The micro-economic impacts of a ban on glyphosate and its replacement with mechanical weeding in French vineyards

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In France, viticulture is the production sector that uses the highest amount of glyphosate per hectare. The prospect of banning this pesticide in France, and in Europe as a whole, has led us to study the existence of alternatives to this herbicide, following article 50.2 of the European regulation 1107/2009, and to estimate the additional costs involved. Based on a national public database, we synthesized the different weed control practices in viticulture and calculated their costs. Our results showed that alternative methods to the use of glyphosate are more or less widespread depending on the wine-producing area in France.

Inter-row non-chemical weed control is widespread and involves mechanical operations, with or without the use of cover crops. The most difficult aspect concerns weed control between vine stocks within the rows (intra-row), without applying herbicide. The size of the farms, the structure of the vineyards and especially the distance between rows largely account for the differences in the adoption rates of glyphosate-free practices in wine-producing areas. In total, the additional cost of mechanical weeding compared to glyphosate chemical weeding is €250/ha on average, and varies from €12 to €553/ha depending on the wine-producing area. The generalization of alternatives to glyphosate-use under the European ban on glyphosate could have economic consequences on the income of farmers, the magnitude of which depends on several factors, including the type of vineyard, availability of labour and equipment on each farm, as well as marketing channels.

Keywords: glyphosate; economic impact; mechanical weeding; labour costs; machinery costs.

Introduction

Reducing the use of pesticides is one of the objectives shared by many European countries in accordance with European Directive 2009/128. This reduction is the subject of public policies established at a European and/or Member State (MS) level that involve incentives for a decrease in pesticide use, such as taxes or subsidies, as well as binding regulatory procedures regarding their marketing, or even their ban. Numerous policies have been implemented, but most of them have not been successful (Finger et al., 2017; Hillocks et al., 2012; Lefevre et al., 2015; Möhring et al., 2020; Skevas et al., 2015; Wossink et al., 2000). In this context, the prospect of a potential total ban on glyphosate after 2022 has provided greater impetus for a continuation of the political debate on pesticides in the European Union (EU) (Kudsk & Mathiassen, 2020).

Glyphosate is the most widely-used herbicide around the world and including in the EU (EC, 2020). It has been used for many years to kill weeds during the period following the harvest of a crop and before the sowing of the next one in field crops and vegetable crops, and as weed control in the production of perennial plants (arboriculture and viticulture). The high efficiency of glyphosate against perennial weeds means it is greatly appreciated and widely used (Duke et al., 2018). However, scientific evidence has demonstrated its negative impacts on the environment and biodiversity and, more recently, on human health.

The renewal of the authorization of the use of glyphosate has been the subject of multiple discussions and debates among decision-makers, citizens, scientists, and agricultural organizations (Kudsk & Mathiassen, 2020). The European marketing authorization for glyphosate, approved by the European Commission (EC) in December 2017 for a period of five years, currently runs until December 15 2022 (EC, 2020). The EU pesticide legislation requires that the approval of all active substances must be periodically reviewed, starting with a scientific assessment by a Rapporteur Member State (extended to four countries: France, Sweden, the Netherlands, and Hungary in the case of glyphosate), and followed by a peer review process overseen by the European Food and Safety Agency (EFSA, 2020). The decision regarding the renewal of the approval of glyphosate will be taken by the EC on the basis of the evaluation reports currently underway.

While European decisions were being made, in 2018, the French government presented a glyphosate exit plan to reduce the use of glyphosate-containing products. It has committed to phasing out the main uses of glyphosate by 2020 where alternatives already exist, and by 2022 for all other uses. This relies on European Regulation 1107/2009 (EC, 2009) which stipulates that, “the withdrawal of Market Authorization for a product containing a molecule approved at European level is possible by a Member State if one or more alternative methods, chemical or non-chemical, exist, ensure prevention or control for the same use, and if they are in common use, in principle without any environmental impact and without any major economic impact".

The economic impact of a glyphosate ban has so far received little attention. On a global scale, the issue has been assessed in relation to the potential economic and environmental impacts that would occur if restrictions on glyphosate-use resulted in the world no longer planting genetically modified herbicide-tolerant crops (Brookes et al., 2017). At a European level, the problem is different, since genetically modified crops are rarely used. Alternative weed control methods are known and practiced, at least in organic agriculture. Only a few studies have assessed the potential impact of a glyphosate ban in European countries. Kudsk & Mathiassen (2020) have reviewed the desk studies conducted in Sweden, Germany, the United Kingdom and France that assess the feasibility and impacts of the switch to glyphosate-free weeding methods for arable crops, and shown that the impact depends on the tillage strategies employed. For farms that already plough their soils, the economic impacts would be relatively low or moderate. Based on a bioeconomic modelling approach for Germany (Böcker et al., 2018, 2020) and Switzerland (Böcker et al., 2019), the authors also concluded that the microeconomic impact would be low.

Our study focuses on the existence of non-chemical alternatives to the use of glyphosate in French viticulture, and on their economic impact. It goes further than a previous study on glyphosate alternatives in French agriculture (Reboud et al., 2019), which mainly focused on arable crops and did not assess the economic costs of alternatives.

French viticulture only covers 3% of the territory, but concentrates 20% of pesticide-uses (herbicides, fungicides and insecticides) (Agreste, 2019). Glyphosate is widely used in viticulture for inter- and intra-row weed control. It is by far the main herbicide used in viticulture (93% of the areas that receive herbicide applications are treated with glyphosate).

The quantities of glyphosate used in viticulture vary from 400g to 1000g a.i./ha (Reboud, 2019). They are similar to the quantities used in other cropping systems in France, however vineyards receive glyphosate applications more frequently than annual cropping systems (Reboud et al. 2019). France is among the five EU countries with the highest use of glyphosate in 2017 (> 320 g of a.i. per ha) (Antier et al., 2020).

