



Quantifying the impact of crop protection practices on pesticide use in wine-growing systems

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1 **Abstract**

2 Reducing pesticide use is a major challenge in agriculture, and farmers are
3 encouraged to develop integrated practices. The aim of this study was to describe,
4 analyse and assess the current contribution of various options to pest, disease and
5 weed management on the reduction of fungicides, herbicides and insecticides by
6 quantifying both their use and their effect on pesticide use intensity, within the
7 context of different wine-growing regions. We conducted a statistical analysis of
8 pesticide use and crop management over two seasons (2006 and 2010) for 11 French
9 wine-growing regions (10,000 data). We used the Treatment Frequency Index (TFI)
10 indicator to characterise the intensity of pesticide use. We analysed three crop
11 management options: timing of first fungicide spray, type of soil cover cropping, and
12 type of weed control. For each management option, we compared alternative or low-
13 input practices to normal chemical-based practices, e.g., mechanical weed control
14 (alternative option) vs. herbicide (normal chemical option). To strengthen the results,
15 two quantitative variables completed the analysis: fungicide mean sprayed dose in the
16 field and number of fungicides sprayed in the field. Results showed that each
17 alternative or low input practice had an impact on TFI, but that this impact differed
18 between wine-growing regions and between the management options under
19 consideration. Regarding fungicides, our results showed that late timing of first
20 fungicide spray (compared to regional reference) contributed to a reduction up to 50%
21 of the part of the TFI due to fungicides, as compared to fields sprayed at median or
22 early timing. Regarding herbicides, results of low-input/alternative practices were
23 more homogeneous in terms of their relative impact on TFI reduction. The differences
24 in use and impact of crop protection practices were more important between regions
25 than between the two studied years. Our results may help policy makers to target
26 methods for decreasing pesticide use, based on particularities of wine-growing

27 regions and locally realistic practices.

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31 Keywords: Treatment Frequency Index; fungicides; herbicides; assessment; *Vitis*
32 *vinifera* L.

1 Introduction

The reduction of pesticide use in agriculture is a major environmental and societal issue. Debates on pesticide use emerged at the end of the 1950s with the worldwide development of chemical-based intensive agriculture. Since then, an increasing number of studies have reported evidence of the negative impacts of pesticides on human health (Alavanja et al., 1996; EFSA, 2013), air (Bidleman and Leone, 2004; Gil and Sinfort, 2005), soil (Arias-Estévez et al., 2008; Riah et al., 2014), water quality (Gregoire et al., 2010; Vereecken, 2005), and on non-targeted organisms (Beketov et al., 2013). These risks have slowly been taken into account in public policies aimed at reducing pesticide use (e.g., in European countries, Barzman and Dachbrodt-Saaydeh, 2011).

In Europe, public incentives encourage farmers to reduce their pesticide use, promoting in particular the development of integrated pest management (IPM) (Lefebvre et al., 2014). IPM includes all practices based on the use of preventive methods, decision-making systems and non-chemical pest control to minimise pesticide use (Boller et al., 2004). Yet it remains only moderately developed in European intensive agriculture, except in orchard and greenhouse production (Lefebvre et al., 2014). Furthermore, for a given crop production, the adoption rate of IPM varies widely among countries (e.g. for strawberry production in Moser et al., 2008). Among the numerous causes of low adoption of IPM, one is often named: the need of extra workload and extra costs for monitoring (Beckmann and Wesseler, 2003). IPM practices are still little used also because of their irregular effectiveness. Indeed, it depends on the crop, the target pest, and on local factors (e.g., weather conditions).

Grapevine is mostly affected by fungi, with fungicides representing on that crop about 80% of the total pesticide use in France (Mézière et al., 2009). One could expect to

59 focus only on fungicides to tackle the problem with certainty and to cause an
60 important reduction of overall pesticide use. However, the other categories of
61 pesticides are of equal concern. In grapevine, herbicides represent a minor proportion
62 of overall pesticides, but their spraying on the soil directly contributes to the pollution
63 of surface and ground water in concentrations that may be high during rain events
64 (Louchart et al., 2001) and deleterious for human health and the environment
65 (CGDD/SOeS, 2014). Solutions for pesticide reduction use thus would need to be
66 found for each category of pesticide. These solutions are based on a change in
67 cropping practices, which will depend on the pesticide target (weeds, fungi, insects).
68 To decrease pesticide use, crop protection practices can be categorized as alternative
69 (i.e., replacing the use of a pesticide by a non-chemical practice, Petit et al., 2015) or
70 low-input (i.e, reducing the applied dose and/or the frequency of pesticide
71 application).

72 To cope with fungal diseases without the application of pesticides, farmers have
73 access to almost no alternative practices. The only practice that may cope with the use
74 of fungicide is the plantation of resistant cultivars. However such resistance can be
75 partial and target-specific (e.g., Wan et al., 2007), and resistant cultivars can display
76 lower wine quality (e.g., Ferreira et al., 2004), while cultivar cannot be changed
77 during the lifetime of the vineyard (i.e., at least 20 years). Most practices aimed at
78 reducing fungicide use (i.e., low-input) are based on Decision Support Systems (DSS)
79 (Bernard et al., 2010). The implementation of DSS makes it possible to act on (i) the
80 start and end dates for pesticide sprays during the vine-growing season, (ii) the
81 frequency of sprays in between and (iii) the spray volume and sprayed dose according
82 to density of vegetation. Regarding herbicides, some alternative practices to chemical
83 weeding have been developed such as its replacement by mechanical weeding or the
84 use of cover crops (Debaeke et al., 2009). Similarly, alternative practices exist to

85 minimise insecticide use, with the development of biocontrol products (e.g.,
86 pheromone-based products to prevent the proliferation of *Eudemis* grape moth larvae)
87 (Mézière et al., 2009).

88 Grapevine is grown in a wide range of pedoclimatic areas. In France, grapevine is
89 found from the Mediterranean to the Atlantic and in more continental climates. Wine-
90 growing conditions are strongly embedded in regional features (historical background,
91 production rules, ecological conditions etc.), so one hypothesis is to expect alternative
92 pesticide practices to replace current pesticide practices to differ among wine-growing
93 regions.

