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Assessing the benefits of irrigation access: the case of southern France vineyards

Juliette Le Gallo, Nina Graveline

UMR Innovation - Innovation et Développement dans l'Agriculture et l'Alimentation, Univ Montpellier, INRAE, CIRAD, Institut Agro, 34000 Montpellier, France.

Auteur de correspondance : juliette.le-gallo@inrae.fr

Abstract. Agriculture worldwide is threatened by climate change. In particular, declining water resource availability combined with increasing water demand is a key challenge in many rainfed areas, where irrigation appears to be a straightforward adaptation option. In this context, assessing the impacts of irrigation adoption on farm yields and incomes is a necessary step to reflect on the impact of both ex-post and ex-ante policies. We develop an empirical setting to assess the benefits of irrigation access and adoption on estates located in the Languedoc-Roussillon wine producing basin between 2010 and 2020 with new irrigation networks being developed. We merge individual estate national agricultural census data with fiscal data and wine register data. We first rely on a propensity score matching analysis to assess the average treatment effect of different levels of irrigation intensity. We show that, on average, more irrigable land within the farm leads to higher yields per hectare, but we don't find any evidence of an effect on farm income. Then, we develop a generalized propensity score approach to assess the average and marginal treatment effect of different irrigation intensities on farm's operating income.

Keywords: Irrigation – econometrics - impact evaluation – agriculture – water - climate change

Classification JEL: Q15, O13, D24.

1. Introduction

Agriculture worldwide is directly threatened by climate change through increasing temperature, water stress, exposure to extreme climate events, etc. (Gurney-Smith et al., 2022). Indeed, the decrease of resource availability as a result of climate change and environmental concern, combined with increasing water needs, is a key concern in many areas. In the European Union, irrigated areas cover 6% of agricultural land (Eurostat, 2016), but this share is higher in the southern member countries (13% in Spain, 20% in Italy). In southern Europe, irrigation demand is increasing and expected to further increase, appearing as a strategy for adaptation to climate change (Fraga et al. 2012). But developing irrigation can, in some cases, be seen as a maladaptation, increasing water stress, introducing potential use conflicts or inequalities of access as illustrated, for example, by the large-scale irrigation project in Navarra, Spain, described by Albizua et al. (2019). Thus, it is important to assess the interest of adaptation measures, particularly those that are collective and / or subsidized by public funds to contribute to public policy assessment. Furthermore, valuing irrigation water is of importance to assist land market transactions and negotiations (D'Odorico et al, 2020).

The production of vine is no exception to the impacts of climate change: droughts and thermal stress are impacting vine yields and quality (Lereboullet et al. 2014), thus changing vine growing conditions (Hannah et al. 2013, Ollat and Touzard, 2020). The impacts of climate change on wine economics is complex and spatially diversified (Ashenfelter & Storchmann, 2016). Mediterranean territories are particularly concerned, as this area has been identified as a climate change "hot spot". In the Languedoc-Roussillon French Mediterranean vine production basin, where grapes have been long cultivated without irrigation, numerous irrigation networks have been deployed to face an increasing water stress. The main arguments for these projects are to maintain a quantitative and qualitative production in the face of increasing international competition, and, more largely, to encourage diversification of crops and short food circuits in the agricultural sector. But there is a controversy on developing wine irrigation and irrigation in general, in France in particular, relying on arguments of water resource conservation (e.g. Ruf, 2015) and more rarely with the conservation of agricultural practices (e.g Le Monde, 2022).

Analysing the economic impact of irrigation development policies is of great interest for several reasons: (i) to evaluate its efficiency in terms of climate change adaptation (yield and consequent revenue) and eventually compare it to alternative adaptation options, (ii) to observe indirect effects of this policy (crop diversification, increase in yields/intensification, for example), (iii) to contribute to future reflections on the development of irrigation networks, assessing their costs and benefits and distribution to address equity issues in climate change adaptation.

There is a significant literature that assesses the link between access to irrigation and income (Sawada et al., 2014; Sellamuttu et al., 2014; Assefa et al., 2022; Weligamage et al., 2014), and/or productivity (Huang et al., 2006; Duflo and Pande, 2007; Dillon, 2011; Bravo-Ureta et al., 2020) relying on econometrics. Other impacts are also studied, for example Buisson and Balasubramanya (2019) study the impact of irrigation on crop choices in Tadjikistan. Li et al. (2020) look at the impact of access to irrigation on rural income and diversification in China. Del Carpio et al. (2011) look at the impact of irrigation rehabilitation on production, employment and income. Most of the literature on the subject is based on case studies in developing countries and/or in regions distant from the French or even European context. Approaches assessing the empirical evidence on the effectiveness of climate change adaptation measures in the Mediterranean or European setting are still relatively scarce. In Italy, Auci and Pronti (2020) assessed the impact of innovative and sustainable irrigation systems (water conservation and saving technics) on Italian Farm's land productivity. In France, Foudi and Erldenbruch (2012) assess the role of irrigation in farmers' risk management, with a microeconomics approach using a Probit model of irrigation and insurance choice. It appears that most of the studies in economics focusing on water use by agriculture in southern Europe are concerned with the development of models capable of simulating the effect of policies with mathematical programming models (e.g. Calatrava and Garrido, 2015 ; Sapino et al. 2022) rather than ex-post analysing the impact of irrigation with econometrics. The assumptions to construct the water production function are often integrated with agronomic observations (Graveline, 2016) rather than rigorous econometric settings. We need empirical ex-post assessments to be able to properly calibrate those models.

This paper thus aims to highlight the impact of irrigation access on vine producing estates, and to understand the mechanisms explaining those impacts. While many irrigating farms in the area have had access to water in the past 10 years, there is a need to assess the impact of these measures for adaptation to climate change. Has irrigation allowed "only" yield maintenance, i.e. strict adaptation to climate change, or more (intensification), and has this strategy had an impact on farm income? To answer this question, we develop an econometric analysis to compare vineyards that benefited from irrigation access between 2010 and 2020 and vineyards without access to water. We acknowledge the heterogeneity of the type of farms and wine produced that range from high yield low value wine to low yield high value wines and which imply different types and range of benefits across types.

This analysis brings three main methodological challenges. First (i), there is a strong risk of selection bias. Indeed, the development of irrigation in an area is not necessarily exogenous: irrigation could have been developed in priority in areas with high production potential, or where access to water is less expensive. Thus, the strict difference in income between irrigated and non-irrigated farms will not only be due to water access, but to other observed or unobserved factors (for example, if irrigation is developed in areas with a higher production potential, the income will likely be higher in the irrigated group, but this will not only be due to water access). Second (ii), the treatment is not binary, i.e. a farm can choose to install irrigation on between 1% and 100% of its land, with a resulting relative impact on its production. We will deal with the continuity of treatment first relying on propensity score matching with several treatment levels, and then with the generalized propensity score approach (Hirano & Imbens, 2004). Third (iii), our study is built on secondary data provided contained in national public statistics databases, including the agricultural census, fiscal declarations, and custom data on vineyard production record. This requires to work precisely on connecting those data sources at farm scale, to obtain exhaustive and unbiased information on those units. Thereby, the methodological approach developed for this study could be adapted and reproduced to assess the impact of similar policies in other French regions or others with similar data.

The paper is organized as follows. Section 2 presents our case study: The Languedoc Roussillon wine basin and the development of irrigation networks. Section 3 describes our empirical approach and data aggregation methodology. Section 4 presents the results and section 5 offers conclusions.

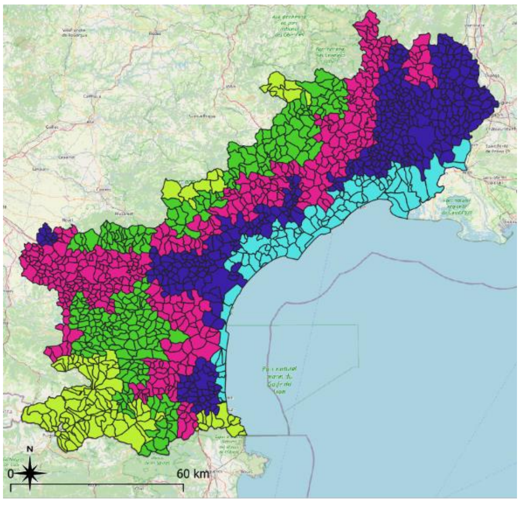
2. The Languedoc-Roussillon vine production basin case study

The Languedoc-Roussillon vine production basin is composed of four departments: Aude, Gard, Hérault and Pyrénées-Orientales. In 2020, these departments account for more than 22 500 farms, including 14 600 specialized in the production of vine over an area of 217 000 ha (Ministry of Agriculture, 2020).