Literature and surveys show that non-chemical alternative techniques do exist, notably in organic vineyards. The effects of organic and conventional practices on weed control have been compared, which suggests that replacing a glyphosate application with cultivation may be an effective method of reducing herbicide-use in vineyards (Baumgartner et al., 2017; Bond et al., 2001; Reboud et al., 2019).

In order to reveal what could be the micro-economic impact of a glyphosate ban for French wine-producing farms, the data from a large national survey on crop practices at field level were used to compare the costs of techniques identified for various farms.

This survey allowed us to compare the crop management practices observed at field level for farms that currently use glyphosate and other chemical herbicides, with those of farms that do not use herbicides under similar conditions. An estimation of the costs of the various techniques thus identified made it possible to calculate what the impact would be if farms were to adopt already existing techniques.

1. Materials and Methods

1.1. Crop management data

In order to obtain data on the weeding practices of winegrowers, we used a survey on farming practices conducted by the French Ministry of Agriculture every four years. This survey ("*Pratiques Culturales*", that is, "crop practices", a survey of the Statistics and Prospective Analysis Service of the Ministry of Agriculture and Food) covered all major French agricultural production systems, and followed a sampling plan that allowed it to be representative of current farming systems. It aimed to describe the technical practices of crop management and, in particular, the use of phytosanitary products by French farmers. The last survey on viticulture (which is the one used in our study), was carried out in 2017 for the 2015-2016 agricultural campaign (Agreste, 2019). A total of 7,800 crop plots located across 21 wine-producing areas across France (Figure 1) were surveyed, with 7,156 questionnaires collected, thus covering an area of 729,424 ha (that is, 93% of the land dedicated to viticulture in France).

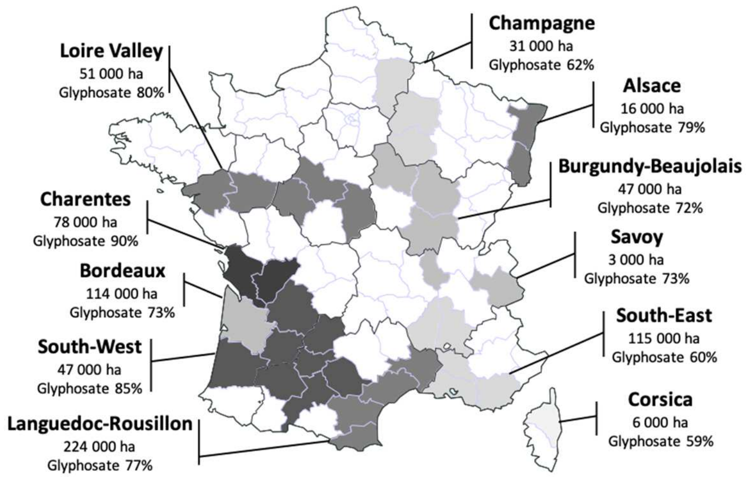

Figure 1: French wine-producing areas and glyphosate-use

From the database used, we retrieved the following variables for each of the 7,156 plots surveyed: localization, row spacing, type of cover cropping (no cover crop, cover crop in every row, cover crop in every inter-row out of two), and inter-row and intra-row weed control operations. For the inter-rows, we retrieved the number of herbicide applications, the product and quantity used, and the number of mechanical interventions per type of practice, while distinguishing between mowing, tillage using a disc tool, tillage using a pronged tool, and the use of an inter-row rotavator; for intra-row operations, we retrieved the number of herbicide applications, the product and quantity used, and the number of mechanical interventions per type of tool, while distinguishing between inter-vine blades, inter-vine rotary tools and intra-row non-reversible vineyard ploughs. We initially identified nine weed management types, by taking into consideration the use of chemicals (exclusively chemical, exclusively mechanical, and mixed) and the type of cover cropping. Then, we described the cultivation operations for each type.

1.2. Calculation of weeding costs

To calculate the working times and costs of each of the cultivation operations identified, we used existing data published by extension services. The national data repositories on the costs of cultivation operations are published each year for the establishment of benchmarks and mutual aid scales among farmers (APCA, 2018) with information for each type of agricultural machinery.

Costs have been estimated for each wine-producing region (V) and weed-management type (TYP)

$CT_{V,TYP} = + CH_{V,TYP} + CTool_{V,TYP} + CTTract_{V,TYP} + CLabor_{V,TYP}$

With $CT_{V,TYP}$ = : total costs; $CH_{V,TYP}$: herbicide costs; $CTool_{V,TYP}$: tool costs; $CTTract_{V,TYP}$: tractor costs; $CLabor_{V,TYP}$: labor costs

Each practice (TYP) corresponds to a succession of interventions on the vine defined by a number of passages (NP) with a specific tool (I). For each element of the matrix NP ($_{TYP,K)}$) which describes the number of operations for nine practices and nine tools, we calculated the different costs.

We chose the appropriate tool to each operation from the database. The tools differ according to the distance between the rows, and the benchmarks we used distinguish between tools for wide vines and tools for narrow vines. Tool costs were calculated based on the price of the equipment (average price excluding tax), on the depreciation costs calculated on the basis of a rate (linear depreciation over a lifespan) and on maintenance and repair costs. We calculated the tool depreciation per hectare on the basis of the observed average vineyard areas of the wine-producing farms in each producing area.

Costs are calculated by adding operations carried for the whole vineyard, for intra row as well as inter-row areas.

$CTool_{TYP,WV} = [\ \sum_{TYP,i1=1}^{i1=1} \mathrm{CTool}_{WV,i1} * dummy_{WV,i1}\ ] + [\ \sum_{TYP,i2=1}^{i2=4} \mathrm{CTool}_{WV,i2} * dummy_{WV,i2}\ ] + [\ \sum_{TYP,i3=1}^{i3=4} \mathrm{CTool}_{WV,i3} * dummy_{WV,i3}\ ]$

With :

WV : inter- row width (large, narrow vines)

I operations : i1 on the whole vineyard; i2 on the row area , i3 on the inter-row area

$dummy_{WV,I}$ = 1 if tool is selected, 0 if not.