94 The effects of low-input and alternative practices to chemical control are mainly
95 assessed at the field and farm level, often through a cost-effectiveness approach
96 (Aven and Kørte, 2003; Hailu et al., 2005) or in terms of the overall impact of the
97 implementation of an IPM package on pesticide reduction in farms (Fernandez-
98 Comejo, 1998). But assessment of their use and impacts remains scarce at the regional
99 and national scales. As far as we know, no study has ever assessed the individual
100 impact of the practices constituting these packages at the scale of wine-growing
101 regions.

102 Based on the analysis of a French national database for the 2006 and 2010 seasons,
103 this study aims to describe and analyse the current patterns in pesticide use and
104 cropping practices for different French wine-growing regions. This study assesses the
105 contribution of ‘normal’ chemical practices, and alternative/low-input practices to
106 fungicide and herbicide use by quantifying both the use of these management options,
107 and the associated pesticide use intensity. Insecticide use is described in this study,
108 but the impact of cropping practices on its use is not included here, as the relevant
109 information was not sufficiently accurate in the studied database.

110

2 Material and method

2.1 Presentation of the French database on crop protection practices in viticulture

We used a database built by the French Ministry of Agriculture's Statistics and Prospective Service (SSP). This database is designed to survey and monitor cropping practices within the country. In viticulture, the surveys were conducted in the main French wine-growing regions for the 2006 and 2010 cropping seasons during the spring of 2007 and 2011, respectively. Vineyards with limited or dispersed areas were not surveyed.

The survey design followed a stratified random sampling of vineyard fields with two strata for each year: county (NUTS3) and wine designation (Protected Designation of Origin, Protected Geographical Indication, table wine, brandy). The samples differed in 2006 and 2010, but both were representative of French vineyards in terms of their surface area and cropping practices.

The surveys focused on practices over the full annual crop cycle, starting after the harvest of the preceding year and ending at harvest of the considered year (2006 or 2010). Information was gathered at the field scale on varieties, soil cover and weeding management, fertilisation, crop protection and harvest (Agreste, 2013; Agreste, 2006). Regarding crop protection practices, information on products, application time, number of sprays and sprayed doses were included.

2.2 Presentation of the studied wine-growing regions and years

Our analysis focused on 11 wine-growing regions surveyed in 2006 and 2010 (Figure 1), with 5,192 and 4,968 fields surveyed respectively. We removed 24 individuals in 2006 and 20 individuals in 2010 due to missing data, which represents less than 0.1% of the total data. In the database, the surface of each field was weighted by the SSP

for the sample to be representative of the overall wine-growing surface area for each considered year. Sampling was performed within a population stratified according to the vineyard region and the type of wine (Designation of Origin -AOP-, Protected Geographical Indication -IGP-, and table wine), defining sub-samples. For each sub-sample, the weight of each field was equal to the ratio between its surface and the probability of this field to be sampled (according to its surface). This weighting procedure is performed in order not to penalize small fields, and accordingly favour big fields. We thus used these weighted data for our analysis; by doing so, the data analysed represented 83% of the French vineyard area in 2006 and 2010.

Pest and disease attacks and pesticide use are closely linked with climatic conditions, especially rainfall (mm) and temperature (Celsius degrees). Mildew and powdery mildew are cryptogamic diseases so their development depends upon humidity and, as a consequence, rainfall during the vine-growing season. In particular, an increase of total rainfall or of number of rainy days favours the occurrence of these diseases. Pest pressure and climatic conditions were extracted from Meteo France's annual syntheses (<http://www.meteofrance.com/climat/france>) and from yearly regional reports (Grosman, 2010; Grosman et al., 2006). According to these syntheses, 2010 was wetter than 2006. Both years were intermediate in terms of rainfall conditions, compared to the climate records for the period 1971-2000. Focusing on the vine-growing season (from April 1st to September 30th), number of rainy days (Figure 1A) and total rainfall (Figure 1B) varied widely between wine growing regions in 2006 and in 2010. 2006 was more contrasted than 2010 in terms of number of rainy days but not in terms of total rainfall. Burgundy and Beaujolais regions get slightly higher amounts of total rainfall in 2010 than in 2006 while western regions get less rainfall in 2010. The average mean temperature during this period tended to be a little colder in 2010 compared to 2006 (Figure 1C), but both years were intermediate in terms of air

temperature conditions, compared to climate records for the period 1971-2000.

Figure 1 approximately here

The year 2006 was characterised by a cold and dry winter, which induced late disbudding, counteracted by a spring and summer with higher than average (1971-2000) mean monthly temperatures. Summer rainfalls were slightly above the seasonal average in northern wine-growing regions (from Charente to Alsace), while the south of France, especially Provence, experienced below seasonal average rainfalls. Downy mildew (*Plasmopara viticola*) had an impact mainly in Bordeaux vineyards, and was almost absent in Mediterranean regions (Provence, Languedoc and Eastern Pyrenees). Powdery mildew (*Uncinula necator*) pressure was medium compared to the 10 previous years but varied among regions, having the most impact in Charente and Languedoc vineyards, locally affecting the grape harvest.

The year 2010 was the coolest year in the period 1991 to 2010 (0.3°C below the average annual temperature), which induced late disbudding and late ripening in all regions (a delay of 10-15 days in Mediterranean regions and up to 15-20 days in northern wine-growing regions). Downy mildew had a greater impact in Mediterranean regions than it did in northern and Atlantic ones; it was unusually scarce in Champagne. The year 2010 was an average year compared to the 10 previous years for powdery mildew pressure, slightly lower than in 2006, with this fungus having its greatest impact in Mediterranean regions. Both years had relatively low insect pressure.

2.3 Pesticide use and crop protection management options

2.3.1 Characterisation of pesticide use: total and partial TFIs

The Treatment Frequency Index (TFI) indicator was used to characterise the intensity of pesticide use at field level, calculated as follows (Eq. (1)).

$$TFI = \sum_P ((Sp_Dose_P / Rec_Dose_P) \times (Sp_Area_P / Tot_Area_P))$$

Eq. (1): TFI indicator calculation (based on OECD, 2001; Pingault et al., 2009) where P is the pesticide product sprayed, Sp_Dose_P is the sprayed dose of product P , Rec_dose_P is the recommended dose per hectare, Sp_Area_P is the surface area on which the pesticide product was sprayed, and Tot_Area_P is the total surface area of the sprayed field. Recommended doses were retrieved from the national e-phy database (French Ministry of Agriculture Agribusiness and Fisheries, 2015). In the surveys, the pests or diseases targeted by farmers during each pesticide spraying were not identified. Then, when a commercial pesticide product was intended to control several pests or diseases, we used as the recommended dose the smallest approved dose for grapevine (which could lead to an overestimation of TFI).