The area is characterized by a diversity of landscapes with soil and weather specificities. The alluvial plans (zone 1, which includes Hérault, Gard, Têt basins), and the seashores (zone 4) are more exposed to hot weather and frequent droughts. Foothills (zone 3) and inland areas (zone 2) have a cooler climate and are less exposed to drought. Mountainous areas (zone 5, near

Pyrenees and Cévennes mountains) have cooler and wetter climates (**Erreur ! Source du renvoi introuvable.**).

Figure 1: Pedo-climatic zones



1	Alluvial plains with large useful reserves, exposed to hot weather with a significant water deficit and frequent drought waves..
2	Inland areas with a marked relief and shallow soils, a cooler climate than the plains and high rainfall.
3	Foothills areas with a low useful reserve but less exposed than the plains to heat and drought.
4	Flat seashores, exposed to the hottest weather and where droughts are most frequent, but which benefit from very deep soils.
5	Mountainous areas, with a cool, wet climate and very shallow soils.

Source: SICLIMA and Météo France data

The Languedoc-Roussillon is the first wine-growing area of France, in terms of area and quantity produced. Its four main grape varieties, Syrah, Grenache noir, Carignan and Merlot, cover half of the area of the vineyard (DRAAF Occitanie, 2018).

The vineyard is characterized by a strong diversity of vine growing estates, which differ in size, in the production's labels (Protected Geographical Indication- PGI, and Protected Designation of Origin –PDO), in the type of structure (independent or cooperative cellars), in their economic strategy and results. The area has also shown a recent strong increase in the share of organic wine production.

The region is characterized by a majority of small farms, with 33% of winegrowing farms with less than 5 ha of land, processing their wine through cooperative cellars (Table 1). Among co-operators, PGI labelled wine is the most represented type of production, with 34% of all co-operators having most of their production (>70%) under PGI, the main label being *IGP Pays d'Oc* (about half of the wine production of the basin). PGI wines can be considered as a middle quality, intermediate category between the PDO and non-labelled wines. The territory is also characterized by a diversity of *terroirs*, home to quality wine production, protected through several PDOs among which the well-known Corbières or Pic Saint Loup. If independent cellars are more likely to produce PDO wine, part of the PDO production is produced through cooperatives (9% of all cooperators devote more than 70% of their production to PDO). In the following sections, we consider as "mixed", farms who produce different types of wines, including PDO, PGI and non-labelled wine in intermediate proportion.

Some types of winegrowers also share their production between a cooperative and their own independent cellar. This applies to more than 500 farms in the region (categories 12 and 13 in Table 1). Finally, 188 farms among the total population are selling their production to wine trading structures.

Table 1: Typology of winegrowing farms in the Languedoc-Roussillon region, based on their main characteristics (source: Agricultural census and wine register, 2020)

	Type of structure	Farm size	Type of production	Number of farms	% of all farms	% of the category having access to irrigation
1	Cooperator	<5 ha	All types	4533	33%	18%
2	Cooperator	5-15 ha	> 70% PDO	515	4%	12%
3	Cooperator	5-15 ha	> 70% PGI	1862	14%	42%
4	Cooperator	5-15 ha	Mixed	449	3%	32%
5	Cooperator	15-50 ha	> 70% PGI	1894	14%	51%
6	Cooperator	15-50 ha	> 70% PDO	545	4%	23%
7	Cooperator	15-50 ha	Mixed	545	4%	41%
8	Cooperator	>50 ha	All types	652	5%	55%
9	Independent cellars	<50 ha	> 70% PDO	462	3%	20%
10	Independent cellars	<50 ha	< 70% PDO	843	6%	29%
11	Independent cellars	>50 ha	All types	348	3%	63%
12	Cooperators & independent cellars	<50 ha	All types	401	3%	35%
13	Cooperators & independent cellars	>50 ha	All types	115	1%	59%
14	Selling the production to wine trading structures	All sizes	All types	188	1%	44%
15	All types	All sizes	> 70% non-labelled	248	2%	35%

Sources : SSP- RA, French customs - CVI

3.1 Development of irrigation in the area

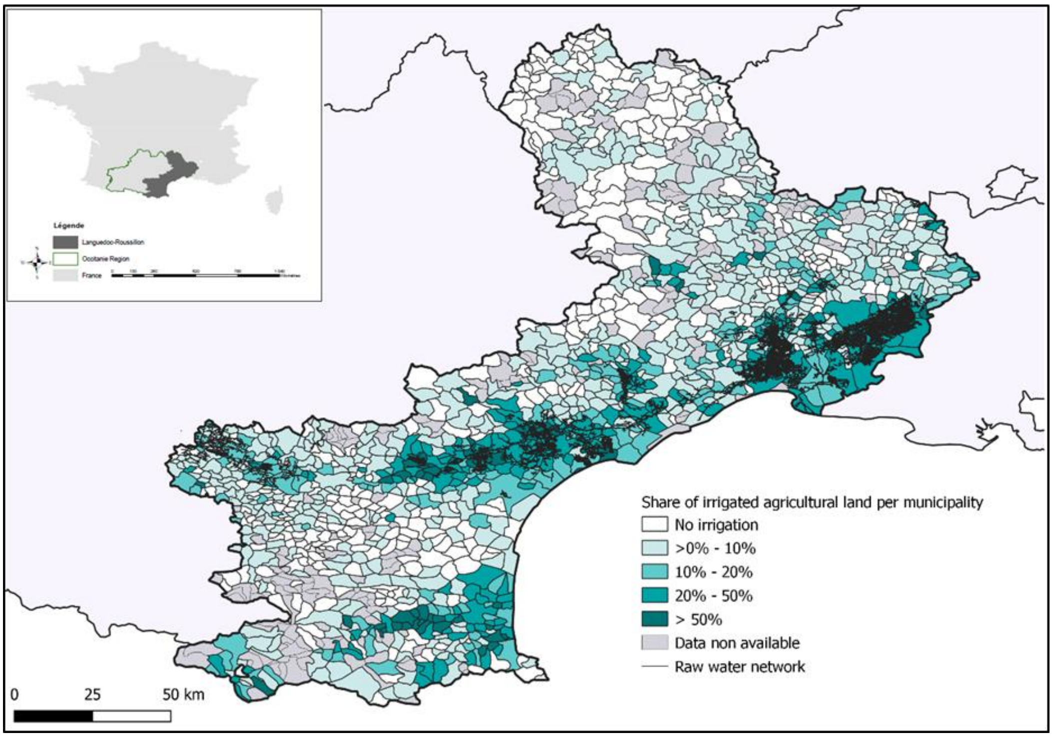
Climate change is impacting the vineyard, notably through the evolution of water deficit and the changes in the seasonal distribution of precipitation, and farmer perceive this change (Graveline & Grémont, 2021). Thus, one of the most needed adaptations is to adjust to water scarcity (Santillán et al., 2019). In response to this, several farms in the region have been equipped with irrigation systems, mostly using drip irrigation. In the Languedoc-Roussillon, between 2010 and 2020, more than 22 700 hectares of vine have been equipped with irrigation, an increase of 115%, and in 2020, 20% of total the region's vines are irrigated.

This evolution reflects the effects of climate change and increasing water stress on regional crops, which led to regulatory changes and a political will to develop irrigation in the region. Initially, irrigation was authorized under derogations for Protected Geographical Indications (PGI) wines, and it was forbidden for vines cultivated with a Protected Designation of Origin (PDO). Decrees of 2006 and 2017 have authorized irrigation until the 15th of August for PGI and for PDO under local derogations. Recently, the French ministry of agriculture announced the removal of the August 15th cut-off date from 2023.

This regulatory evolution has been followed by a development of irrigation networks in the 2010s, financially supported by regional authorities and European programs (FEADER). Aquadomitia, the Rhône raw water transfer project to the Languedoc area is at the heart of the development of irrigation networks in the last decade. Launched in 2012, this project allowed for the irrigation of 4100 hectares, and additional perimeters are still under development. Other development occurred (i) individual access (through drillings) and (ii) extension from irrigator association's networks that take water from other resources.

The following map presents the share of irrigated agricultural land per municipality in 2020 and the Aquadomitia raw water network. The map suggests that, except in Roussillon (south west), irrigation is mainly located in areas serviced by Aquadomitia network.

Figure 2: Share of irrigated land per municipality and Aquadomitia's water network in Languedoc Roussillon (2020).