Tractor costs and labor costs depend on the working time which itself depends on the tool used, and its speed. Tractor costs include repairs and fuel, and the depreciation based on a number of hours used annually.

$$WT_{TYP,WV} = [\ \sum_{TYP,i1=1}^{i1=1} NP_{TYP,i1} * Perf_{WV,i1}\ ] + [\ \sum_{TYP,i2=1}^{i2=4} NP_{TYP,i2} * Perf_{WV,i2}\ ] + [\ \sum_{TYP,i3=1}^{i3=4} NP_{TYP,i3} * Perf_{WV,i3}\ ]$$

With Perf : speed of the tool

As the working time provided in the database on the costs of cultivation does not include the time related to adjustments, cleaning, getting started, etc., and as the expert and extension service publications consulted state that where new techniques and machinery are not well mastered by the farmers, extra time could be significant: we have thus maintained a common assumption of 30% extra time (Gaviglio, 2013). An hourly working rate of €18/hour, which corresponds to the average skilled labour rate, has been taken into account.

1.3. Impact on farmer income

In order to measure the importance of estimated additional costs in relation to farmer income, we used French data from the Farm Accountancy Data Network (FADN) for wine-producing farms. The French FADN database includes 1,130 wine-producing farms, which constitutes a representative sample of the 43,928 French wine-producing farms, whose annual Standard Gross Product is greater than €25,000. We used three indicators of economic results to compare the costs of shifting from chemical weeding to a non-chemical alternative to its benefits: the Gross Product (total sales of products plus changes in stocks), Gross Operating Profit (Gross Product plus subsidies minus intermediate consumptions, expenses and taxes) and Farm Net Income (total remuneration of fixed factors and entrepreneurial risks in the accounting year). Detailed definitions are available on the FADN website (https://ec.europa.eu/info/food-farming-fisheries/farming/facts-and-figures/farms-farming-and-innovation/structures-and-economics/economics/fadn_en).

Finally, we also retrieved channels, prices and yields associated to different weed management strategies from the "*Pratiques Culturales*" survey information on sales and marketing, so as to shed light on the valorization of herbicide-free practices.

1.4. Sensitivity analysis of the calculation of working time and depreciation

Two sensitivity tests were carried out on our calculations.

The first concerns working time. In our basis (scenario H1), a 30% increase in working time with the use of mechanical weeding machines was included. In scenario H2, this increase was not taken into account.

The second test (H3) related to the depreciation calculation method, which was no longer carried out on the basis of the size of the farms in each wine-producing area, but on an average wine-producing area of 20 ha.

2. Results

2.1. Wine-producing areas and weed- control methods

At national level, 80% of the vineyard areas used at least one herbicide in 2015-2016. Glyphosate was used on 75% of the vineyard areas, where it and was the only herbicide to be used on 24% of these cultivated areas, with while another herbicide was used on 51% of these areas. The other top-ranked herbicides were flazasulfuron (28%), aminotriazole (17%) carfentrazone-ethyl (13%), flumioxazine (12%) and glufosinate ammonium (10%). Since then, aminotriazole and glufosinate ammonium have been removed from the French market, in 2015 and 2018, respectively.

Three weed control methods categories were identified (Figure 2): exclusively mechanical (20% of the areas), chemical herbicides used on across the whole area (14%), and mixed, which is a combination of intra-row chemical weed control intra-row and inter-row mechanical inter-row weed control (66%).

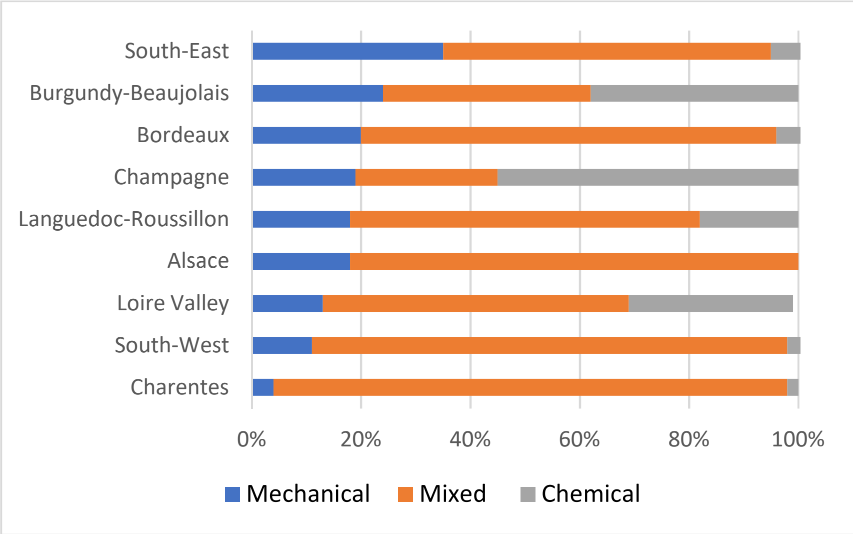

Figure 2: Mechanical, mixed and chemical weeding control methods in as a % of the land area for the main wine- producing areas

2.2. Typology of weeding practices

We carried out the analysis for all wine-producing areas (with the exception of Corsica and Savoy, for which we had insufficient data). By pooling the plots according to the weed control method and type of cover crop used for each wine-producing area, we identified types of crop practices (Table 1).