In this study, we distinguished three partial TFIs, corresponding to: (1) herbicide products only (TFI_h), (2) insecticide and acaricide products only (TFI_i), and (3) fungicide products only (TFI_f). We also considered total TFI (TFI_{tot}), which corresponds to the sum of the three previous described TFI. Hereafter, insecticides and acaricides are both named ‘insecticides’.

2.3.2 Crop protection and soil management options

Four variables were built to characterise crop protection and soil management options for each field surveyed in 2006 and 2010.

2.3.2.1 Fungi-control management options

According to Equation (1), reducing fungicide use results from decreasing (1) the sprayed doses, and/or (2) the number of fungicides sprayed during the vine-growing season, the latter being achieved by increasing the delay between sprays (i.e., decreasing fungicide sprays frequency) or shortening the duration of fungicide spraying (delaying the date of first spray, or stopping fungicide spraying as soon as

possible).

As a preliminary analysis, we used two quantitative variables to explore variation of TFI_f : total number of fungicides spray in the field (“*total_fungi*” variable) and mean fungicide sprayed dose in the field (“*mean_dose*” variable). *Mean_dose* was estimated as the ratio of TFI_f divided by the total number of fungicides sprayed on the field throughout the cropping season.

Another variable was built to analyse timing of first fungicide spray (“*first_fungi*” variable) (Table 1), whose delay (with respect to local ‘normal/usual’ timing) may be associated with lower pesticide spray. The timing of the last fungicide spray was not considered here since it varied widely according to the date of grape harvest (and so depended on wine-growing regions and grape varieties) and to the pest pressure due to a pathogen, whose attacks occur at the end of berries’ ripening and greatly vary between wine-growing regions. In the database, pesticide spray dates were available only in a fortnightly format (i.e., two modalities for each month: the 1st-14th or the 15th-31th of each month). The timing of first fungicide spray ranged from the second fortnight of February to the first fortnight of August. *First_fungi* variable was classified in three modalities: *early*, *regular* or *late*. Timing was considered as “*regular*” if equal to the median fortnight, “*early*” or “*late*” if occurring respectively before or after the median fortnight. The median fortnight for the timing of first fungicide spray was the fortnight 1st-15th May for all wine-growing regions in 2006 and 2010; except Alsace where it was 16th-31st May in 2006 and 2010. In order to be able to compare regions, we used fortnight 1st-15th May to build the timing modalities for all regions.

2.3.2.2 Soil management options

Two variables were built to characterize the soil management options (Table 1). The

weed control practices (“*weed_control*” variable) could be *chemical* weeding only, *mechanical* weeding only or *mixed* weeding i.e. a combination of chemical and mechanical weeding over time and/or space. A temporal combination is a succession of mechanical and chemical operations through time; a spatial combination is a different type of soil management between alleyways and vine rows. The type of soil cover cropping (“*soil_cover*” variable) could be *permanent*, *temporary* or *bare soil*. *Permanent* modality was assigned if farmer kept permanent grass cover (either natural vegetation or sown species) for at least two years in alleyways. *Temporary* grass cover corresponded to natural vegetation controlled by the farmer during the winter and destroyed at the beginning of spring. If the field was not considered as having permanent nor temporary grass cover, it was assigned as being *bare soil*.

Table 1 approximately here

2.4 Statistical analyses

The effect of a given variable on the associated partial TFI was tested for each wine-growing region and each year by performing non-parametric Kruskal-Wallis rank tests. Each modality with less than five individuals (which represented up to 2.4% of the extrapolated surface area) for a given year and region was not considered for the analysis. The significance of Kruskal-Wallis tests was corrected using the Holm correction *post hoc* test, which is more powerful than the Bonferroni method commonly used (Aickin and Gensler, 1996).

Statistical analyses were achieved using the R software version 2.15.3 (R Core Team, 2013) and the R packages *Survey* (Lumley, 2012, 2004) and *Plyr* (Wickham, 2011). Maps were created with the R packages *GISTools* (Brunsdon and Chen, 2014), *maps* (Becker et al., 2013) and *rgdal* (Bivand et al., 2014). Spider charts were performed with the R package *plotrix* (Lemon, 2006), and boxplots with the R package *ggplot2* (Wickham, 2009, 2015).

3 Results

3.1 Total pesticide use at regional scale

The regional average of TFI_{tot} varied between 7 and 22 in 2006 and between 9 and 18 in 2010 (Figure 2A), with national averages of 12.9 and 13.0 in 2006 and 2010, respectively. Large variations in TFI_{tot} were observed within wine-growing regions for the two years studied. The ranking of wine-growing regions was similar between the two years, the lowest average TFI_{tot} being observed in Provence and the highest one in Champagne. The average TFI_{tot} was lower in 2010 than in 2006 in six wine-growing regions by 0.4 to 3.4, and higher in the other five wine-growing regions by 0.1 to 2.4.

Figure 2 approximately here

3.2 Impact of fungi-control management options on fungicide use intensity

Fungicides (TFI_f) were the pesticide sprayed with the largest quantities in all wine-growing regions (Figure 2B). Fungicides corresponded to 60%-89% and 69%-92% of TFI_{tot} in 2006 and 2010, respectively. Champagne was the wine-growing region with the highest average TFI_f value in both years. In Champagne, the lower average TFI_f in 2010 compared to 2006 related to better climatic conditions and lower pest pressure in 2010. In contrast, TFI_f was higher in 2010 than in 2006 in Provence and Beaujolais, partially due to worse climatic and pest pressure conditions in 2010 than in 2006 (Figures 1 A and B).