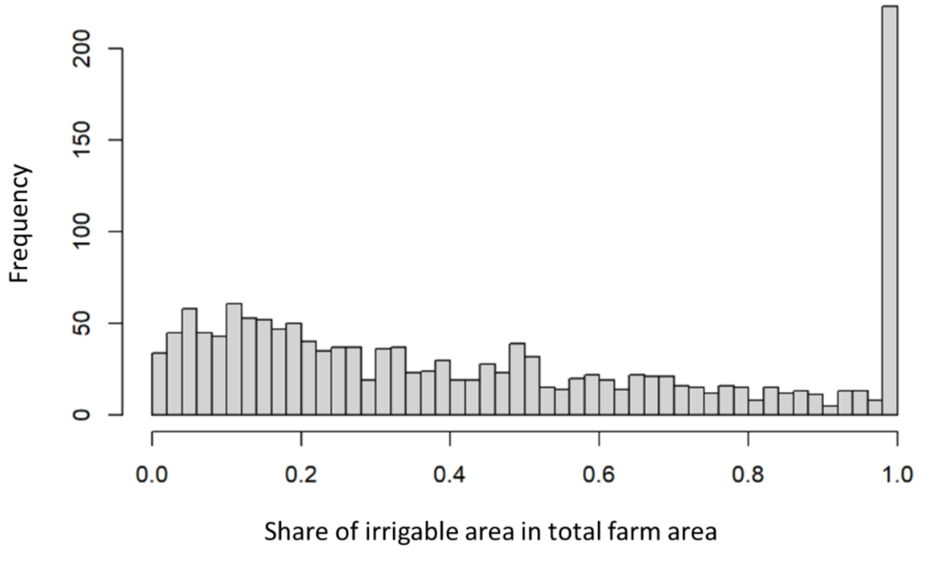
Source: SSP- Agricultural census, BRL (Own elaboration)

30% of winegrowers are irrigated in the area, mostly through collective networks. Still, a significant share of farms benefits from water through individual access, mostly using drillings and we observe 300 farms that have one or more complementary water sources in addition to collective networks. Drip irrigation is the most developed irrigation technology in the region, resulting from a will to invest in water efficient networks. Some types of farms are more likely to be equipped with irrigation than others: co-operators producing PGI wines (categories 3 and 5 in Table 1), which are mostly located in the wine-growing plains where collective irrigation networks have been developed, and large independent cellars (>50 ha, corresponding to categories 11 and 13 in Table 1).

If we observe a high degree of heterogeneity in the profiles with access to water, we also observe strong disparities in the way this access is configured within the farms. In addition to being connected to an individual or collective source, farmers may have equipped all of their plots, or just part of them, by choice or because of constraints (topological, agronomic or financial). As a result, there are a variety of configurations within farms, ranging from 1% to 100% of irrigable agricultural area (i.e. the surface area of the farm equipped with irrigation systems).

Figure 3 shows the distribution of the share of irrigable agricultural area in total farm area, within the group of farms that have access to irrigation. On average, this share is 45%.

Figure 3: Distribution of the share of irrigable area over total farm area within the group of farm having access to irrigation.



Sources : SSP- RA

For the sake of simplicity and for the following analyses, we will break down the characteristics of the farms into five groups: no irrigable area, less than 25% irrigable surface area, between 25% and 50%, between 50% and 75% and finally more than 75% irrigable surface area. Table 2 shows the distribution of the sample studied between these five configurations.

Table 2: Number of farms per irrigation status

Irrigation level	Number of farms

No irrigation (not in 2010 neither in 2020)	6041 (80%)
Less than 25% of agricultural land irrigable	582 (8%)
Between 25% and 50% of agricultural land irrigable	348 (5%)
Between 50% and 75% of agricultural land irrigable	239 (3%)
More than 75% of agricultural land irrigable	353 (5%)

Sources : SSP- RA, French customs - CVI

Table 3 below shows the main farm characteristics by irrigation status. We can see that the proportion of farms growing organically in 2010 is lower in the group with the most irrigable land (4.5% of the group growing organically) than in the group with less than a quarter of its plots equipped (8.1% of the group). We can also see that the group with more than three-quarters of its plots equipped has, on average, a smaller total agricultural area than the other equipped groups. A smaller area means lower total equipment costs for the farm, which may explain this trend. The share of PGI production in farm's production increases with the intensity of irrigation: from 67% on average for the group with irrigable areas of between 0 and 25M, to 84% for farms with more than 75% irrigable areas. There does not appear to be any link between having irrigation equipment and the proportion of production sent to cooperative wineries, nor with the age of the farm manager, which varies between 46 and 51 years depending on the group. Also, regarding geographical location of farms, almost half of the total population is located in the area with alluvial plains which is most likely to be exposed to high droughts (**Erreur ! Source du renvoi introuvable.**). Few irrigated farms are located in the zones 2 and 5, which are inland and mountainous areas, less exposed to heat and drought.

Table 3: Farm characteristics by irrigation status

Characteristics	**No irrigation**	**0-25%**	**25-50%**	**50-75%**	**75-100%**
	N = 6,041	*N = 582*	*N = 348*	*N = 239*	*N = 353*
Organic label 2010 (1/0)	394 (6.5%)	47 (8.1%)	19 (5.5%)	16 (6.7%)	16 (4.5%)
Total land 2010 (hectares)	17 (24)	35 (41)	24 (28)	26 (35)	19 (31)
Share of production in PGI 2010 (%)	0.60 (0.40)	0.67 (0.38)	0.77 (0.32)	0.81 (0.32)	0.84(0.30)
Unknown	*139*	*20*	*16*	*9*	*12*
Share of production sent to the cooperative (%)	0.84 (0.36)	0.74 (0.42)	0.80 (0.39)	0.76 (0.42)	0.82(0.38)
Unknown	*138*	*19*	*14*	*8*	*11*
Age of farm owner (years)	50 (12)	46 (11)	47 (11)	46 (12)	51 (13)
Geographical location:					
Pedoclimatic zone 1	2638 (44%)	330 (57%)	204 (58%)	140 (59%)	186 (52%)
Pedoclimatic zone 2	444 (7%)	22 (4%)	7 (2%)	-	4 (1%)
Pedoclimatic zone 3	1963 (32%)	150 (26%)	67 (19%)	40 (17%)	45 (13%)
Pedoclimatic zone 4	829 (14%)	76 (13%)	72 (21%)	58 (24%)	117 (33%)
Pedoclimatic zone 5	185 (3%)	4 (1%)	0 (0%)	0 (0%)	4 (1%)
Average yield (Hl/ha) (2019-2021)	45 (22)	49 (19)	53 (22)	59 (21)	60 (23)

Unknown	*1,121*	*56*	*41*	*27*	*70*
Average operating income (€/ha) (2020-2022)	286 (1,501)	242 (1,162)	-18 (1,282)	295 (1,366)	47 (2,065)
Unknown	*5139*	*432*	*282*	*185*	*314*

Note: Standard error in parentheses for continuous variables. *Sources : SSP- RA, French customs - CVI*

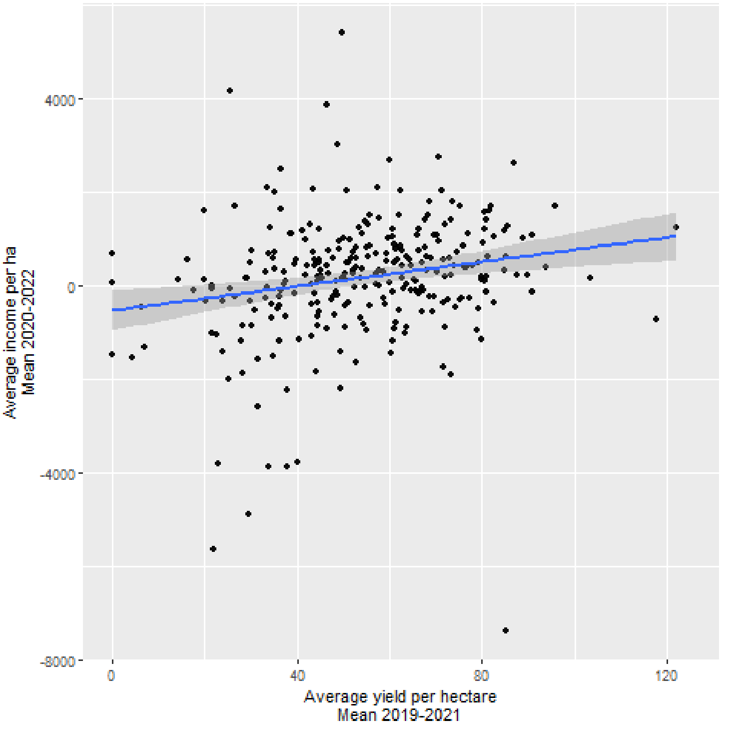
The average yield per hectare is higher for irrigators and increases according to the intensity of treatment: 45 hl/ha for the non-irrigated group, 46hl/ha for those with between 0 and 25% irrigable area, and up to 60 hl/ha for those with more than 75% irrigable area. On the other hand, there is no clear trend in operating results, and the averages vary widely from group to group.

3.2 Water, yields and farm income

In this paper, we wish to explore the links between the development of irrigation, productivity of vineyards and farm income. A simplified view of farm economics is that operating profit is the total gross revenue (quantity produced x prices) minus total charges. As the positive link between irrigation and yields no longer needs to be proven, we could naively say that irrigation mathematically implies an increase in farm income simply by increasing the quantity of wine produced. But the reality is not that simple, because farm strategies are varied among types of wine growers: some will rely on maximization of yields when others will look for improvement of wine quality, relying more on higher prices than on quantity (Graveline & Grémont, 2021). Breaking down the analysis of irrigation impacts into yield, gross income, charges and operating income is therefore of real interest in terms of economic analysis.