We observed that the practices were represented differently according to the wine-producing area. In the regions of Alsace, the South-West and Bordeaux, over 80% of the plots surveyed are cover-cropped (entirely or one row out of two), while in Languedoc-Roussillon, the South-East and Burgundy-Beaujolais, where drought conditions are often more pronounced, less than 30% of the plots are cover-cropped. The relative soil surface allotted to cover cropping (for example, every inter-row, one inter-row out of two, etc.) and the type of flora used affects the intensity of the competition for soil, nutrient and water resources exerted on vineyards, but also relates to the risks of erosion and runoff effects, in particular in steep-slope vineyards (Celette et al. 2008; Prosdocimi et al., 2016; Vrsic et al., 2011). The advantages and disadvantages of cover cropping or tillage differ according to soil characteristics, rainfall and drought intensity in France, which are somewhat variable given that wine production occurs under oceanic, Mediterranean and continental climates (Raclot et al., 2009; Ripoche et al., 2011).

Mechanical weeding practices are observed in all wine-producing areas, however they are more frequently used in the South-East and Burgundy-Beaujolais regions.

By retaining only the practices that concern more than the 30 plots monitored for each wine-producing area, we ultimately selected 43 crop practices for the cost estimations (see shaded areas in Table 1)

Table 1: Distribution of technical management methods as a % of the land area of each wine-producing area and number of plots observed

	Mechanical			Mixed			Chemical		
	No cover crop	cc	cc 1/2	No cc	cc	cc 1/2	No cc	Cc	cc 1/2
Bordeaux	**9%**	**4%**	**7%**	**3%**	**34%**	**39%**	**4%**	**1%**	**-**
	50	*21*	*37*	*16*	*180*	*205*	*19*	*4*	-
Alsace	**1%**	**5%**	**12%**	**-**	**29%**	**53%**	**-**	**-**	**-**
	3	*13*	*33*	-	*77*	*141*	-	-	-
Burgundy-Beaujolais	**20%**	**3%**	**1%**	**15%**	**19%**	**4%**	**36%**	**2%**	**-**
	142	*25*	*5*	*106*	*153*	*27*	*290*	*15*	-
Champagne	**7%**	**11%**	**1%**	**8%**	**13%**	**5%**	**53%**	**2%**	**0%**
	37	*53*	*6*	*43*	*61*	*26*	*260*	*9*	*1*
Charentes	**1%**	**1%**	**2%**	**20%**	**21%**	**53%**	**2%**	**-**	**-**
	5	*4*	*13*	*107*	*112*	*283*	*10*	-	-
Languedoc-Roussillon	**12%**	**5%**	**1%**	**44%**	**13%**	**7%**	**17%**	**1%**	**-**
	108	*43*	*10*	*334*	*97*	*50*	*147*	*7*	-
South-East	**27%**	**4%**	**4%**	**41%**	**10%**	**9%**	**6%**	**0%**	**-**
	313	*58*	*71*	*480*	*168*	*110*	*74*	*1*	-
South-West	**1%**	**3%**	**7%**	**4%**	**21%**	**62%**	**3%**	**0%**	**-**
	14	*33*	*77*	*42*	*250*	*583*	*24*	*3*	-
Loire Valley	**6%**	**6%**	**1%**	**3%**	**33%**	**20%**	**28%**	**2%**	**-**
	62	*69*	*7*	*69*	*239*	*101*	*181*	*11*	-

Source: Our calculations are based on "*Pratiques Culturales*" 2017 data; cc: cover crop, cc ½: one inter-row out of two is cover-cropped, the other just being bare soil.
NB: The grey-shaded cells correspond to a sample that comprises more than 30 plots and that was retained from the analysis of practices for reasons of statistical representativeness.

2.3. Labour and Machinery Cost estimation

2.3.1. Working time

For each of these 43 "types" of crop management systems, the data relating to the distance between the rows, the number of operations, as well as the type of machines used made it possible to calculate the working time of each practice type (Table 2).

Table 2: Working time (in hours per ha)

	Mechanical			Mixed			Chemical		
	No cc	cc	cc ½	No cc	cc	cc ½	No cc	cc	cc ½
Bordeaux	17.7	-	10.8	-	7.5	6.6	-	-	-
Alsace	-	-	12.6	-	11.2	9.7	-	-	-

Burgundy-Beaujolais	17.1	-	-	13.1	9.5	-	6.4	-	-
Champagne	18.1	19	-	9.8	13.5	-	6.6	-	-
Charentes	-	-	-	11.6	8	8.3	-	-	-
Languedoc-Roussillon	10.5	7.3	-	7.1	5.9	6.3	1.8	-	-
South-East	11.1	9.7	11	8.6	5.9	6.6	1.8	-	-
South-West	-	7.5	8.8	7.1	6.9	6.4	-	-	-
Loire Valley	15.3	16.7	-	10.6	10	9.7	5.8	-	-

We observed a clear increase in working time when switching from chemical to mechanical weeding in the inter-row (mixed vs chemical) and intra-row (mechanical vs mixed). We also observed that working times are higher in the absence of cover crop. Intra-row (and, to a lesser extent, inter-row) mechanical weed control involves a large number of field operations. Such weed control work is generally carried out between May and July and can compete with other necessary operations (with the level of difficulty of weed control depending on soil conditions). Chemical weed control requires less time and can be carried out at more flexible times. The lack of skilled staff and the difficulty in appointing new workers is mentioned by winegrowers organizations as potential hindrances for a successful transition to non-chemical weeding.

Differences among regions are mainly explained by inter-row spacing. Overall, 21% of the vineyards have an inter-row distance of less than 170cm, which refers to the entire Champagne wine-producing area, 96% of the Beaujolais producing area and 94% of the Burgundy producing area. This spacing occurs in only a small area of the Bordeaux wine-producing area (that is, the Pauillac appellation). The time required per hectare for a single operation is greater in vineyards with narrow rows, because of the greater number of rows. In the Burgundy-Beaujolais, Champagne, Loire Valley and Alsace wine-producing areas, vineyards generally have narrow rows and the working time for chemical weed control systems is around 6 hours/ha, which increases to 9 to 13 hours/ha for mixed systems and to 13 to 19 hours/ha for mechanical weed control systems. In the Languedoc-Roussillon, South-East and South-West wine-producing areas, around 2 hours/ha are required for chemical weed control systems, 6 to 8 hours/ha for mixed systems and 7 to 11 hours/ha for mechanical weed control systems.