Total_fungi variable was strongly linked to TFI_f since it is directly involved in the construction of TFI_f . The total number of fungicides sprayed varied broadly between wine-growing regions, in a similar way as TFI_f but with higher variations (Figure 3).

Figure 3 approximately here

At the national scale, fungicides were sprayed on average at 0.9 ± 0.2 times the recommended dose. About 75% of the wine-growing surface area had a fungicide mean sprayed dose lower than the recommended dose ($\text{TFI}_f < 1$). However, Beaujolais, Burgundy and Champagne stood out with regional medians slightly above 1 (Figure 4).

Figure 4 approximately here

The timing of first fungicide spray was fairly homogeneous between wine-growing regions for both years. At the national scale, more than half of the surface area was on *regular* timing; and a quarter as *early* timing, based on regional references, and for the two years (Figure 5A, Appendix A). *Late* timing led to a significant reduction in the TFI_f at the national scale, down to 7.5 ± 3.8 in 2006 and 9.2 ± 3.5 in 2010 (Table 2), which was significantly lower (by 16% to 30% depending on years) compared to *regular* or *early* timing. On the contrary, TFI_f associated to *early* and *regular* timing were not statistically different at the national scale.

At the regional scale, most of the vineyards received their first fungicide at *regular* period in 2006 and 2010 (Figure 5A, Appendix A). The later the first fungicide was sprayed, the lower the TFI_f was, whatever the region and year (Table 2). TFI_f was always significantly lower for *late* timing compared to *early*, with a decrease ranging between 16% and 50% (Burgundy in 2006 and Centre in 2010, respectively). TFI_f reduction comparing *late* to *regular* timing ranged from 11% to 39% for both years. *Regular* timing tended to reduce TFI_f when compared to *early*, but the reduction was significant for only half of the region-year couples, and was always lower than 20%.

Table 2 approximately here

3.3 Impacts of soil management options on herbicide use intensity

Herbicides (TFI_h) accounted for 6.5 to 11.5% and 3.7 to 10.8% of TFI_{tot} according to the wine-growing regions in 2006 and 2010, respectively (Figure 2C). Herbicides

were, on average, less used in drier regions (Eastern Pyrenees, Languedoc, Provence and Alsace).

Mixed weed_control was the leading practice for the two years, representing 70.6% and 65.9% of the national surface area in 2006 and 2010, respectively. *Mechanical weed_control*, thus without herbicide, represented 10% of the national surface area in 2006, but tripled in 2010 (Figure 5B, Appendix A). At the national scale, the TFI_h value associated with *mixed weed_control* (1.0 ± 0.7 in 2006 and 0.7 ± 0.6 in 2010) was significantly lower than for *chemical weed_control* (1.6 ± 0.9 in 2006 and 1.6 ± 0.8 in 2010 (Table 3).

Four wine-growing regions used only chemicals for *weed_control* in 2006 on the very large majority of the surveyed fields (Beaujolais, Champagne, Centre and Loire Valley), with the Centre and Loire Valley shifting part of their surface area to *mixed weed_control* in 2010 compared to 2006 (20 and 25% respectively). The surface area managed with *mechanical weed_control* was very diverse between wine-growing region, ranging from 3% to 21% in 2006 and from 6% to 36% in 2010. The average TFI_h values associated with the *chemical* or *mixed weed_control* varied greatly between wine-growing regions. Indeed, TFI_h ranged from 0.9 ± 0.6 to 2.0 ± 0.9 for chemical in both years and from 0.5 ± 0.5 to 1.4 ± 0.8 for *mixed weed_control*, in both years. Variations of TFI_h values within wine-growing regions were also broad (standard deviations up to 68% of TFI_h). Areas under *mixed weed_control* practices received from 6% less to half less pesticides than areas under *chemical weed_control* (Burgundy in 2006 and Languedoc in 2010, respectively, Table 3).

Regarding soil_cover cropping, *permanent soil_cover* represented about one-third of the national surface area in both years. *Bare soil* represented 40% and 51% in 2006 and 2010, respectively, while the *temporary soil_cover* surface area was 23% in 2006 and 12% in 2010. TFI_h values tended to be lower in this order: *permanent* < *temporary*

< *bare soil*.

The use of soil cover practices differed between regions. *Permanent soil_cover* was prevalent in Alsace, Bordeaux and Charente for the two years (Figure 5B, Appendix A). *Bare soil* was the most common option in the Eastern Pyrenees, Champagne, Beaujolais, Languedoc and Provence in 2006 and 2010, and in Centre and Burgundy in 2010 only. *Temporary soil_cover* management was the least common (except for Burgundy in 2006), and decreased in all wine-growing regions (except in Alsace and Eastern Pyrenees, involving a small surface area) between 2006 and 2010, while the surface area with *bare soil* increased. Fields with *permanent soil_cover*, as compared to *bare soil*, had a significantly lower TFI_h value (between -16% and -56 % of TFI_h in 2006, in Languedoc and Centre, respectively, Table 3). TFI_h values were also significantly lower under *temporary soil_cover* management as compared to *bare soil* management in most wine-growing regions and years, except in Charente and Bordeaux in 2006.

Table 3 approximately here

3.4 Insecticide use intensity

Insecticides (TFI_i) accounted, depending on the wine-growing region, from 4% to 30% and from 3% to 26% of TFI_{tot} in 2006 and 2010, respectively (Figure 2D). Charentes, Languedoc and Eastern Pyrenees were the wine-growing regions with the most intensive insecticide spray, while Burgundy and Provence used less insecticide spray (average TFI_i value lower than 0.7 in both years).

4 Discussion

4.1 Impact of crop protection management options on pesticide use reduction

In our study, we explored four pathways for pesticide use reduction in wine growing systems. Our results showed that each alternative practice had an impact on TFI, but

that this impact differed between wine-growing regions and between the management options under consideration. We discuss below the impact and use of alternative practices, by pesticide category.

