06	-0.10	-0.16*	0.07	1.00														
Yield	**0.32***	0.23*	0.11	0.05	0.05	-0.04	0.26*	-0.04	0.06	-0.02	-0.25*	-0.29*	0.11	0.12*	**-0.36***	**-0.45***	1.00													
Price	-0.17*	-0.21*	-0.10	-0.15*	0.01	-0.07	-0.18*	-0.01	-0.05	0.05	0.22*	0.26*	-0.08	-0.07	**0.36***	0.22*	**-0.49***	1.00												
MecHarv	**0.30***	**0.31***	0.23*	0.10	0.07	-0.05	0.25*	-0.06	0.10	0.03	-0.09	-0.24*	0.10	0.07	-0.29*	**-0.45***	**0.66***	**-0.50***	1.00											
WatCost	-0.15*	-0.21*	-0.05	-0.18*	0.17*	-0.18*	-0.03	-0.01	-0.04	-0.14*	0.03	-0.10	-0.09	0.04	0.04	0.18*	-0.20*	0.10	-0.24*	1.00										
Organic	-0.03	-0.16*	-0.06	-0.07	0.13*	-0.13*	-0.05	-0.03	0.03	0.11*	**0.33***	0.24*	-0.05	0.15*	**0.35***	0.05	-0.29*	0.26*	-0.22*	0.05	1.00									
O.Quality	-0.04	-0.03	0.02	-0.15*	0.14*	-0.17*	-0.21*	-0.06	0.12*	0.10	0.17*	0.11*	0.01	-0.03	0.24*	0.08	-0.22*	0.15*	-0.15*	0.07	0.07	1.00								
O.Revenu	0.13*	0.18*	0.14*	-0.01	0.03	-0.02	0.05	-0.20*	-0.06	0.05	0.01	-0.11*	0.05	-0.03	-0.12*	-0.14*	0.19*	-0.16*	0.22*	-0.12*	-0.10	-0.03	1.00							
O.Enviro	-0.03	-0.11	-0.07	-0.10	0.04	-0.05	-0.05	0.04	-0.01	-0.04	0.09	0.26*	0.04	0.08	0.09	0.01	-0.14*	0.10	-0.16*	0.06	**0.33***	0.14*	-0.10	1.00						
O.Innovat	0.03	0.17*	0.12	0.07	0.00	-0.00	-0.06	-0.10	0.03	0.07	0.01	0.17*	0.16*	0.08	-0.00	-0.11	0.09	-0.04	0.09	0.01	-0.02	0.14*	0.05	0.14*	1.00					
HydStress	-0.07	**0.44***	**0.44***	0.17*	-0.22*	0.22*	0.09	-0.06	-0.02	0.03	-0.02	-0.04	0.03	-0.15*	-0.05	-0.15*	0.07	-0.15*	0.26*	-0.16*	-0.09	-0.10	0.04	-0.03	-0.01	1.00				
ClimaC	0.01	0.28*	0.17*	0.10	-0.15*	0.12*	-0.13*	0.03	0.01	-0.04	0.07	-0.01	0.10	-0.03	-0.00	-0.02	-0.01	-0.07	0.07	0.05	0.06	0.02	0.01	0.12*	-0.03	0.26*	1.00			
RegulC	0.10	0.10	0.06	0.03	-0.03	0.02	-0.02	-0.02	-0.01	0.07	0.10	-0.01	0.05	0.06	-0.01	0.07	0.09	-0.02	0.05	0.05	-0.10	0.01	0.00	-0.03	0.11*	0.02	0.02	1.00		
EcoC	-0.06	0.01	0.07	-0.01	-0.09	0.04	-0.02	-0.07	0.02	0.08	0.09	0.09	0.07	0.09	0.08	0.04	-0.15*	0.03	-0.10	0.03	0.03	0.05	0.06	-0.01	0.14*	0.07	0.08	0.13*	1.00	
TechnoC	0.13*	0.07	0.05	0.15*	-0.09	0.11	-0.04	0.07	-0.00	-0.00	0.05	-0.01	0.08	0.03	0.00	-0.07	0.07	-0.09	0.15*	-0.00	-0.00	-0.01	0.01	0.05	0.10	0.09	0.15*	0.17*	0.08	1.00

4.1.1. Overview of adaptations

Three types of adaptations were considered: (i) farming practices; (ii) farm organization; and (iii) production choices. Table 3 shows each of the farming practices considered and indicates whether they have already been adopted and/or whether they are envisaged for the future.