2.3.2. Cost estimations

Table 3 shows that the diversity observed in costs for different wine-producing area is significant. The highest costs are observed for vineyards with narrow rows (in the Champagne, Burgundy-Beaujolais and Loire Valley producing areas), and mainly reflect the differences in working hours.

Table 3: Costs in €/ha (depreciation excluded)

	Mechanical			Mixed			Chemical		
	No cc	cc	cc 1/2	No cc	cc	cc 1/2	No cc	cc	cc 1/2
Bordeaux	660	-	297	-	298	269	-	-	-
Alsace	-	-	470	-	506	447	-	-	-
Burgundy-Beaujolais	638	-	-	471	459	-	433	-	-
Champagne	673	709	-	445	595	-	450	-	-
Charentes	-	-	-	417	355	356	-	-	-
Languedoc-Roussillon	291	202	-	258	228	320	183	-	-
South-East	307	269	302	300	232	251	184	-	-
South-West	-	207	242	263	273	266	-	-	-
Loire Valley	569	621	-	474	459	426	397	-	-

The total costs involved (Table 4) include the cost of labour, the use of traction tools and the depreciation of materials specific to each farming operation. The depreciation of specific equipment was defined based on the average size of farms in each wine-producing area, as given in the FADN. The differences in the size of the farms largely accounted for the differences observed in equipment costs (for example, the high costs per hectare in Champagne and Alsace are related to small vineyard surface areas per farm).

Table 4: Total costs in €/ha (depreciation included)

	Mechanical			Mixed			Chemical		
	No cc	cc	cc 1/2	No cc	cc	cc 1/2	No cc	cc	cc 1/2
Bordeaux	779	-	486	-	320	357	-	-	-
Alsace	-	-	1 129	-	615	576	-	-	-
Burgundy-Beaujolais	769	-	-	645	528	-	476	-	-
Champagne	1 072	1146	-	978	1 156	-	584	-	-

Charentes	-	-	-	551	378	499	-	-	-
Languedoc-Roussillon	436	282	-	321	271	363	198	-	-
South-East	526	422	507	387	275	346	199	-	-
South-West	-	265	341	323	295	329	-	-	-
Loire Valley	686	730	-	579	493	487	418	-	-

Figure 3 illustrates the composition of the total costs for the different management systems in the Languedoc-Roussillon producing area, which is the most important in terms of vineyard area. We can observe that labour costs are the main factor for the additional cost of mechanical practices, followed by the costs of traction tools, which are also directly linked to the working time. The total fuel consumption in liters /ha is indicated on the second axis of the ordinates and shows a significant increase in fuel consumption linked to mechanical weed control.

The two entirely herbicide-free techniques showed contrasting figures in terms of total costs, as well as in fuel consumption. Using cover crops has a positive influence on the two indicators.

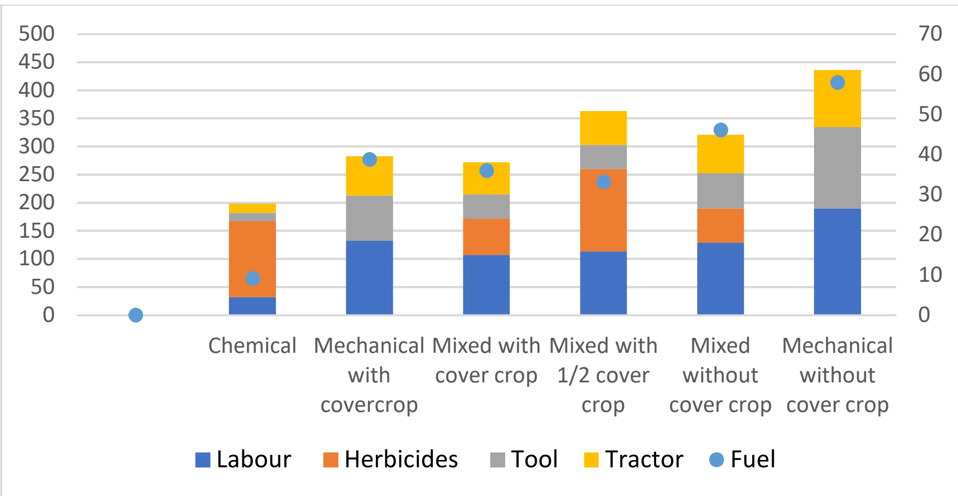

Figure 3: Costs per hectare (broken into bars and expressed in €/ha on the left axis) and fuel consumption (point expressed in liters/ha on the right axis) in the Languedoc-Roussillon producing area

2.4. Sensitivity analysis

The additional cost calculated for each wine-producing area corresponds to the difference between the cost of the most frequently used weed-control method and that of the most widespread herbicide-free practice with the same inter-row cover cropping method. This additional cost varies from €12 to €553/ha, depending on the producing area. The additional cost is particularly high in regions where the most widespread weed control technique is chemical weeding (Champagne and Burgundy-Beaujolais). We chose to base our estimation on the most frequently used weed-control method. The results would not be exactly the same if we took the second most frequently used method, but there would be no great difference, except to a certain extent for the Loire Valley where chemical weeding is also significantly present compared to the mixed weeding method retained in our calculation.

Table 5: Sensitivity of the additional cost (€) of non-chemical weeding to different hypotheses

	H 1 Basic scenario	H2 "Net" working time	H3 Depreciation on a 20ha farm
Bordeaux	129	106	144
Alsace	553	537	205
Burgundy-Beaujolais	293	235	254
Champagne	488	426	272
Languedoc-Roussillon	115	97	120
South-East	139	126	147
South-West	12	-1	16
Loire Valley	237	201	249

In Table 5, we can see that the scenario regarding working time (H2 vs H1) does not significantly change the results obtained. On the other hand, the depreciation calculation method has a strong impact, in particular, on the wine-producing areas where farms are small-sized (Alsace, Champagne), since in H3 equipment depreciation is calculated based on a significantly larger farm size than in H1.