4.1.1 Fungicides

Our results showed that TFI_f was strongly linked with the total number of fungicides sprayed. Timing of first fungicide spray was the only management option analysed to act on a reduction of number of fungicides sprayed. Postponing the first fungicide spray was proved to significantly reduce fungicide use, up to 50 % of TFI_f , as compared to fields sprayed at median or early timing. These results are consistent with the observations made when the Mildium® DSS method was implemented in experimental fields (Delière et al., 2015). Mildium® gives indications to spray (at recommended doses) in relation with climatic conditions and some sensitive phenological stages of the vines (i.e. flowering) combined with a predictive model of mildew attacks. It has been shown that the implementation of this type of DSS could lead to a 50% reduction in fungicide spray, with a low impact on yield in average pest pressure years (Delière et al., 2015). Nevertheless, it could be argued the Mildium® DSS shall be valid at field scale, but cannot be applied at the farm level with the same accuracy, as was the case in experimental fields. Research is in progress concerning the way to apply Mildium® at the farm level (Delière et al., 2015) but the results are not yet sufficiently established for guiding farmers towards this lever.

The variable *mean_dose* in our study provided another insight on farmers pesticides use, as it suggested the occurrence of both overdosing and underdosing fungicides practices. It is important to note that recommended dose is set at national level for each pesticide type of use, and rules are uneven between countries (Codis et al., 2012). While in Germany or Switzerland for example, recommended dose is adjusted depending on density of vegetation, in France the recommended dose is set

independently of such considerations. Overdosing could be an artefact of TFI_f calculation, due to a possible underestimation of recommended doses used in our study. Yet, overdosing practices have been observed by Aubert et Enjolras (2014); and they analysed the determinants of such behaviours in viticulture. On the other hand, under-dosing of fungicide has recently been promoted and advised to farmers in many wine-growing regions in Europe, including France, with the use of a DSS computer model (Davy et al., 2010; Gil et al., 2011; IFV, 2015). The DSS tool Optidose® helps farmers estimate the most adapted dose to spray on each application for powdery and downy mildew, taking into account the vine phenological stage, leaf area of the vine to be treated, disease pressure and field sensitivity. In experimental situations, this DSS tool can lead to a drop of 40-50 % of fungicide use over the entire crop season compared to the farmers' usual spraying practices for these two main diseases (Davy et al., 2010). On the contrary, other scientific studies warn against possible resistance phenomena, which could be favoured by under dosing (e.g., Gressel 2011).

Our results allow us to classify the wine-growing regions in three categories, strongly related with climatic conditions. In the wine-growing regions with high TFI_f values (Champagne, Burgundy and Beaujolais), both mean pesticide sprayed doses and total number of fungicides were high, while the timing of first spray was relatively homogeneous. These regions were also those with wetter climatic conditions during the vine-growing season (number of rainy days, total rainfall). The other regions used with different intensities the three levers (i.e., timing of first fungicide spray, reduced dose and reduced number of spray events). The Mediterranean regions, as well as Alsace, Centre and Loire Valley were the regions with the lowest median number of fungicides sprayed (this contributed to their low average TFI_f value); and correspond to regions with drier climate (in particular, less rainfall). Regions under Atlantic

climate (Charente and Bordeaux) can be grouped as intermediate category, both in terms of rainfall conditions, and use of fungi control management options. However, if climate, and essentially rainfall, can explain different regional profiles in terms of fungicide spray, the results obtained in Alsace (humid climate and low TFI_f) demonstrate that other reasons should be considered, as for instance the varieties, targeted yields, planting density and inter-row width, slopes etc. Unfortunately, our database did not offer the possibility of investigating such questions.

4.1.2 Herbicides

In contrast to fungicides, herbicides can be excluded or strongly reduced in vineyards, as effective alternative strategies already exist. Herbicides can be replaced by *mechanical weed_control* or by *permanent* or *tempory soil_cover*.

Our results showed that the use of *permanent* or *tempory soil_cover* and *mechanical weed_control* led to a decrease of 50% and more in TFI_h. *Chemical weed_control* only was commonly used in regions with wet climate conditions, such as Champagne and Beaujolais, whereas it was scarce in Mediterranean areas (Languedoc and Provence). However, this climatic characteristic cannot explain all the differences as some wine-growing regions with similar climate conditions to Champagne and Beaujolais made larger uses of *mechanical* and *mixed weed_control* (typically Burgundy and Alsace). At this point it is necessary to stress the influence of the field slope and the plantation structure: it is much more challenging to use *mechanical weed_control* in vineyards with steep slopes and in higher density plantations with narrow alleyways (i.e. 90% of Beaujolais vineyards are planted with more than 8,500 vines per hectare, while 85% of Languedoc's vineyards are planted with less than 4,500 vines per hectare (source: SSP database).

Regarding *soil_cover* cropping, the Mediterranean wine-growing regions tended to present mostly *bare soils*, in order to avoid water and nitrogen competition with

weeds in arid conditions (Celette and Gary, 2013). *Permanent or temporary soil_cover* was also very little implemented in Champagne, for example, while widely spread in Alsace: the plantation structure (density and inter-row width) as well as yield objectives higher in Champagne may explain these differences.

4.2 Variability of practices within time and space

In this study, we analysed normal, alternative and low-input practices. Other practices can indirectly contribute to decrease pesticide spray. For example, techniques of canopy management (cluster thinning, pruning, shoot trimming, etc.) are often applied to control grape yield and quality. They can also contribute to prevent damage from fungi attacks (i.e., (i) the effect of cluster thinning on botrytis, e.g., Spring & Viret, 2009; (ii) the effect of grapevine training systems on powdery mildew, e.g., Zahavi et al., 2001). However, as the primary objective associated to these practices for farmers is not necessarily preventing pests and diseases, these techniques are not automatically associated with fungicide spray reduction. For example, repeated shoot trimming may represent more a reaction to rapid vegetative growth, which favours fungi attacks (Valdés-Gómez et al., 2011, 2008) than an explicit lever to reduce pesticide spray.

For fungicides, we noticed very small differences between 2006 and 2010 in terms of the relative proportions of the practices under study (and this for each growing region). Pesticides spray differed more between regions than between years. Similarly, the impacts of the studied crop protection practices tended to be quite similar in both years for each region. Considering the similarity of these two years in terms of climate and pest and disease pressure, one may conclude that there was no evolution in the studied farmers' practices related to fungicide and insecticide spray between these two years.