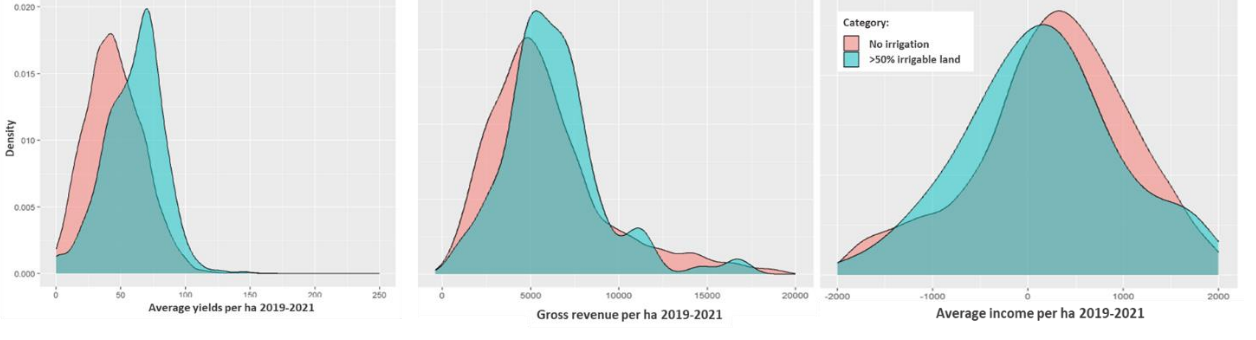
Overall, looking at average yields and operating income (Figure 4), we see a positive correlation but still a lot of dispersion in the data. The link between yields and revenues is not linear and must be investigated distinguishing different types of farms.

Figure 4: Average yields per hectare and average operating income per hectare



When linking those two variables with irrigation access, we see that there is a link between irrigable land, yields, and gross revenue per hectare. The first two graphs in Figure 5 below show the distribution density of average yields and gross revenue per hectare between non irrigated and irrigated farms (with more than 50% of irrigable land). The distribution is skewed to the right for the irrigated group, which suggests higher yields and gross revenues for irrigators. However, when looking at net operating income, the distribution is skewed to the left for the irrigated group.

Figure 5: Distribution density between irrigated (>50% irrigable land) and non-irrigated farms



These initial figures, although only descriptive, confirm the interest of this analysis and the initial intuition about the not so simple relationship between irrigation, yields and income in the wine sector.

3. Methodological approach

3.3 The evaluation problem

We want to measure how the development of irrigation over the past decade (between 2010 and 2020) has affected farms in terms of production (wine yields) and operating income. In the next sections, we will refer to those two variables as the outcomes.

The main methodological challenge behind this question is to isolate the effect of access to irrigation on outcomes, from other external factors that may affect them. For an estate i, we want to measure the proper effect of irrigation on the outcome, comparing the two potential outcomes with irrigation (Yi^1) and without irrigation (Yi^0). It is impossible to observe these two situations, we will either observe Yi^1 for a farm with access to irrigation or Yi^0 for a farm without access to irrigation. So the main challenge is to construct a proper counterfactual, i.e. a measure of a situation without irrigation that is comparable. In other words, we need to identify non-irrigated farms that are the most comparable to irrigated ones.

An important point is that the development of irrigation in an area is not necessarily exogenous: irrigation could be developed primarily in areas with high production potential or where access to water is less expensive. Thus, the strict difference in income between irrigated and non-irrigated farms will be due not only to access to water, but also to other observed or unobserved factors: for example, if irrigation is developed in areas with higher production potential, the income of the irrigated group is likely to be higher, but this will not only be due to access to water. We also need to take into account climate variability, as it affects the production of farms and the extent to which they would rely on irrigation for their production.

3.4 Estimation of the treatment effect

As the treatment considered (access to irrigation) is not binary (1= the farm has irrigable land, 0= the farm does not have irrigable land), but continuous (the farm has a certain percentage of its land that is irrigable), we need to consider a method that allows for that treatment setting. This continuity parameter is important because the impact of irrigation access might differ a lot regarding the intensity of irrigation. This analysis will give us interesting insights in terms of public policy analysis: this would allow us to assess whether there is a certain amount of irrigation beyond which marginal benefits are limited.

For this assessment, we develop two analyses. First (i), we start with a propensity score matching method that applied at several treatment levels. We define 4 treatment levels which are defined by the share of irrigable area in the total farm area: 0-25%, 25-50%, 50-75% and

75-100%. We consider as control units the farms that had no irrigable area in 2010 and 2020. We do that analysis on yields per hectare and on operating income per hectare. Second (ii), we apply a generalized propensity score, to estimate the average and marginal outcome corresponding to different irrigation levels. This approach will provide a better detailed information on the impact of irrigation access and will allow to explore the likely non linearity of the marginal effect of the treatment.

3.4.1 The propensity score matching approach

Several works have relied on propensity score matching with binary treatment (Rosenbaum and Rubin, 1983) to estimate the effects of irrigation on revenues (Chankrajang and Vechbanyongratana, 2018; Hagos et al., 2012; Buisson and Balasubramanya, 2018; Bravo-Ureta et al, 2020).

As specified by Rosenbaum & Rubin (1983), we consider that the outcome (Y) is independent from the irrigation status (T) conditionally on observable characteristics (X):

Equation 1:

$$Y^1, Y^0 \perp T \mid X$$

The propensity score is the probability that a unit (in our case, a farm) has access to the treatment (a certain irrigation level): P(T=1|X). If the conditional independence assumption is verified, then the outcome is also independent from the irrigation status (T) conditionally on the propensity score (p(X)):

Equation 2:

$$Y^1, Y^0 \perp T \mid p(X)$$

P(X) is estimated using a probit model in which we consider a vector of covariates including farm’s characteristics that both affect the treatment assignment and the outcome.

We can then estimate the average treatment on the treated as:

Equation 3:

$$\Delta^{ATT} = E(Y^1 - Y^0 | T = 1, p(X))$$

We consider 3 different outcomes: (i) average yields per hectare 2019-2020, (ii) average operating income per hectare 2020-2022, and (iii) difference in yields per hectare between 2020 and 2020. The two first outcomes are measured on 3 year's averages to smooth out annual fluctuations and gaps between grapeseed production period and wine sales period. The third outcome measures the differential in outcome before and after access to irrigation, to compare the average change in yields over time between irrigators and non-irrigators. This third approach is close to a difference in difference setting with propensity score matching, and the average treatment effect in this case is:

Equation 4:

$$\Delta^{ATE} = E\left(Y_{2020}^{1} - Y_{2010}^{1} \middle| p(X)\right) - E(Y_{2020}^{0} - Y_{2010}^{0} | p(X))$$

We then run four analysis corresponding to four levels of treatment (0-25%, 25-50%, 50-75%, 75-100% of irrigable land) using the same set of covariates and a propensity score matching with nearest-neighbour without replacement. Other matching estimators will be tested for robustness checks in further developments of this work.

The covariates we use are expected to include all observable pre-treatment variables that affect the treatment assignment and the outcome variable. To estimate the propensity score, we use the following covariates: total farm land, share of production in PGI, share of production sent to the cooperative, age of the farm owner, organic farming. Those covariates are measured in 2010, i.e prior to the treatment. We also add a variable indicating in which pedo-climatic zone is the farm located, with 5 different types of zones (**Erreur ! Source du renvoi introuvable.**), as the location of the farm is likely to affect irrigation access and the outcomes, regarding both climate characteristics (i.e exposure to drought), and terroirs.

3.4.2 The generalized propensity score approach

As mentioned before, in our setting, adoption of irrigation is continuous, meaning that a farm can implement an irrigation system on from zero to 100% of its plots. To account for that specificity, we follow the methodology of Hirano and Imbens (2004) on generalized propensity score (GPS), or dose-response function approach. In line with propensity score matching, this method allows to overcome the self-selection bias, as it compares farms with similar observable characteristics. In contrast to propensity score matching, GPS allows to evaluate both the average treatment effect of irrigation on farm's revenue, but also the marginal effect of irrigation on farm's revenue. This method has already been applied at farm scale, e.g. to evaluate the impact of innovation processes (Läpple and Thorne, 2019), the impact of food safety measures on farm's performance (Kumar et al., 2017), or the impact of direct payments within the common agricultural policy (Ciliberti et al., 2022). To our knowledge, this method has not yet been applied to irrigation or climate change adaptation measures.

In our case, the “dose” is the share of irrigated land over total farm’s land and the “response” is annual farm’s revenue per hectare. We assume that farm’s adoption of irrigation is determined by observed covariates, including their characteristics (farm size, land use, type of farming), types of vine producers (PDO, PGI, organic or not, co-operators or independent cellars). They are also influenced by climate and soil variables that are not yet available.