Adaptations	Type	Adopted	Envisioned
Farming practices		%	%
Cropping ("rognage")	*Foliage*	62,2	10,7
More tillage	*Soil*	55,8	24,9
Green cover (Controlled natural sodding "Enherbement Naturel Maîtrisé")	*Soil*	30,6	16,4
Irrigate (young plants only)	*Irrigation*	26,8	68,6
Irrigate	***Irrigation***	**24,0**	**40,7**
Change the pruning system	*Foliage*	19,8	22,2
Convert to organic production	*Strategy*	19,7	19,5
Planting more closely	*Plantation*	16,1	11,5
Thinning vine ("Eclaircissage")	*Foliage*	15,7	9,5
Increase irrigated area	*Irrigation*	12,6	42,0
Leafing ("Effeuillage")	*Foliage*	10,5	8,0
Reduce the area with green cover	*Soil*	8,7	7,7
Planting grass	*Soil*	8,1	12,6
Increase chemical weeding	*Soil*	4,6	5,8
Increase green cover	*Soil*	3,6	9,8
Planting less dense	*Plantation*	3,3	6,1
Plastic mulch (" Paillage plastique")	*Soil*	1,3	2,6
Plant mulching ("Paillage végétal")	*Soil*	1,2	15,1
Farm organisation			
Shift to cooperative cellar	*Vinification*	79,6	3,5
Reorganize fields ("Remembrer")	*Strategy*	17,4	22,2
Shift to private cellar	*Vinification*	15,9	10,3
Increase my vine area	*Strategy*	12,4	28,5
Diversify the crops	*Strategy*	12,0	21,9
Get some fields out of the "appellation"	*Appellation*	6,0	9,1
Reduce the area with vine	*Strategy*	5,0	20,6
Relocate my farm	*Strategy*	0,8	7,0
Production choices			
Diversify the vintages	*Plantation*	60,0	19,4
Concentrate on wine growing (reduce other crops)	*Strategy*	52,3	15,8
Changing the rootstocks and clones	*Plantation*	32,3	28,6
Relocate the vintages on fields	*Plantation*	27,8	24,6
Diversify wine varieties	*Vinification*	25,1	11,5
Mass selection	*Plantation*	3,9	12,9

Table 3 Frequency of adaptations and future projects (in % of total sample)

All three categories of adaptations are frequently adopted by farmers. Among the most-implemented adaptations stand cropping, increase in tillage and green covering which belong to farming practices, past shifting to cooperative cellars which is a change in farms' organization, diversification of wine varieties, and choosing to concentrate on vine cultivation which belongs to production choices. Future adaptations envisaged by the farmers are mainly related to farming practices i.e. installation of irrigation, increase in irrigated area, and changes in the type of pruning and tillage. Among all the actions considered, irrigation is ultimately the most frequently envisaged for the future.

There is no positive correlation between rain-fed vine and other kinds of adaptation studied, which would have allowed us to suggest that in order to manage the hydric stress, those who have no irrigation option resort to certain practices that enable water to be retained in the ground or that reduce the plants' needs for water. Accordingly, no strategy to supplement or substitute for irrigation can be identified in this analysis (see Appendix D for the correlations between practices).

4.1.2. Irrigating the vines

Irrigation is currently practiced by 28% of farmers. Among irrigators, 91% use a drip system and 80% are supplied from surface water network systems. Details of the source of water available by type of wine grower are given in the Appendix E. 42% of farmers located near a water resource are planning to irrigate. Access to a water distribution system seems to promote the use of irrigation, which is not the case for proximity to a water resource. Among current irrigators, 15% do not wish to increase their irrigated areas in the future, 33% envisage doing so under the baseline scenario (for an average additional area of 15 ha for an average existing irrigated area of 14 ha in the sample), and 59% envisage increasing their water requirements under the climate-change scenario. Demand for irrigation water would thus tend to grow with climate change.

The main reasons for irrigators to employ irrigation are to secure yields for non-Mediterranean varieties (78% of irrigators), to improve the quality of wine (56% of which 11 for white wines) or to increase yields for Mediterranean varieties (39%). 5% do so to reduce their working hours and 5% to comply with requirements or a contract, which highlights other reasons than hydric stress. These same reasons appear for farmers who envisage irrigating in the future. It is interesting to note that among those who have plans to irrigate, 25% mention the desire to improve the quality of whites versus only 11% of those already irrigating.

Conversely, 34% of farmers do not irrigate and have no plans to irrigate under the baseline scenario, versus 32% under the climate-change scenario. The main reasons are a lack of water resources near the farm (43%), a principled opposition to irrigation (28%), and the absence of a need to irrigate (19%). The low profitability of irrigation is an obstacle for only 13% of non-irrigators. It should also be noted that farmers who are against irrigation on principle are not necessarily located on parcels that lack access to water.