In the case of herbicides, more substantial changes were detected between 2006 and 2010 (more *mechanical weed_control*). This evolution was certainly due to public policies (incentives) aiming at tackling the problem of water catchments being mainly contaminated by herbicides (Biarnès et al. 2012). To explain the prominence of regional variability, it is necessary to recall that wine production is strongly embedded in regional features. This is not only due to particular ecological conditions, but also to long historical backgrounds, know-how, statements of regional identity and peculiar rules (technical norms for grape and wine production in ‘Protected Designation of Origin’); all of this being shaped in the concept of ‘terroir’ (van Leeuwen and Seguin, 2006). In each wine-growing region, a very large diversity of ‘terroirs’ exist and this could explain the great variability of the crop protection practices observed (Goulet and Morlat, 2011).

4.3 Potential limitations

The first limitation to our results concerns the exclusion of alternative practices regarding insecticide control, due to the inaccurate information on the use of alternative biocontrol products in the studied database. However, the use of insecticide can also be omitted in case of low insect pressure, leading to vines suffering little damage. Moreover, the wine-growing regions considered in this study were not submitted to similar insect pressure, which may even largely vary inside a wine-growing region. Farmers face two main pests: grape berry moths and leafhoppers, the latter being the vector of the phytoplasma agent of grapevine ‘flavescence dorée’. Treatments against leafhoppers may be compulsory by law in areas where grapevines are affected by the disease (as is the case in Languedoc, Provence, Eastern Pyrenees and Charente). For each pest, two or three successive sprays may be necessary to cope with the problem and, as a consequence, regions or sub-regions where both pests are present may yield a TFI_i value of 4 to 6 (and 0 in

regions where no insects are detected at all, i.e., in Alsace). Even if, in general, farmers try to use multi-purpose insecticides to control both insects simultaneously, this uneven insect pressure could explain the large differences in TFI_i between wine-growing regions as found in this study. Therefore, developing alternatives to insecticides is important for some areas of wine-growing regions, especially as broad-spectrum insecticides are very harmful for the environment. In our study we could not investigate uses and effects of biocontrol pesticides products (notably we could not look at pheromone-based products), and further studies with a proper database are needed because these alternatives seem to be promising to further reduce insecticide uses (e.g., Oliva et al., 1999; Trimble et al., 2003).

The second main limitation also concerns the type of data provided in the studied database, which includes only the description of individual cropping practices for two discontinuous years. No information on the global strategy of the farmer was available, so we had to define classes of practices, thus hypothesizing low-input practices with regards to their regional context (e.g., for fungicide), without being able to link it to the use of a Decision Support System, or to a real choice of the farmer for practices leading to a lower use of pesticides. Such information would be difficult and time-consuming to gather, given the very large number of field surveyed. However, our results showed that the use of such practices actually lead to a lower intensity of pesticide use, and call for a more comprehensive large-scale assessment of farmers' strategy regarding crop protection practices.

5 Conclusion

We used simple statistical analyses to explore a large national dataset. Our results suggest that the relative use and impact of each analysed practice tended to differ more between wine-growing regions than between years. Although further analysis would be necessary to explore the determinants of these variations with a sample of

this dataset, our results already showed that the use of effective methods to decrease pesticide use differed among wine-growing regions. Such results could be used to adapt national policies targeting the reduction of pesticide spray to local specificities, in order to promote methods that are both locally effective and realistic.

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Figure 1
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Figure 1. Location of the 11 wine-growing regions studied and number of rainy days (A), amount of rainfall (mm) (B) and average mean temperature (celsius degrees) (C) during the growing period (from April 1st to September 30th) in 2006 and 2010. Data extracted from the INRA Climatik platform.