This empirical approach follows three main steps. First (i), we estimate the global propensity score. To do so, we start by modelling the conditional distribution of the treatment, given the covariates. This relies on the assumption of a normal distribution of the treatment given the covariates (Equation 1 below).

Equation 1 (Bia and Mattei, 2008):

$$G(t_i)|X_i \sim N\{h(\alpha X_i), \sigma^2\}$$

With $G(t_i)$ being the transformation of our treatment variable (irrigation intensity), X_i the covariates, $h(\alpha X_i)$ a function of covariates. This equation returns two estimated parameters α and σ, and gives the conditional density of irrigation level given the observed covariates.

Using those estimated parameters, we are now able to calculate the GPS for each observation:

Equation 2 : Estimation of the Generalized Propensity Score

$$\widehat{GPS}_i = \frac{1}{\sqrt{2\pi\hat{\sigma}^2}} exp\left[-\frac{1}{2\hat{\sigma}^2}\{G(T_i) - h(\hat{\alpha}, X_i)\}\right]$$

Equation 2 represents the conditional density of irrigation intensity given the observed covariates. $\hat{\alpha}$ and $\hat{\sigma}$ are the parameters estimated in Equation 1.

In line with propensity score matching method (Rosenbaum and Rubin, 1983), we need to verify the balancing properties of the propensity score, i.e. to see how the propensity score affects the balance of the covariates. To do so, the potential treatment values are divided into k intervals ($k = 4$), with approximately the same number of observations in each interval. Within each interval (G_k), we compute the GPS at the mean level of the treatment variable (t_{Gk}). Then, for each k, we divide the computed GPS into m intervals ($m=5$). $B_j^{(K)}$ $(j=1 \ldots m)$ are the m GPS interval for the K^{th} treatment interval. Within each interval $B_j^{(K)}$, we calculate the mean difference of each covariate, between units in the treatment interval, and units in the same GPS interval but in another treatment interval. Then, we combine the differences in means using a weighted average. Those steps are repeated, adjusting the GPS until the results are satisfying, i.e. until the differences in means are low enough to ensure there is no selection bias.

Second (ii), we estimate the conditional expectation of gross revenue per hectare (*Yi*) given the treatment (*Ti*) and the global propensity score (*GPSi*). The equation includes all second order moments of irrigation level (*Ti*) and score (*GPSi*).

Equation 3: Conditional expectation of Yi given Ti and GPSi

$$E(Y_i|T_i, GPS_i) = \beta_1 + \beta_2 T_i + \beta_3 T_i^2 + \beta_4 GPS_i + \beta_5 GPS_i^2 + \beta_6 T_i GPS_i$$

As specified in Hirano & Imbens (2004), the estimated coefficients in this model are only used to test whether the covariates introduce any bias, and to calculate the dose-response function.

In the last step (iii), we estimate the dose response function at each level of treatment t: $E\{\widehat{Y(t)}\}$.

For each level of treatment (from zero irrigation to 100% irrigation), we obtain an average potential outcome. The method also allows us to compute the marginal effect of irrigation. The results of this approach are presented in section 4.2.

3.5 Construction of the data set

Two alternative strategies can be thought of to rely on data: the resort to existing data sources or the production on own produced data through surveys. In this case, and unlike the majority of the literature on the topic, France has a lot of official state databases that inform about agriculture, some that are uniform with European Community countries. Thus we choose to rely, at least in a first stage, on official and already existing data sources, which should make our method reproducible on other cases in France or in Europe.

This work relies on coupling data at an individual scale that is classified as confidential and can be accessed through a convention and a specific device with biometric identification. It can only be extracted from the device once aggregated in a way that individuals cannot be identified.

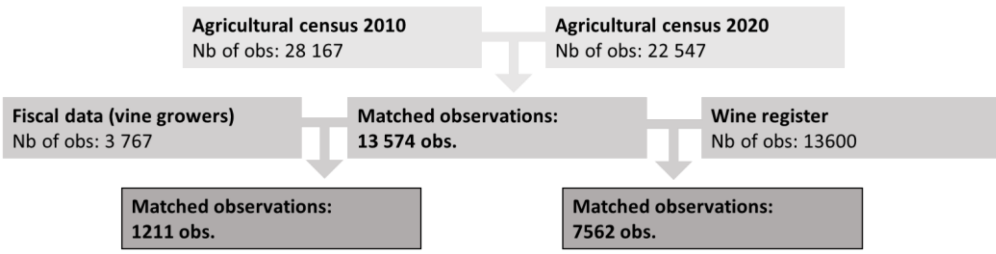
The sources of data we use at this stage are:

1. The official and public agricultural census (Ministère de l'agriculture- SSP, 2010, 2020) Carried out every ten years, the agricultural census collects detailed and exhaustive information on all French farms. It contains information on, among others, crops, irrigation, livestock, labour (cf. questionnaire). For each farm, it indicates whether the farm has access to irrigation, with the detail of irrigated crops, the total irrigable land, origin of irrigation water, type of irrigation (sprinkler, drip, gravity). We use the two last agricultural censuses of 2010 and 2020.

2. Fiscal declarations data (Ministère des finances, 2020-2022). The public finance general directorate collects fiscal data from farms that are under a specific regime: the agricultural real benefits regime. Real benefits are collected by the public finance general directorate and those databases indicate the result and balance sheets of farms. This data is available from 2016 to 2022. For this first analysis we use data from the year 2020 to 2022.
3. Wine register (French customs, 2019-2021). Winemakers in France are obliged to declare their annual production to customs. This includes quantity produced, with types of wines (PGI/PDO/non labelled) and destination of the production (cooperative, independent cellar). This data is available from 2013 to 2021. For this first analysis we use data from the year 2019 to 2021.

Those three databases are aggregated using farm identification numbers (SIRET, PACAGE, EVV). We only keep the observations for which production of vine is the main activity of the farm.

Figure 6: Combination of the databases



Matching those databases, we obtain a population of 7562 winegrowers on which we have data on their characteristics pre and post treatment, and their wine production. This sample is satisfying on size and repartition of farms by their characteristics. Regarding farm's operating income, we obtain a population of 1211 farms for which we have information on their characteristics and their fiscal declarations. Our future analysis on income might be limited by the lack of representability of this sample.

We identify treatment and control units using information on irrigation provided by the agricultural censuses 2010 and 2020. Treated farms are those that did not have irrigable land in 2010, and that have irrigable land in 2020. Control farms are those that did not have irrigable land in 2010 and still don't have irrigable land in 2020. We clean the database removing rows for which the fiscal data presents outliers or missing values.

4. Results

4.1 Propensity score matching

4.1.1 Impacts of irrigation on yields

First, we look at the impact of irrigation on yields, considering two outcomes: average yields 2019-2021, and difference in yields between 2020 and 2010.

We first present the results from the estimation of the propensity scores from the probit regressions, on the four levels of treatment. Using the covariates listed in section 3.2. *Estimation of the treatment effect,* we construct propensity scores to ensure matching on those covariates for units in each treatment group and the control group. The propensity score estimates are slightly different for the two approaches (average yields and difference in yields), as the sample is not the same: we have more observations that are available for 2010 and 2020 (N=6777), than for the period 2019-2021 (N=6248), although their signs are the same in both estimations.

The results from the propensity score estimates show a significant and negative effect of being in the pedoclimatic zones 2 and 3 (Table 4). It means that on average, farms that are in inland areas, or on foothills areas, less exposed to drought, are less likely to be equipped with irrigation than farms in alluvial plains exposed to hot weather and drought waves (**Erreur ! Source du renvoi introuvable.**). The size of farms has a significant and positive impact on the probability to be treated at each irrigation level, as well as the share of production in PGI. The share of production sent to the cooperative and the age of the farm owner have a significant and negative impact on the probability to be irrigated.