2.5. Additional cost and impact on farmer income

The additional cost of replacing chemical weeding with mechanical weeding is compared to the economic results of farms, issued from the FADN data for each wine area (Table 6). The additional cost thus represents from 0.3 to 4.4% of the Gross Product (GP), from 1 to 11.5% of the Gross Operating Profit (GOP) and from 2 to 18% of the Farm Net Income (FNI), depending on the wine-producing areas. Overall, an average additional cost of €250/ha represents 2.6% of the GP, 7.1% of the GOP and 10.6% of the FNI. By using the GOP as the most relevant income indicator for our analysis, the additional cost represents less than 5% of the GOP in several wine-producing areas, around 7.5% in the Loire Valley and Languedoc-Roussillon, and 11.5% in Alsace. The result for Alsace is essentially related to our hypothesis concerning the calculation of equipment depreciation, because of the limited vineyard surface area per farm. Using the H3 hypothesis will significantly change this result for Alsace, with an additional cost that thus represents only 4.3% of the GOP.

Table 6: Additional cost of mechanical weed control compared to chemical weed control (value and % of economic indicators)

	Additional cost	GP	GOP	FNI	Additional cost in % GP	Additional cost in % GOP	Additional cost in % FNI
	€/ha	**€/ha**	**€/ha**	**€/ha**			
Alsace	**553**	12677	4791	3077	**4.40%**	**11.50%**	**18.00%**
Bordeaux	**129**	11354	2618	1334	**1.10%**	**4.90%**	**9.70%**
Burgundy-Beaujolais	**293**	19934	7893	5499	**1.50%**	**3.70%**	**5.30%**
Champagne	**488**	29969	12205	9411	**1.60%**	**4.00%**	**5.20%**
Languedoc Roussillon	**115**	4834	1486	679	**2.40%**	**7.70%**	**16.90%**
South-East	**139**	7605	3078	2237	**1.80%**	**4.50%**	**6.20%**
South-West	**12**	3685	1349	773	**0.30%**	**0.90%**	**1.60%**
Loire Valley	**237**	9797	3227	2081	**2.40%**	**7.30%**	**11.40%**

Source: Our calculations based on "*Pratiques Culturales*" 2017 and average FADN data for 2015-2016-2017 for vineyards. NB: The insufficient amount of data available concerning herbicide-free weed control for the Charentes producing area does not allow us to consider this area in our estimations. GP: Gross Product; GOP: Gross Operating Profit; FNI: Farm Net Income.

2.6. Marketing channels and wine prices

The majority of the grapes harvested by winegrowers are paid per liter of wine produced (77%), the rest being paid either according to the degree of alcohol (Cognac) or per kilo of grapes. Winemakers can sell bottled wine or bulk wine, and wine prices will differ accordingly, however, prices also differ according to the geographical areas of production (or "*appellation*") and to the specifications of the production methods (that is, organic or biodynamic farming, among others). Over 50% and up to 97% of the wine is sold in bottles in Bordeaux, Alsace and Champagne, whereas bottled wine represents less than 30% in the Languedoc-Roussillon, South-East and South-West regions. Figure 4 shows the prices in €/liter for bottled wine and bulk wine, according to the weed control practices previously identified. We observed that the prices for wine produced without the use of herbicide is sold in almost all cases at a higher price than the wine produced using chemical herbicides (either mixed or chemical only). This difference reflects the fact that in areas with an appellation, it is possible to value the efforts made in the management of vineyards, including weeding practices, for example.

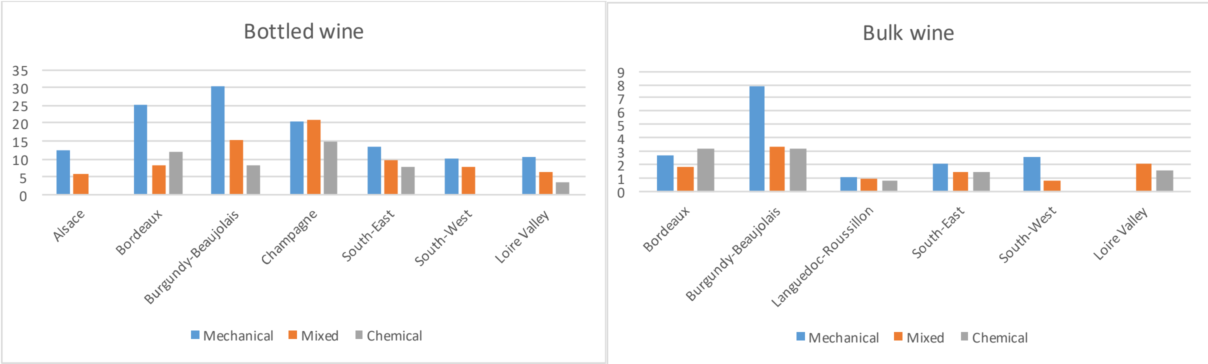

Figure 4: Wine price €/liter for bottled wine and bulk wine according to weed management method

Part of the differences in price is, however, correlated with the variations in the maximal production per hectare that can be certified under the appellation. As a result, the benefits of higher prices compensate for the lower volumes produced (see Figure 5). Weeding practice is therefore only one component of the differences between the different situations.