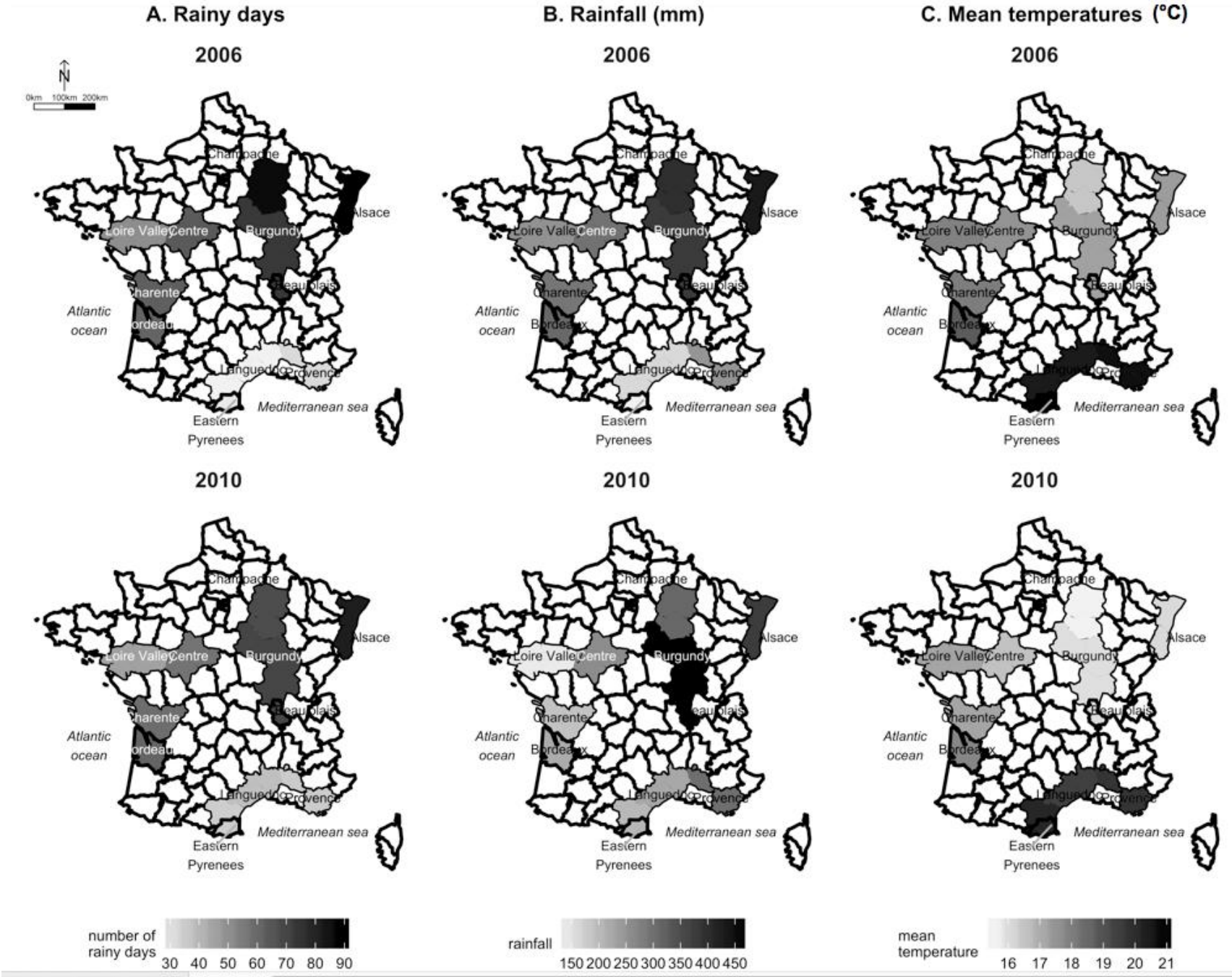


Fig.2 A,B,C,D
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Figure 2. Boxplots of TFI_{tot} (A), TFI_f (B), TFI_h (C), and TFI_i (D) in 2006 (grey box) and 2010 (white box) in the 11 studied French wine-growing regions. Outliers are not represented. Whiskers display the 5th and 95th percentiles, horizontal bars indicate first quartile, median and third quartile.

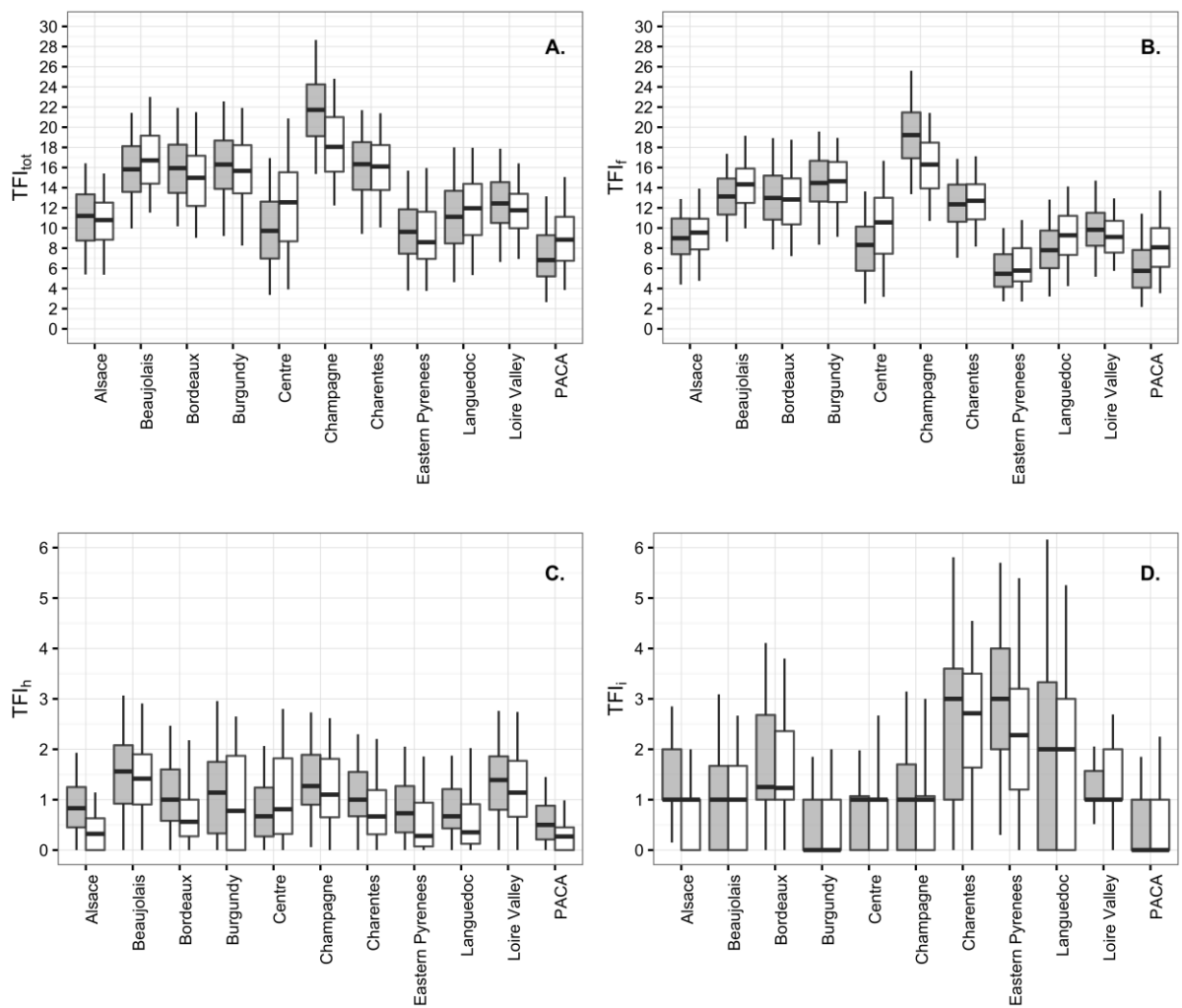


Figure 3
[Click here to download Figure: fig.3_v3_vf.doc](#)

Figure 3. Boxplot of total number of fungicides sprayed in 2006 (grey box) and 2010 (white box) in the 11 studied French wine-growing regions. Outliers are not represented. Whiskers display the 5th and 95th percentile, horizontal bars indicate first quartile, median and third quartile.