Table 4: Estimation of propensity scores with different levels of irrigation access (first analysis on yields)

	PSM average yields 2019-2021 *N=6248*				**PSM Difference in yields 2020-2010** *N=6777*			
	0-25%	**25-50%**	**50-75%**	**75-100%**	**0-25%**	**25-50%**	**50-75%**	**75-100%**
(Intercept)	-1,02 (0,25) ***	-1,98 (0,33) ***	-2,48 (0,39) ***	-3,669 (0,374) ***	-0,88 (0,24) ***	-1,81 (0,32) ***	-2,36 (0,37) ***	-3,55 (0,35) ***
Pedoclimatic zone 2	-1,078 (0,248) ***	-1,08 (0,25) ***	-1,43 (0,39) ***	-15,67 (332,55)	-1,13 (0,25) ***	-1,5 (0,39) ***	-16,66 (523,3)	-2,15 (0,59) ***
Pedoclimatic zone 3	-0,607 (0,115) ***	-0,61 (0,12) ***	-0,88 (0,16) ***	-0,96 (0,2) ***	-0,56 (0,11) ***	-0,9 (0,16) ***	-0,96 (0,19) ***	-1,27 (0,2) ***
Pedoclimatic zone 4	-0,26 (0,149) .	-0,26 (0,15) .	0,17 (0,16)	0,22 (0,18)	-0,24 (0,14)	0,16 (0,15)	0,17 (0,17)	0,41 (0,14) **
Pedoclimatic zone 5	-0,969 (0,601)	-0,97 (0,6)	-14 (375,92)	-14,36 (607,28)	-1,17 (0,6) .	-14,01 (332,89)	-15,36 (890,29)	0,23 (0,62)
Organic farming (2010)	-0,223 (0,2)	-0,22 (0,2)	-0,23 (0,28)	-0,23 (0,33)	-0,25 (0,19)	-0,32 (0,27)	-0,16 (0,3)	-0,49 (0,33)

Agricultural land (2010)	0,016 (0,001) ***	0,02 (0,00) ***	0,01 (0,00) ***	0,01 (0,00) ***	0,01 (0,00) ***	0,01 (0,00) **	0,01 (0,00) ***	0,00 (0,00)
Share of production in PGI	0,423 (0,133) **	0,42 (0,13) **	1,33 (0,2) ***	1,82 (0,26) ***	0,44 (0,13) ***	1,24 (0,19) ***	1,74 (0,24) ***	2,04 (0,23) ***
Share of production sent to the cooperative	-0,378 (0,133) **	-0,38 (0,13) **	-0,69 (0,18) ***	-0,76 (0,2) ***	-0,45 (0,13) ***	-0,63 (0,17) ***	-0,75 (0,2) ***	-0,79 (0,19) ***
Age of farm owner	-0,027 (0,004) ***	-0,03 (0,00) ***	-0,02 (0,01) ***	-0,03 (0,01) ***	-0,03 (0,00) ***	-0,03 (0,01) ***	-0,03 (0,01) ***	0,00 (0,00)

*Note : Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1. Standard errors are in parentheses.*

Details of the estimation, including covariate balance, are specified in *Appendices* : Propensity score matching – Covariate balances.

When estimating the average treatment effect on the treated on average yields 2019-2021, using nearest neighbour propensity score matching, we measure a positive and significant impact of the treatment on yields over 25% of irrigable land. The effect if of 4,8 hl/ha for farms with irrigable land between 25 and 50%, 5,7 hl/ha for farms with an irrigation land between 50 and 75% and 10,8 hl/ha for farms with more than 75% of irrigable land.

When looking at the difference in yields between 2020 and 2010, the average treatment effect is positive and significant at each level of treatment. The effect is of 3,2 hl/ha below 25% of irrigable land, 6,7 hl/ha between 25 and 50% of irrigable land, 10,3 hl/ha between 50 and 75% of irrigable land and 7,4 hl/ha above 75% of irrigable land.

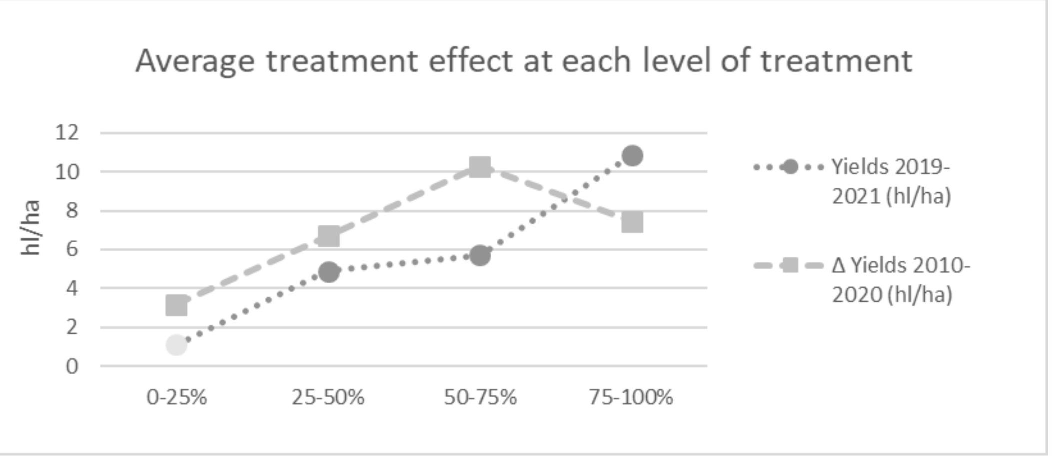
Table 5: Average treatment effect on the treated (ATT) using nearest neighbour matching

	Irrigation levels (% of irrigable land)			
	0-25%	**25-50%**	**50-75%**	**75-100%**
Yields (hl/ha) 2019-2021	1,06 (1,08)	4,89 (1,59) **	5,71 (1,76) **	10,86 (1,81) ***
Number of matched observations	508	287	206	270
∆ Yields 2020-2010 (hl/ha)	3,18 (1,47) *	6,69 (2,09) **	10,28 (2,26) ***	7,45 (2,52) **
Number of matched observations	537	306	219	301

*Note : Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1. Standard errors are in parentheses.*

The two estimations give interesting contrasted results. The effects are slightly higher (+ 2 to + 5hl/ha) for the difference in difference estimates below 75% of irrigable land. But at the highest level of treatment (above 75%), the effect is higher when looking at average yields 2019-2021. In the first approach (looking at average yields), it seems that more irrigable land leads to more productivity (increasing marginal effect). In the second one, marginal effects are decreasing. Sensitivity analysis is needed to investigate those contrasted results.

Figure 7: Average treatment effect on yields



4.1.2 Impacts of irrigation on average operating income

Studying farm operating income requires to work with a smaller sample, as data is not available for all farms. Consequently, although the covariates used are the same, the estimation of the propensity score is different in this second case. In this case, we see that only location in pedoclimatic zone 3 and share of production in PGI have a positive and significant impact on the probability of being treated (Table 6).

Table 6: Estimation of propensity scores with different levels of irrigation access (second analysis on income)

	Irrigation levels (% of irrigable land)			
	0-25%	**25-50%**	**50-75%**	**75-100%**
(Intercept)	0,499 (-3,02) **	-2,953 (0,746) ***	-2,234 (0,78) **	-4,564 (0,896) ***
Pedoclimatic zone 2	0,419 (-1,793) .	-1,037 (0,743)	-15,93 (788,2)	-15,46 (794,4)
Pedoclimatic zone 3	0,236 (-3,408) ***	-1,072 (0,385) **	-0,894 (0,379) *	-2,008 (0,752) **
Pedoclimatic zone 4	0,292 (-0,606)	0,247 (0,347)	0,202 (0,365)	1,094 (0,37) **
Pedoclimatic zone 5	1,078 (-0,219)	-13,079 (794,015)	-14,61 (2123)	-14,43 (2164)
Organic farming (2010)	0,395 (-1,615)	-0,489 (0,56)	-0,853 (0,633)	0,178 (0,588)
Agricultural land (2010)	0,003 (1,409)	-0,008 (0,007)	-0,011 (0,008)	0,0011 (0,008)
Share of production in PGI	0,267 (2,185) *	1,857 (0,455) ***	2,226 (0,509) ***	1,955 (0,593) ***
Share of production sent to the cooperative	0,241 (1,449)	-0,207 (0,336)	-0,799 (0,337) *	-0,808 (0,384) *

Age of farm owner	0,009 (-1,808) .	-0,006 (0,012)	-0,02 (0,013)	0,014 (0,014)

*Note : Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1. Standard errors are in parentheses.*

We cannot measure any significant treatment effect on the treated when looking at the impact of irrigation on farm income (Table 7).

Table 7: Average treatment effect on the treated (ATT) using nearest neighbor matching

	Irrigation levels (% of irrigable land)			
	0-25%	**25-50%**	**50-75%**	**75-100%**
Operating income (€/ha)	22,122 (148,991)	309,638 (309,638)	322,360 (261,451)	-174,874 (346.975)
Number of matched obs.	286	122	108	78

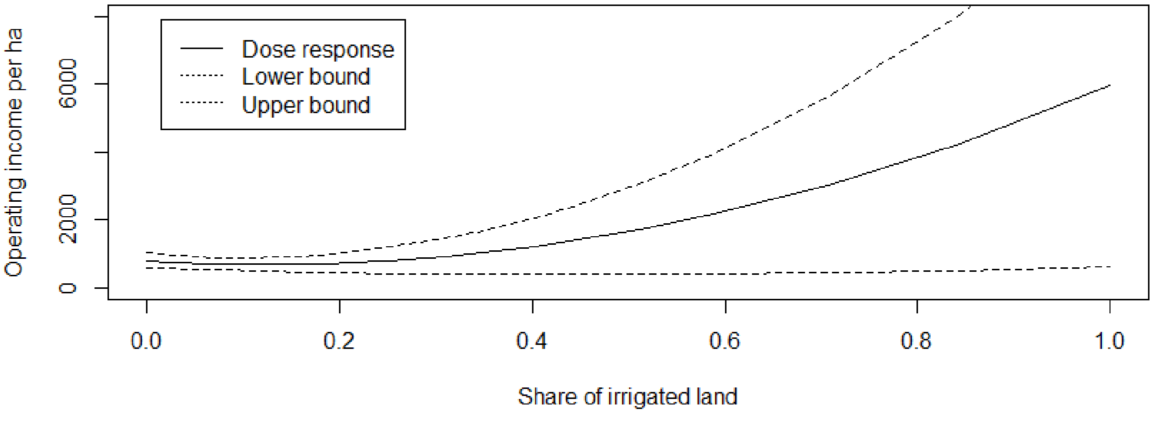
*Note : Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1. Standard errors are in parentheses.*

4.2 Generalized propensity score

As we are in a continuous treatment setting, we apply the generalized propensity score to measure average and marginal effect of irrigation on farm's operating income. A similar analysis will be done on yields in further developments. We use the same list of covariates as in propensity score matching above.