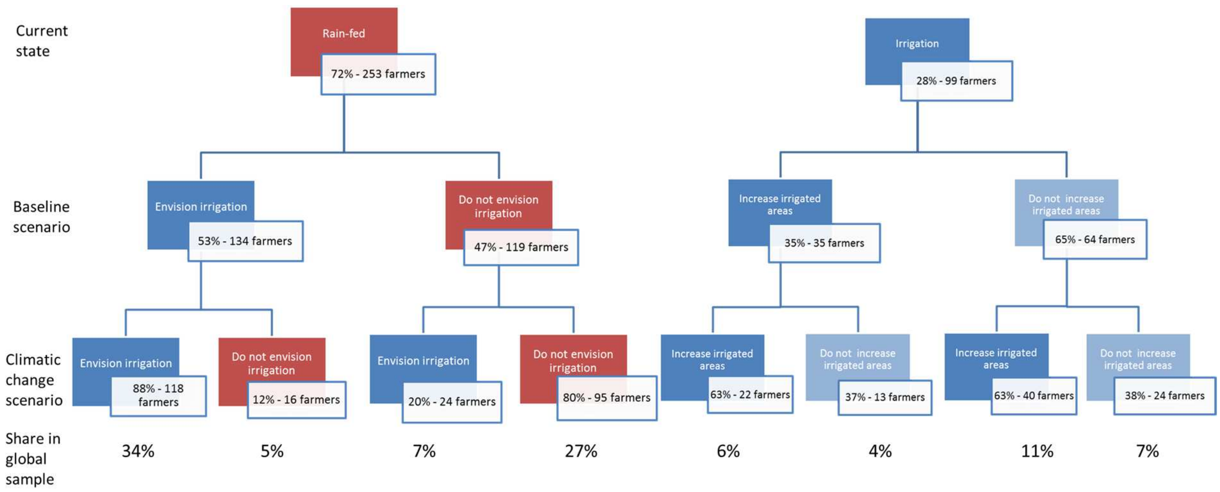

Figure 2 Distribution of wine growers of the sample according to their irrigation practice or plans under the different scenarios

Along with tillage, irrigation is the action that growers turn to the most to limit the risk of hydric stress.

Among the rain-fed farmers, 53% envisage irrigating in future, and this proportion rises to 59% under the climate-change scenario (resp. 39 and 41% of the total sample) (See Figure 1). Almost all of those who envisage introducing irrigation in the future do so under both scenarios. Thus the new information provided by the climate-change scenario does not drastically alter farmers' decisions to irrigate. This tends to show that climate stress is already taken into account into their decision processes. 20% of the rain-fed farmers do not envisage irrigating, but state that they would turn to irrigation under the climate-change scenario.

The water requirements associated with irrigation should therefore rise in the future, owing to the cumulative effect of increasing numbers of irrigators (about two thirds of current non-irrigators envisage irrigating in future) and the desire of many current irrigators to increase their irrigated areas or their per-hectare consumption.

4.1.3. Analysis of perceptions of past and future changes

More than 90% of wine growers find that global changes have affected their farm since they began to work in the vineyards. The changes experienced are regulatory (77% of respondents), climatic (73%), economic (69%) and technical (62%). Two thirds of the growers are simultaneously affected by at least three types of changes, which testifies to the diversity of the driving factors to which wine-growing in LR is subjected. Among the climate changes experienced, the increased frequency and duration of periods of drought and the decline in average annual precipitation are the most frequent. Respondents also spontaneously mention the increase in extreme weather events (floods, frosts, violent winds, etc.) and the earlier date for beginning the grape harvest. Climatic changes also appear to be more chaotic (55%) than linear over time (18%). Among the economic changes the most meaningful concern the increase in production costs (78%) and growth in the demand for better-quality wines (55%) and that better respect the environment (44%).

The perceptions of wine growers who irrigate are also characteristic: they are more sensitive to regulatory and technologic changes and less so to climatic and economic changes than the non-irrigators. Their lesser perception of past climatic changes may be explained by the fact that irrigation mitigates the effects of climatic changes such as increased drought. Conversely, wine growers who envisage irrigating under the baseline scenario feel climatic changes more strongly, which probably justifies their wish to irrigate.

4.1. Factors determining irrigation or intention to irrigate

We examined the factors that could influence the choice of irrigation with econometrics. Table 4 shows the results of three logistical regressions and gives the marginal effects or odds ratio for each variable. Three models are presented:

- Model A regresses the probability of current irrigation for a farmer,
- Model B regresses the probability of irrigation under the baseline scenario,
- Model C regresses the probability of irrigation under the climate-change scenario.