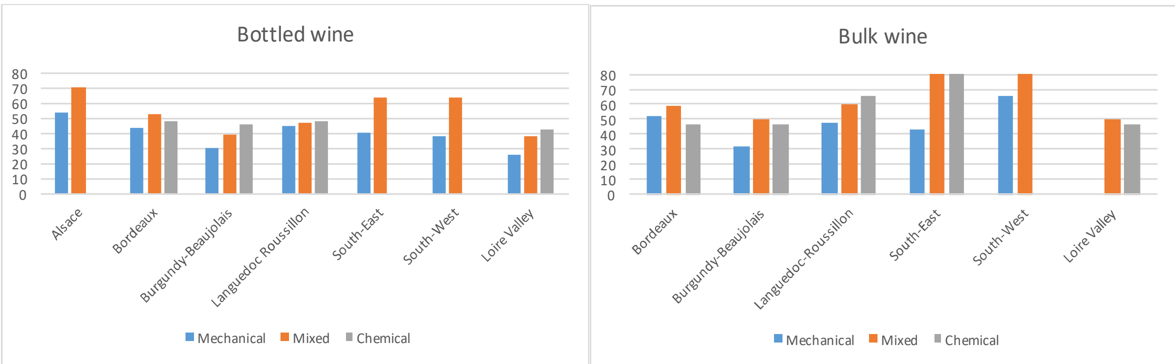

Figure 5: Yields in hectoliter /ha for bottled wine and bulk wine according to weed management methods

3. Discussion

3.1. Mechanical weeding and its impact on vine growth

Even if the lower yields for mechanical weeding observed in Figure 5 are mostly due to the maximal production per hectare that can be certified under the appellation, we can question the negative impact of mechanical weeding on vineyard productivity; an issue that is often highlighted by farmer associations as an obstacle to adopting mechanical weeding methods. There are relatively few references on this issue. One study (Sanguankeo et al., 2009) shows that the impact of alternative techniques compared to herbicide treatment can be negative in a dry year, especially in the case of cover crops. Most experts agree that mechanical weeding depends on the mastery of the technique.

Poor technical skills applied to mechanical weeding operations may certainly cause damage to the vine stocks and disrupt the surface root system, which can lead to yield losses. During the transition from glyphosate to non-glyphosate-based weed control methods, the vines will reorganize their root systems to a greater depth. The time required to reach a new equilibrium may vary, depending on the physiological state of the vine, soil-climate conditions and yield objectives. Nonetheless, tests show that not all varieties are affected in the same way, though it remains extremely challenging to determine what is due to the grape variety, the vigor of the chosen rootstock, the methods of implantation and the corrective actions taken (Gaviglio et al., 2013). When mechanical weeding is used in young vineyards, the vine stocks will set their roots at a depth adapted to mechanical weeding techniques.

3.2. Mechanical weeding and weed flora

The underlying hypothesis in the direct comparison of glyphosate versus mechanical weed control, as seen in the present study, concerns the stability of the weed flora. This hypothesis, however, may be wrong. If the flora changes over time under mechanical weeding, it may be easier (or more difficult) to control. Fried et al. (2019) showed a limited effect of chemical versus mechanical weed control on species composition, with a few specialized species, a more diverse weed flora with more annual species under mechanical weeding, and less troublesome weeds along the rows in three wine-producing areas in France. This confirmed the findings of Steenwerth et al. (2010) in California, who also documented a limited modification of the weed seed bank. The limited impact on weed flora with more annual species and less troublesome weeds suggests that the transition should not lead to more difficult weed management and/or extra costs.

The absence of herbicide-use will also lead to a change in inter-row management with a lower frequency of bare soil, and more cover crops. Indeed, cover crops can have a positive impact on soil carbon content, on the consequences for soil fertility (Guzman et al., 2019), and on biodiversity and the provision of ecosystem services (Garcia et al., 2018; Hoffmann et al., 2017; Richards et al., 2020; Winter et al., 2018). One limitation of the more widespread use of cover crops, however, concerns water availability in dry areas during summer, and it remains a challenge to find cover crops suitable to vineyards in these areas (Messiga et al., 2016; Sweet et al., 2010)

3.3. Why do some farmers adopt alternative weeding techniques when they are more costly than chemical weeding?

As we have seen, the majority of farmers only use herbicides below the row and a number of them do not use any herbicides at all. This is despite the additional costs that we have calculated. Therefore, what are the reasons for this discrepancy?

First, aid for investment in specific equipment that contributes to the agro-ecological transition currently exists, though due to a lack of homogeneous data we have not included it in our calculations. Such aid comes from the French "Farm competitiveness plan", co-financed by the European Agricultural Fund for Rural Development (EAFRD), the State, and regional authorities. It usually covers up to 40% of the value of the equipment purchased.

Secondly, the working time included in our analyses corresponds to skilled and paid working time valued at market price. However, the share of family work represents 46% of the total labour force of wine-producing farms on average (FADN). The additional labour required for mechanical weeding techniques is not necessarily valued by the farmer in the same way as if employees were to be hired.

Finally, herbicide-free practices are often included in the production methods associated with the specifications of designations of origin or organic production. Consumers are indeed willing to pay more according to these specifications. (Schäufele et al., 2017; Sellers-Rubio et al., 2016). In our case, we cannot attribute the price difference observed solely to the difference in the weeding method, as other plant protection aspects are also contained in the specifications. It is therefore difficult to attribute the part of glyphosate-free weeding practices in the additional costs and price difference observed in Figure 4. However, we believe that it plays a significant role for a certain number of farmers.

Other non-economic motivations, particularly those that may be linked to environmental preferences, may also be important for some winegrowers (Lozano-Vita et al., 2018). The collective dimension of behaviors (such as the behavior observed by different farmers involved in a single cooperative committed to an environmental approach**)** should also be taken into account, and recent research shows that the intention to reduce pesticide-use is strongly determined by whether or not other farmers also act in the same way (Bakker et al., 2020).

3.4. Glyphosate ban vs other policies

The difficulties in the adoption of alternative techniques as highlighted by farmer organizations have led to the postponement of the deadlines for totally banning glyphosate at both national and European levels. This raises questions concerning other public policy instruments that could be put in place, either instead of the ban, or to support producers in a gradual change of practices whilst waiting for the ban to be implemented.