The figure below reports the average effect, i.e the level of gross revenue per ha with respect to irrigation level. Overall, a higher level of irrigation is associated with a bigger increase in the gross revenue per hectare. This preliminary result needs to be considered with a lot of caution: the sample is very reduced, and the methodology is not yet stabilized. Moreover, we see that the lower and upper confidence bounds are very large as we tend to 100% irrigation level: this is probably due to a low number of observations in the sample and strong heterogeneity in this group (>50% irrigated land).

Figure 8: Average effect of irrigation on operating income per ha



This very large confidence interval suggests a very strong heterogeneity of the effects for intensive levels of irrigation. We need to further investigate their case. Looking at the irrigation levels below 30% (168 observations in the sample), for which the confidence interval is reduced, suggests a positive but moderate net benefit of irrigation: around +700 €/ha for irrigation intensities between 0 and 20%, and up to +1000 €/ha for irrigation levels of 30%. A too important confidence interval for higher intensities prevents us from exploiting the results.

5. Conclusion

This paper explores the way to assess the impact of irrigation development. This is a straightforward adaptation to the effects of climate change that is at the heart of controversies because of water resources and social externalities. In this context it is of urgent importance to assess empirically the economic impacts and benefits of this adaptation on farms, among other impacts. In this work we show how we combine the use of an original database and the resort to econometrics to assess this adaptation option. We found that on average, in the Languedoc-Roussillon basin, irrigated wine activities are indeed significantly more productive than rainfed activities when studying the average treatment effect of different levels of irrigation on yields. This approach does not show any significant results on the operating income of farms. In a second part, we explore the application of the generalized propensity score approach, in order to observe the effects of irrigation as a continuous treatment.

The perspectives of this work are numerous. First, we need to deepen our investigation on the impacts of irrigation on farm income, looking at the different components of income (gross revenue, charges) and their evolution with irrigation and over time. The fiscal declaration database we use is interesting but restricted because we obtain a small sample of farms that is not representative of the entire population. Moreover, we suspect that it contains elements that are not only linked to the production of wine (such as revenues from other activities – wine tourism, restaurants…), or resulting from tax optimization strategies that we can hardly control for. Another solution could be to use FADN data, which will highly reduce the size of our sample but is more commonly used for analyses in agricultural economic analysis.

Also, we would like to distinguish these effects between different types of winegrowers, especially distinguishing PGI and PDO wines, which are subject to different production strategies, rules – for example regarding maximum yields limitations - and price ranges.

Finally, we would like to be able to compare the situation of farms before the implementation of irrigation, and after the implementation of irrigation, using data on revenues from 2010 and 2020. Having data on farm's revenue on the entire period would allow us to build an empirical framework using differences-in-differences and dose response models.

Those more detailed specifications will enable us to assess the adaptation potential of irrigation and produce estimates that can be integrated in cost-benefits analysis of future projects and to calibrate adequate production functions that will integrate hydro-economic modelling to assist stakeholders in the exploration of alternative future and policy scenarios.

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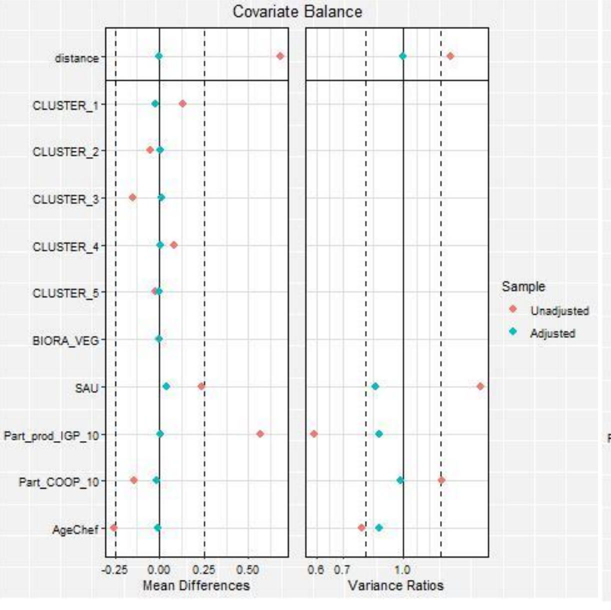
Appendices : Propensity score matching – Covariate balances

Table A1: Impacts of irrigation on average yields (2019-2021) – Covariate balance

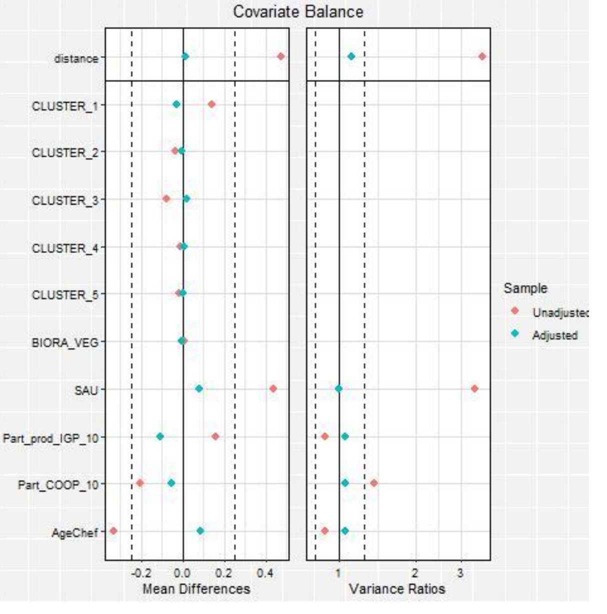
		Treatment levels															
		0-25%				25-50%				50-75%				75-100%			
Variable	**Type**	**Diff.Un**	**V.Ratio.Un**	**Diff.Adj**	**V.Ratio.Adj**	**Diff.Un**	**V.Ratio.Un**	**Diff.Adj**	**V.Ratio.Adj**	**Diff.Un**	**V.Ratio.Un**	**Diff.Adj**	**V.Ratio.Adj**	**Diff.Un**	**V.Ratio.Un**	**Diff.Adj**	**V.Ratio.Adj**
	Distance	0,47	3,62	0,01	1,11	0,68	1,32	-0,00	1,00	0,69	2,70	0,00	1,02	0,86	1,45	0,00	1,00
Pedoclimatic zone 1	Binary	0,14		-0,03		0,13		-0,02		0,14		-0,02		0,12		-0,01	
Pedoclimatic zone 2	Binary	-0,04		-0,00		-0,05		0,01		-0,07		-		-0,06		-0,01	
Pedoclimatic zone 3	Binary	-0,08		0,02		-0,15		0,01		-0,16		0,01		-0,21		0,02	
Pedoclimatic zone 4	Binary	-0,01		0,01		0,09		0,00		0,12		0,01		0,17		-0,01	
Pedoclimatic zone 5	Binary	-0,02		0,00		-0,02		-		-0,02		-		-0,01		0,01	
Organic farming (2010)	Binary	0,01		-0,00		-0,00		-		-0,01		0,04		-0,03		-0,01	
Agricultural land (2010)	Contin.	0,44	3,41	0,08	1,00	0,24	1,57	0,04	0,85	0,26	2,70	0,08	0,95	-0,01	1,16	0,02	0,76
Share of production in PGI	Contin.	0,16	0,88	-0,10	1,06	0,57	0,59	0,01	0,87	0,75	0,55	-0,04	1,05	0,86	0,52	-0,03	1,15
Share of production sent to the cooperative	Contin.	-0,21	1,37	-0,05	1,06	-0,14	1,26	-0,02	0,98	-0,15	1,29	-0,10	1,17	-0,05	1,13	-0,05	1,12
Age of farm owner	Contin.	-0,33	0,88	0,09	1,05	-0,26	0,78	-0,01	0,87	-0,27	1,02	0,05	1,09	0,13	0,99	-0,02	0,97