Note that the models are built on samples that are smaller than the samples presented before, because the variables were not fully provided for all observations. In addition, the condition for retaining the observation in the samples is that the farm has access to at least one source of water, and for the last two (envisioning irrigation) that the growers are not currently irrigating.

		Unit	Metric	Effect	Irrigation	Effect	Envision irrigation	Effect	Envisage irrigation with CC sc.
Terroir	Scarcity index (Temperature/Precipitation)	C°/mm	AME	+	0,04*** (0,01)	-	-0,01 (0,03)		
	Soil water holding capacity	Mm	AME	-	-0,00 (0,00)				
Perception of water stress	Share of parcels under water stress in summer	%	AME			+	0,01*** (0,02)	+	0,01*** (0,03)
Management	Age	Year	AME	-		-	-0,01* (0,00)	-	-0,01 (0,00)
	Succession planned	0/1	OR	-	0,20* (0,15)				
	Higher education	0/1	OR	-	0,13** (0,10)				
	Professional groups	[0;5]	AME			+	0.04 (0,04)		
	Non risk-averse	0/1	OR			-	0,04* (0,05)	-	0,22* (0,14)
Farm & Wine characteristics	Diversification	0/1	OR	+	10,20** (7,63)				
	Winery	0/1	OR	+	3,06+ (1,97)				
	AOC area > 50%	0/1	OR	-	0,13** (0,09)				
	Average wine price	€/HL	AME			-	-0,00 (0,00)		
	Mechanical harvesting	[0-4]	AME	+	0,04+ (0,02)				
	No network water/Proxy for cost	0/1	OR	-	0,23+ (0,21)	-	0,04*** (0,04)		
Goals	Increase revenues	0/0,5/1	OR	+	18,24* (21,03)				
	Produce quality wine	0/0,5/1	OR			+	9.84 (17,77)		
	Preserve environment	0/0,5/1	OR			-	0.29 (0,48)		
	Innovate	0/0,5/1	OR			+	34,01** (40,72)	+	5.73 (6,96)
Perception	of past climatic change	0/1	OR			+	1.47 (1,61)	-	0.31 (0,23)
	of past regulatory change	0/1	OR	+	11,50** (10,23)	+	5.52 (6,95)		
	Number of obs.				116		95		95
	Pseudo R2				0,32		0,60		0.27
	chi2				28,31		28,25		10,39
	Correctly specified*				78,45%		92,63%		84,21%

Standard errors in parentheses; signs of effects are given* goodness of fit measure for non-weighted sample (“estate classification” in STATA)

+ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 4 Logit regression models: irrigation and irrigation plans for farmers with access to at least one source of water. Average marginal effects (AME) or odds ratio (OR) of independent variables according to the nature of the variable : qualitative (AME) or quantitative (OR) (weighted sample)

4.1.1. *Terroir* and perception of water stress

The effect of the *terroir*-related variables on irrigation matches expectations. The higher the scarcity index (temperature/precipitation), the more likely famers are to irrigate. Irrigation appears as a mean to regulate excessively dry climate conditions which tends to confirm the influence of the climate-water relationship for optimum grape growing. As for the likelihood of irrigating in the future, although it seems not to be influenced by current water-scarcity[5], it is positively and significantly impacted by the perception of water stress (captured through the share of parcels perceived as being under water stress during summer). Soil water holding capacity does not emerge as a significant driver of current irrigation.

Perception of water stress results from both objective factors such as the hydric conditions (grape variety, type of soils, local micro-climate) and the intrinsic perception. The variable "proportion of parcels at risk for water stress" is not included in the irrigation model because this variable is endogenous (irrigation should reduce the perception of hydric stress) and we have no appropriate tool for suppressing the endogenous effect of irrigation on this stress. Since it is not significantly correlated with temperature, precipitation or available soil water holding capacity, perceived water stress provides supplementary information to *terroir*-related characteristics. The higher the share of parcels perceived as being under water stress during summer, the more likely farmers are to intend to irrigate in the future for both the baseline and the climate change scenarios. The model suggests that an increase of 10 points in the percentage of parcels under hydric stress causes a 6% increase in the probability of envisioning irrigation in the baseline scenario and a 8% increase in the climate-change scenario.

[5] Even in a model without the variable "perception of water stress".