From the point of view of economic theory, taxation is the most appropriate instrument because it allows negative externalities to be internalized into the price and the decisions made by farmers. If it is accompanied by a redistribution of the tax revenue to farmers, it can globally have a no effect on farmer incomes. One of the criticisms of the tax is that, given the low elasticity of pesticides (Skevas et al., 2013), extremely high tax levels are required to achieve a significant reduction. This is because there is no easily implementable substitute, even if herbicides are found to be more elastic, as mechanical alternatives are available. In the case of taxation, a targeted re-distribution of tax revenues to farmers is thus crucial to create leveraged effects on pesticide-use, and to increase the acceptability of pesticide taxes (Böcker et al., 2016; Jacquet et al., 2011). Furthermore, differentiated taxation schemes, according to the hazard associated with each pesticide, could be implemented to reduce risks caused by pesticide-use (Finger et al., 2017). A glyphosate tax with redistribution to support the adoption of alternatives could thus be a suitable option.

Among the public policies that may help to modify agricultural practices, the agri-environmental schemes (AES) are an important component of the European agri-environmental policy. One study shows how the adoption of AES by French winegrowers has contributed to a decrease in the use of herbicides within a range of 38 to 53% below usual consumption levels (Kuhfuss et al., 2018). This clearly indicates that support to compensate for additional costs is efficient.

Policy targets are critical tools for providing strong and persistent signals to all stakeholders. It is thus important to encompass all stakeholders across the food value chain in any future policies. Pesticide policies should thus be articulated with other policies that target the different issues, and by stakeholders involved in pesticide reduction (Möhring et al., 2020). In our case, labelling and information for consumers are part of the solution.

Conclusion

Our analyses show that the main difficulty for vine growers in the removal of glyphosate is the intra-row weeding of vines. We have shown that the additional cost of herbicide-free techniques averaged €250/ha, and varied from €12 to €550/ha, depending on the wine-producing area. The working time and the purchase of new equipment are the two main reasons for such additional costs. The remuneration of the workforce accounted for in the costs could be lowered if farmers or their family carry out certain farming operations themselves. Certain winegrowers already benefit from the possibility of promoting the non-use of chemical herbicides, either by means of an individual approach via a direct increase in the price per bottle of wine (independent winemakers), or by using a collective approach via environmental certification (specifications implemented by winemaking cooperatives).

In order to facilitate the transition towards a total glyphosate ban, we suggest three measures : 1) giving agro-industrial firms sufficient time to produce alternative mechanical tools; 2) strengthening governmental support to finance new investments; and 3) labelling the production methods that justify the associated higher prices for consumers.

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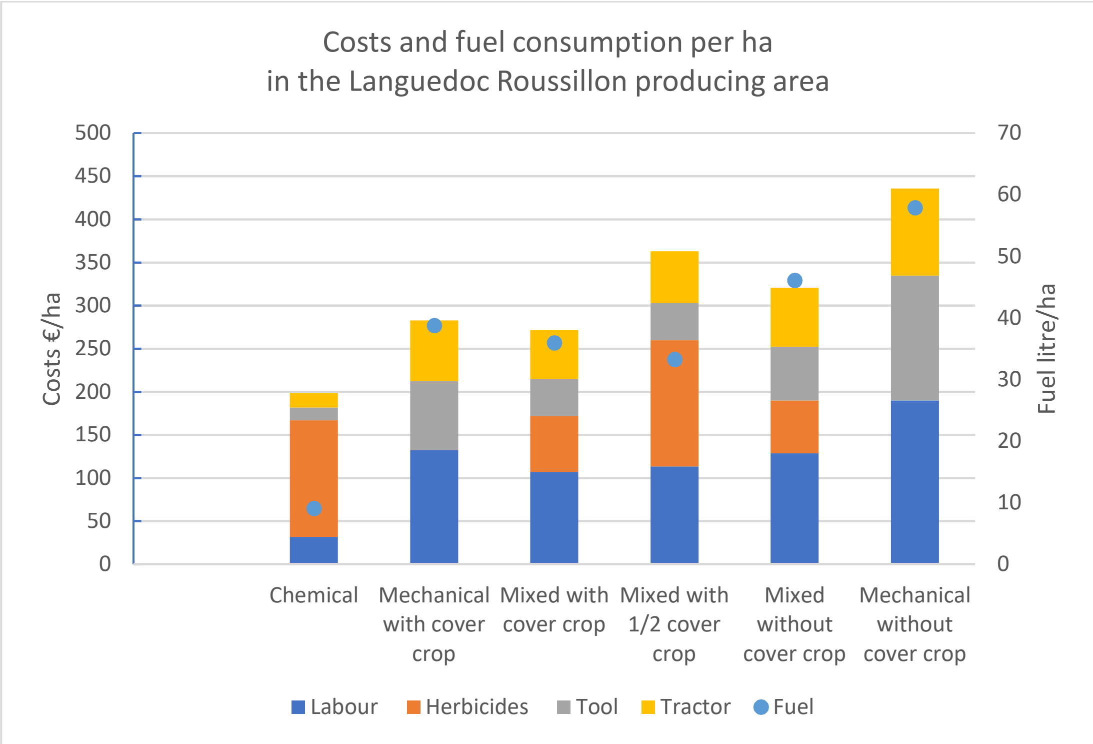

Costs and fuel consumption per ha
in the Languedoc Roussillon producing area
Costs €/ha
Fuel litre/ha
500
450
400
350
300
250
200
150
100
50
0
70
60
50
40
30
20
10
0
Chemical
Mechanical with cover crop
Mixed with cover crop
Mixed with 1/2 cover crop
Mixed without cover crop
Mechanical without cover crop
Labour
Herbicides
Tool
Tractor
Fuel