Figure 9: Impacts of irrigation on average yields (2019-2021) - Balance plots

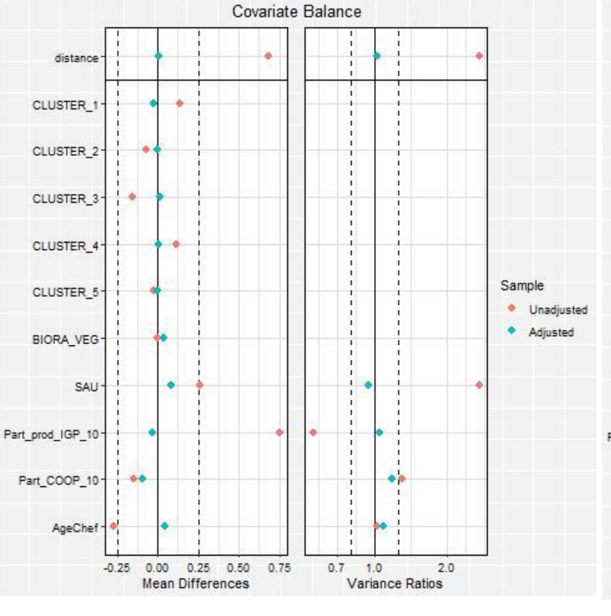
Treatment level 1 : 0-25%



Treatment level 2 : 25-50%



Treatment level 3 : 50-75%



Treatment level 4 : 75-100%

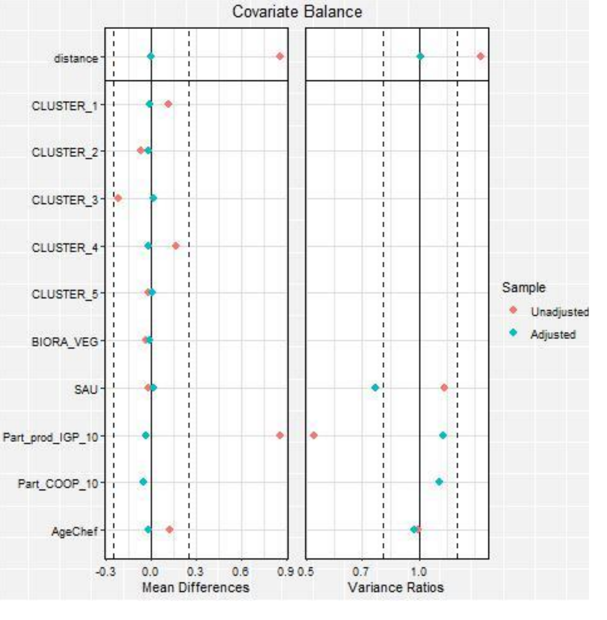
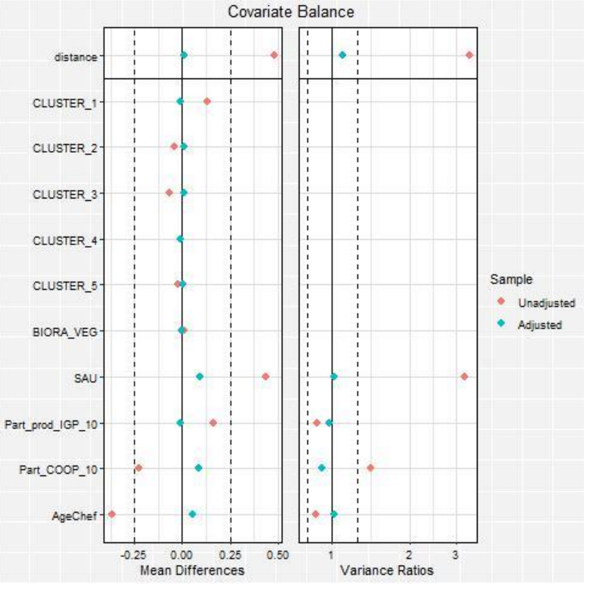


Table A2: Impacts of irrigation on difference in yields (2020-2010) – Covariate balance

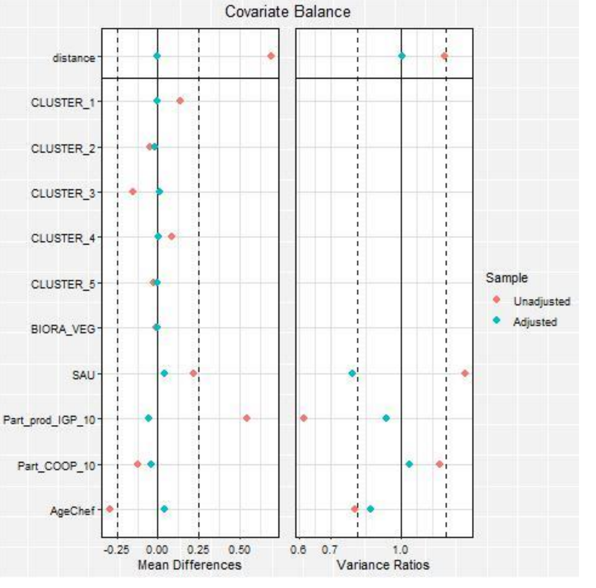
		Treatment levels															
		0-25%				25-50%				50-75%				75-100%			
Variable	**Type**	**Diff.Un**	**V.Ratio.Un**	**Diff.Adj**	**V.Ratio.Adj**	**Diff.Un**	**V.Ratio.Un**	**Diff.Adj**	**V.Ratio.Adj**	**Diff.Un**	**V.Ratio.Un**	**Diff.Adj**	**V.Ratio.Adj**	**Diff.Un**	**V.Ratio.Un**	**Diff.Adj**	**V.Ratio.Adj**
	Distance	0,48	3,38	0,01	1,10	0,69	1,24	0,00	1,00	0,71	2,30	-0,00	1,00	0,87	1,45	0,00	1,01
Pedoclimatic zone 1	Binary	0,13		-0,01		0,14		-0,00		0,15		-0,00		0,12		-0,02	
Pedoclimatic zone 2	Binary	-0,04		0,01		-0,05		-0,02		-0,07		-		-0,06		-0,01	
Pedoclimatic zone 3	Binary	-0,07		0,01		-0,15		0,01		-0,16		-		-0,22		0,02	
Pedoclimatic zone 4	Binary	-0,01		-0,01		0,08		0,01		0,10		0,00		0,17		0,02	
Pedoclimatic zone 5	Binary	-0,02		0,00		-0,02		-		-0,02		-		-0,01		-0,00	
Organic farming (2010)	Binary	0,01		-0,00		-0,01		-0,00		-0,00		-0,01		-0,03		-0,01	
Agricultural land (2010)	Contin.	0,44	3,24	0,10	1,02	0,22	1,37	0,04	0,78	0,25	2,33	-0,00	0,82	0,03	1,22	0,08	1,58
Share of production in PGI	Contin.	0,16	0,87	-0,01	0,97	0,55	0,61	-0,05	0,93	0,72	0,57	0,02	1,09	0,88	0,51	-0,02	1,05
Share of production sent to the cooperative	Contin.	-0,22	1,40	0,09	0,91	-0,12	1,21	-0,04	1,04	-0,15	1,30	0,04	0,97	-0,04	1,12	-0,01	1,02
Age of farm owner	Contin.	-0,37	0,87	0,06	1,02	-0,30	0,79	0,04	0,86	-0,29	1,01	0,00	0,97	0,09	1,00	-0,10	0,80

Figure 10: Impacts of irrigation on difference in yields - Balance plots

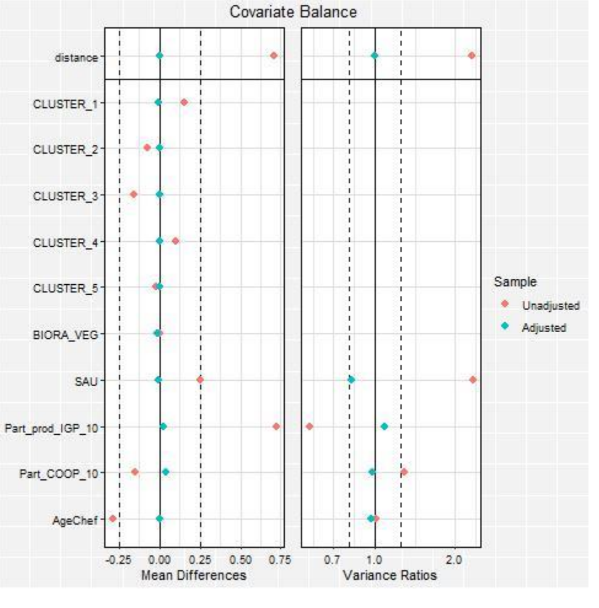
Treatment level 1 : 0-25%



Treatment level 2 : 25-50%



Treatment level 3 : 50-75%



Treatment level 4 : 75-100%