4.1.2. Individual characteristics

The younger the growers are, the more likely they are to envisage irrigation. This is in line with intuition since investing in irrigation is a strategic long-term project that requires an ability to look into the future, whereas oldest growers are generally less inclined to invest for the future of their farm. However, this effect is no longer significant in the climate-change scenario. Having provided for one's succession inversely affects the probability of irrigating today. The safety provided by the assurance of having a successor could reduce the need for securing the continuity of the farm by the adoption of technologies such as irrigation.

The higher the level of education, the less likely farmers are to irrigate. This result may contribute to the argument that education enables the development of other practices for the conservation of soil water (tillage, green cover, spacing, etc.) with the capacity to collect information in a large variety of sources and learn new practices that avoid the necessity of irrigating. This effect is not related to price or average yields and is therefore independent of the economic model of the grower.

Membership in professional groups is not a driver of irrigation. On the other hand, it has a fairly large effect on the probability of envisaging irrigation. The model suggests that belonging to professional groups would increase by a factor of about 2 the probability of envisaging irrigation in the baseline scenario. The farming professional organisms seems to encourage the implementation of irrigation, notably through the argumentation around the construction of the AquaDomitia project.

Because irrigation is frequently used as a risk reduction strategy to limit climate-related risks caused by the inadequacy between precipitations and water requirements for crops, wine-growers' risk aversion would be expected to influence irrigation. However, the sizable investment of irrigation may also be seen as a risk, because the return on investment is uncertain. Our results validate the first hypothesis according to which, risk aversion of farmers increases their likelihood of irrigating in the future.

4.1.3. Economic characteristics of the farm and of wine production

Although one could assume that the area under cultivation would affect the probability of irrigation, the sample does not validate any related assumption.

Farm mean yields and prices and income per hectare are also likely to have an effect on irrigation adoption. The data confirm that yields and average prices are significantly inversely correlated (-0.49) and irrigating the vines is positively correlated with average yield, to a significant degree (0.32)[6]. The correlation data supports the idea that a farm whose economic model[7] depends on high yields is more likely to want to irrigate in the future to safeguard its high yield objective (which is at risk of losing yield) compared to a farm with a lower yield objective that will be less sensitive to water stress. Yields are endogenous[8] because irrigation is likely to have an effect on yields, so the same conclusion cannot be advanced even if possible. The model does not confirm the effect of higher prices on the probability of irrigating less. A negative effect on prices, though not a significant one, is observed on the probability of envisioning irrigation in the future[9], which agrees with the line of argument touched on above. The analysis of the results shows an absence of average-income effect on the probability of irrigating or envisioning irrigation.

Results suggest that the probability of irrigating is ten times greater for a farm whose crops are diversified (crops other than vines, often fruit trees that need water) than for a farm specialized in viticulture. Farmers having a private cellar are three times more likely to irrigate than those who deliver their grapes to a cooperative cellar. This effect is not found for future irrigation. Having more than 50% of the areas in PDO would also be significantly determining for non-irrigation, which was expected because certain PDOs do not allow

[6]And the fact of irrigating is weakly negatively correlated (-0.17) with the average prices of wine.
[7]There seems to be a consensus on the fact that the costs per hectare vary much less between farms than the income component. The economic model could thus be defined by high prices or high yields, each of the two strategies allowing production costs--more or less similar between operations--to be covered.
[8]To suppress this endogenous effect, it would have been necessary to have data for a wet year without irrigation.
[9] There is no more endogeneity here as the project to irrigate has no effect on current yields

irrigation[10] and those farms aim at quality more than quantity. Farms that harvest mechanically would be almost twice as likely to irrigate.

Having access to network water have a strong significant positive effect on the probability of envisioning irrigation and only weakly significant for actual irrigation. However, water access and user cost cannot be dealt with in detail since the data are not available and highly variable from one area to another (groundwater resources can be located in shallow aquifers a few meters deep, implying low water costs, while others may be deeper, with higher water costs; the prices for surface water are also very variable).

4.1.4. Farmers' goals

Goals or objectives that are considered by farmers as their most important priorities include, in decreasing order of importance: producing quality wine, maintaining or increasing income, preserving the environment, innovating on the farm and preserving traditional practices.

Only the goal of increasing income is a highly significantly determinant of irrigation, with a substantial effect: considering this to be a key objective would increase the probability of irrigation by a factor of about 18. Only the "innovation" objective seems to have a significant effect on the probability of envisioning irrigation in the future. The effect of pursuing the goal of quality wine is suggested as positive (but not statistically significant) and that of wanting to preserve the environment as negative. These two effects are consistent with intuition.

4.1.5. The role of perceptions of change

Perceptions of past changes are expected to be a driver of both present and future adaptation thus irrigation. The data confirm that the perception of recent regulatory changes has a significant influence on the probability of irrigation (11 times greater chance

[10] The number of PDO in the area prevented us from collecting the data on specific irrigation regulation for each

of irrigating). Regulation has changed since 2006 to make the irrigation of vineyards systematically possible. There is no effect of the perception of climate change on past irrigation. Its effect on future irrigation is intriguing at first glance: it acts positively on future irrigation in the baseline scenario but negatively in the climate-change scenario. These effects validate the hypothesis that wine growers who have not noticed climate change in the past do not plan to irrigate in a baseline scenario but react to a future climate-change scenario by envisioning irrigation; while those who have already perceived it envision irrigation immediately, without any given climate-change scenario.

5. Discussion

Our results are closely dependent upon the peculiarities of the studied area and our sample is, like all web based surveys potentially biased by self-selection. Hence, empirical results must be carefully considered and other studies should examine these findings in order to validate them. However, this case study provides interesting insights on the adaptation processes in farming and winegrowing in particular.

Interestingly, results show that the drivers of current irrigation differ from those of future irrigation. This suggests that we are facing a change in the profiles of irrigators, with future irrigators being motivated by other drivers than actual irrigators. Our results suggest that current irrigation is characterized by higher water-scarcity index parcels, less-educated farmers, growing other crops, wine-making in the own cellar, less than 50% of Origin Controlled Certification area or the willingness to increase revenues, while future irrigation adoption is characterized by risk-averse farmers, farmers who pursue the objective of innovation on their farms and perceive a high water stress of their fields. Envisaging irrigation characterizes younger growers, which is in line with Koundouri et al. (2006) findings. We also find that the perception of water stress seems to drive future irrigation projects much more than real water scarcity. This should question the effect of thinking of adopting irrigation on the declared perception of water scarcity, in other words the possible endogeneity of perceptions in the model of future irrigation probability. Also the results suggest that these perceptions have a significantly higher effect on future irrigation projects than water scarcity has on current irrigation[11].

Our results counterbalance the statement of Ashenfelter and Storchmann (2016) who argue that adaptability of viticulture to climate change is more limited in Europe than in the New World because its populations are more closely tied to their geographical origins and thus might be more reluctant to adopt new practices or technologies, like irrigation. Our work illustrates this is not the case for irrigation at least in Languedoc-Roussillon with more than half of the wine growers without irrigation that envisage this practice in the future.

We also found that farmers that irrigate are less likely to perceive past climatic changes than those who plan to irrigate. This is coherent with intuition. It is also in line with findings from Niles and Mueller (2016) who found that irrigating farmers do not perceive recent drying and warming conditions acknowledged by meteorological data[12]. We also argue that this reduced or absence of perception might induce a lesser preparedness for other climate change potential risks such as flooding, hail or frost or salinization of aquifers...

6. Conclusion

Understanding the drivers of individuals' adaptations is key to better anticipate society's adaptation capacity. It contributes to enhancing the reliability of economic and environmental impact assessments of adaptation policies and therefore allow their adjustment in light of local peculiarities. Irrigation is one of the straightforward and technically efficient adaptations: it can obviously help to secure grape yields in dry years and ensure wine quality in areas where the optimal weather for wine growing has already been surpassed. However, by extracting water from natural resources, irrigation can also increase the vulnerability of water resources and destabilize pre-existing balances among water users (drinking water, industry, and other farmers). Irrigation can also increase individual vulnerability to water use restrictions. Being capital intensive, it may also increase farmers'

11 if we construct models with only these as independent variables

12 They argue this non perception of climatic change would make it harder to enroll irrigating farmers in greenhouse gas mitigation actions.

economic vulnerability and as such be considered a *maladaptation*. This paper contributes towards a better knowledge and comprehension of climate-change adaptation of wine growers and the status of irrigation.

The originality of our dataset is that we supplement the survey data with physical data that characterize the *terroir*, which is a combination of climate, soil and terrain characteristics (in this case precipitation, temperature, and soil water holding capacity), to explore the respective contributions of individual and physical data in the choice of irrigation as an adaptation to climate change. 28% percent of growers in the sample are already irrigating their vines, while up to 39% are considering this option in the baseline scenario. When faced with a given scenario involving climate change by 2050, 41% say they would implement irrigation.

As far as we know, this work is the first to investigate the drivers of irrigation adoption processes in the case of a crop that has long been farmed without irrigation water in France and northern Europe. Results show that water irrigation demand is likely to rise in the future, due to both increasing numbers of irrigators and increasing water demand (larger irrigated areas and higher per-hectare consumption). Results show that the profile of irrigators and the pattern of irrigation are changing and will further change in the future as a consequence of a set of regulatory, economic and environmental changes. This is noteworthy and suggests that a simple projection of existing trends might lead to significant errors. In other words, these results carry important implications for forecasting and water-supply planning and policy.

Apart from being different, we show that irrigation patterns seem to be motivated by drivers that rely not only on physical “terroir” characteristics but also on farm-specific and growers’ characteristics. These socio-economic drivers include farmers’ perceptions of water stress, age, risk aversion or objectives. Interestingly, perceptions of water scarcity seem to drive future irrigation projects much more than real water scarcity. These perceptions have a significantly higher effect on future irrigation projects than water scarcity has on current irrigation practice. We also find that a non-trivial portion of farmers (about a quarter) are not interested in irrigation even if they have or will have access to network water, e.g., water access that is subsidized. Also no practice, nor bundle of practices, are found to substitute irrigation in our sample. Although alternatives to irrigation such as tillage and canopy management strategies should still be investigated, since they are of major interest for conserving water resources.

The policy implications of these findings are important: they suggest that irrigation projects might have differing benefits and rationales depending on the characteristics of the farm considered, and that a water-access policy based only on physical considerations would be inefficient because it would set aside significant socio-economic drivers of irrigation. Results also suggest that increasing the farmer's understanding of the water stress (inducing a reduced gap between perception and real water stress) might improve the relevance of individual irrigation adoption patterns and thus a relevant use of the water resource.

These results could help other regions that will face similar questions of irrigation development and will provide food for local debate and opportunity assessments regarding irrigation development and investment in the area.

Shortcomings of this work are linked to the fact that our data stem from a web survey and contain a self-selection bias (more people already interested in irrigation probably responded to the survey because its title mentions climate change's impacts on wine production and they wish to lobby for the expansion of irrigation zones) although this was partially corrected by sampling weighting. Another issue is the fact that we relied on declarations rather than observations, which is unavoidable in the case of future adaptations, but we cannot be sure of the farmers' specific objectives for the envisioned irrigation, and whether they would be ready to invest in the technology. Lastly, availability of the true costs of water (access and use) per farm would be a significant improvement for the economic analysis suggested in this paper: we were able to use only a proxy cost instead of the real water costs.

One perspective of this work would be the implementation of similar surveys in other winegrowing regions or on other crops, to determine whether similar or different patterns emerge, and to further explore whether farmers implement substitutes for irrigation and what they are, e.g., bundles of practices that contribute to conserving water in the soil or planting of drought-resistant crops. Our survey also includes several questions designed to recover data on the potential impact of drought or economic shocks (e.g. vine price decrease) on farms. Analyzing these data would allow testing whether current irrigation would increase the resilience of farms to drought or economic shocks.

7. Acknowledgments

This work has been financed by BRGM (project SIMADAPT) and conducted while the authors worked for BRGM. The authors wish to especially thank Laurent Gourdon of the Chambre d’Agriculture de l’Hérault as well as Emmanuel Rouchaud, Jacques Oustric and Alain Halma of the Chambre d’Agriculture de l’Aude, du Gard et des Pyréenées-Orientales. We also thank the Centres d'Initiatives pour Valoriser l'Agriculture and the Milieu rural de l’Aude, du Gard, de l’Hérault et des Pyrénées Orientales, the Vignerons indépendants de l’Aude et des Pyrénées Orientales, and the Coopératives de France de l’Aude, de l’Hérault et des Pyrénées Orientales. Camille Tedesco and Jean-François Desprats also helped with face-to-face interviews and providing temperature and precipitation data respectively. We thank Tatiana Paricaud and Etienne Besançenot for testing the questionnaire and helping in its diffusion. We thank Jean-Marc Touzard for discussions on this work. We acknowledge support from Guy Bray for translation and revision of the English language.

8. Appendices

A - Details of the internet questionnaire

To limit 'precedence bias' (Delahaye, 2004), which implies a tendency to select the first item in multiple-choice responses without further thought (for example, the farmer's principal goals which is not straightforward unlike a “male or female” question) we randomized the order of appearance of responses in the questionnaires.

Over the eight weeks during which the questionnaire was put online, 874 individuals clicked on the link to the questionnaire. Among these, 381 farmers responded in full. The average time for responding to the questionnaire was 35 minutes. After validation of the observations, only 352 surveys were retained for analysis, because of missing data. However, not all of the variables are available for all of the 352 valid responses, because not all of the questions are obligatory.

The validation process corresponds to cleaning the data set from incomplete or doubtful observations. This process has excluded the surveys that (i) are not completed, (ii) are explicitly not in the targeted perimeter (e.g. some winegrowers has responded from outside the targeted region), (iii) show data that has been miscompleted (errors)

B - Representativeness of the sample

The distribution of the sample of available agricultural area for wine-producing vines and of the number of farmers per *departement* (~county) is on the whole representative of the regional distribution, although the Aude *departement* is slightly under-represented in the sample. The distribution of the number of farmers per method of wine-making exactly matches their distribution in the region, namely 84% of farmers making wine in cooperative cellars, 11% making wine in private cellars and 5% in both private and cooperative ones. The sample represents 2% of the farmers making wine in each manner. This is also the case for the portion of the irrigated vine area, which represents 10% of the total for wine grapes.

County	Nb of wine growers	Share in the county	Surface of wine-grapes	Share in the county
Aude	30	1%	1298	2%
Gard	68	3%	1773	3%
Hérault	191	2%	3814	5%
Pyrénées Orientales	62	3%	1014	4%
Total	*352*	*2%*	*8094*	*4%*

Table 5. Composition of the sample

C - Additional information on the *terroir* data

The precipitation and temperature variables were obtained from calculations carried out by Météo-France (Modèle AURHELY® Méteo-France 2002). The data were then transposed from the kilometer grid to the 50-meter grid (IGN scale). The available reserve was obtained from INRA's Soil database. The days of sunshine (winter and summer) were not retained because the precision of the location data did not allow representation of the variability that might exist for this parameter, at the scale of a single farm. The same applies to the slope, which could have been an interesting indicator for explaining farming practices, irrigation in particular. Elevation is very strongly correlated with temperature, which is why it was not considered for characterizing the *terroir*s.

D - Correlation between practices

The correlation matrix provides information about potential systematic relationships between practices. Table 6 shows that a number of practices are mutually correlated, but it appears that few of them are correlated with irrigation.

"Identifying" practices	**Correlated practices**	**Correlated Organization/Management**
Irrigation	Pruning, changing the height	Increasing my vineyard area, **diversification of varieties,** devoting myself to wine-growing
Rain-fed (non-irrigating)	-	**diversification of vine varieties,** **increasing my vineyard area**
Increasing irrigation	Planting more closely	Increasing my vineyard area. Quitting the *appellation*, diversification of wine varieties
Organic	Planting grass, increasing green cover, controlled natural sodding, plant mulching	**Switching to a private cellar,** quitting the *appellation*, reducing the areas under vines, diversifying the crops, diversifying the vintages, **mass selection**
Private cellar	**Organic**, planting grass and increasing green cover, controlled natural sodding, plant mulching, thinning out, leafing, planting more closely	Quitting the *appellation,* **diversification of vintages, Mass selection**
Increase in chemical weed control	Mulch film	Diversification of wine varieties, changing rootstocks and clones
More soil preparation	Reducing green cover, **cropping**, thinning vine, and planting more closely	Reducing the vineyard area, diversifying the wine varieties and vintages, changing the rootstocks and clones, concentrating on vine-growing
Green cover	**Increasing the green cover,** leafing, thinning out, **controlled natural sodding**, Organic	Diversifying the wine varieties of wine and the vintages, changing rootstocks and clones, concentrating on wine growing, **mass selection**
Repositioning the varieties on the parcels	**Planting less densely, changing pruning style,** green cover, controlled natural sodding	**Increasing the area planted to vines, Diversifying the vintages and wine varieties**

Table 6 Table of correlations of practices (for correlation > 0.10: and in bold corr. > 0.2)

A.5 - Percentage of water type availability per wine-grower with or without irrigation, (CC sc.: climate-change scenario)

Category			% wine-grower with this type of water available				
	Number	% of total	Network system water	Surface water	Groundwater	No access to water	*Including future system*
Farmers with irrigation	99	*28%*	80%	11%	20%	-	-
Rain Fed	253	*72%*	92%	13%	19%	26%	-
Baseline scenario							
Envisage irrigation	134[13]	*38%*	72%	12%	21%	0	-
Climate-change scenario							
Envisage irrigation	142[14]	*40%*	68%	10%	21%	8%	*2%*
No irrigation plans (all scenarios)	95	*27%*	11%	*2%*	*18%*	58%	*19%*
Total sample	352	*100%*	49%	7%	11%	19%	*6%*

Table 7 Percentage of water-type availability per wine-grower, with and without irrigation

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[13] including 16 without plans under Climate change sc.

[14] including 24 without plans under baseline

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