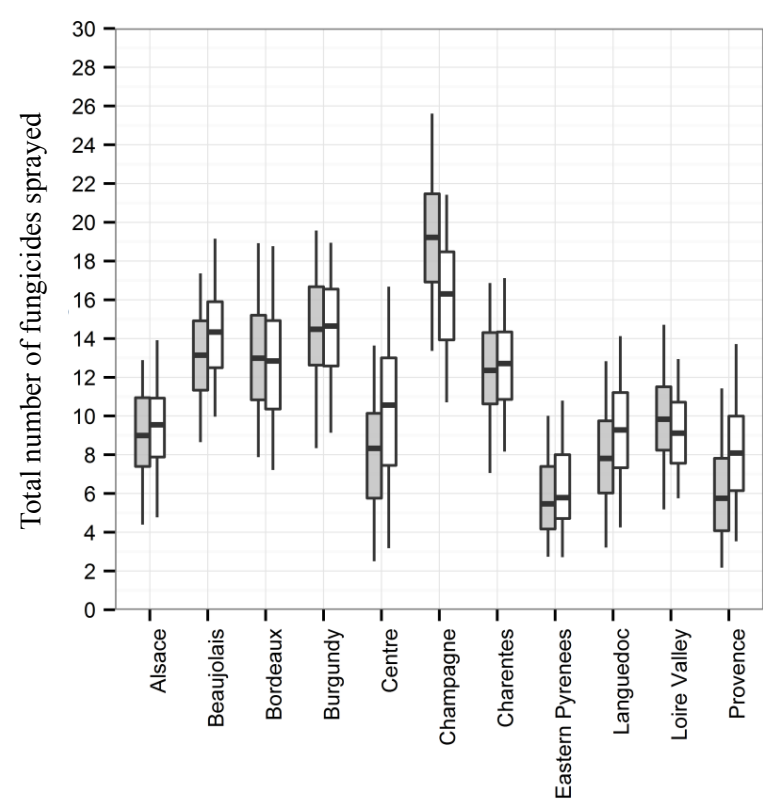


Figure 4
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Figure 4. Boxplot of fungicide mean sprayed doses in 2006 (grey box) and 2010 (white box) in the 11 studied French wine-growing regions and at national scale. Outliers are not represented. Whiskers display the 5th and 95th percentiles, horizontal bars indicate first quartile, median and third quartile. *Mean_dose* was estimated as the ratio of TFI_f divided by the total number of fungicides sprayed on the field throughout the cropping season.

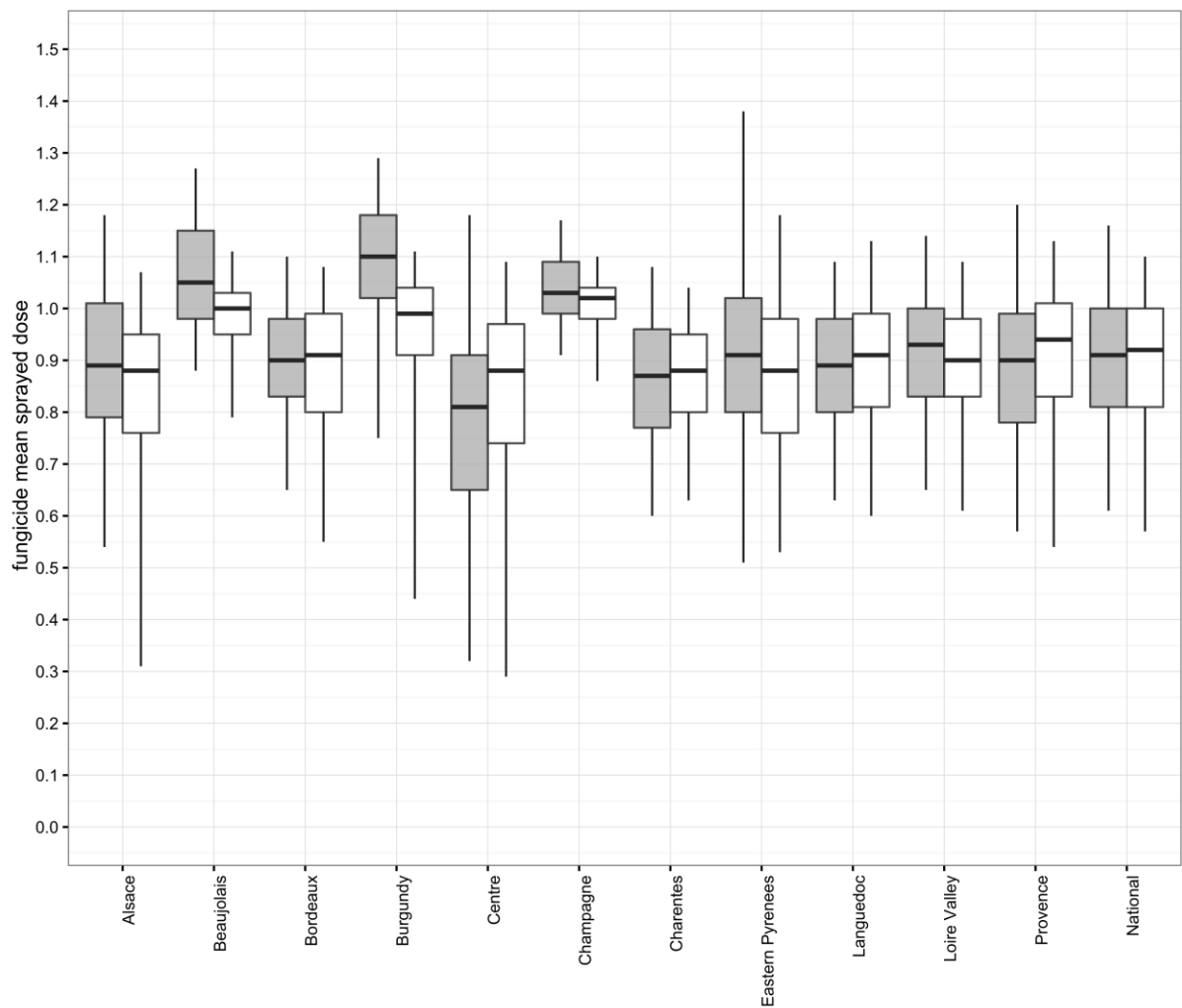


Figure 5
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Figure 5. Proportion of use of the practices related to fungicides (A) and herbicides (B and C) management in the 11 wine-growing regions in 2006 and 2010 (see Appendix 1 for the numbers of data cases). Data are expressed as a fraction of the total regional area cultivated with grapevine (see Table 1 for variable definition).

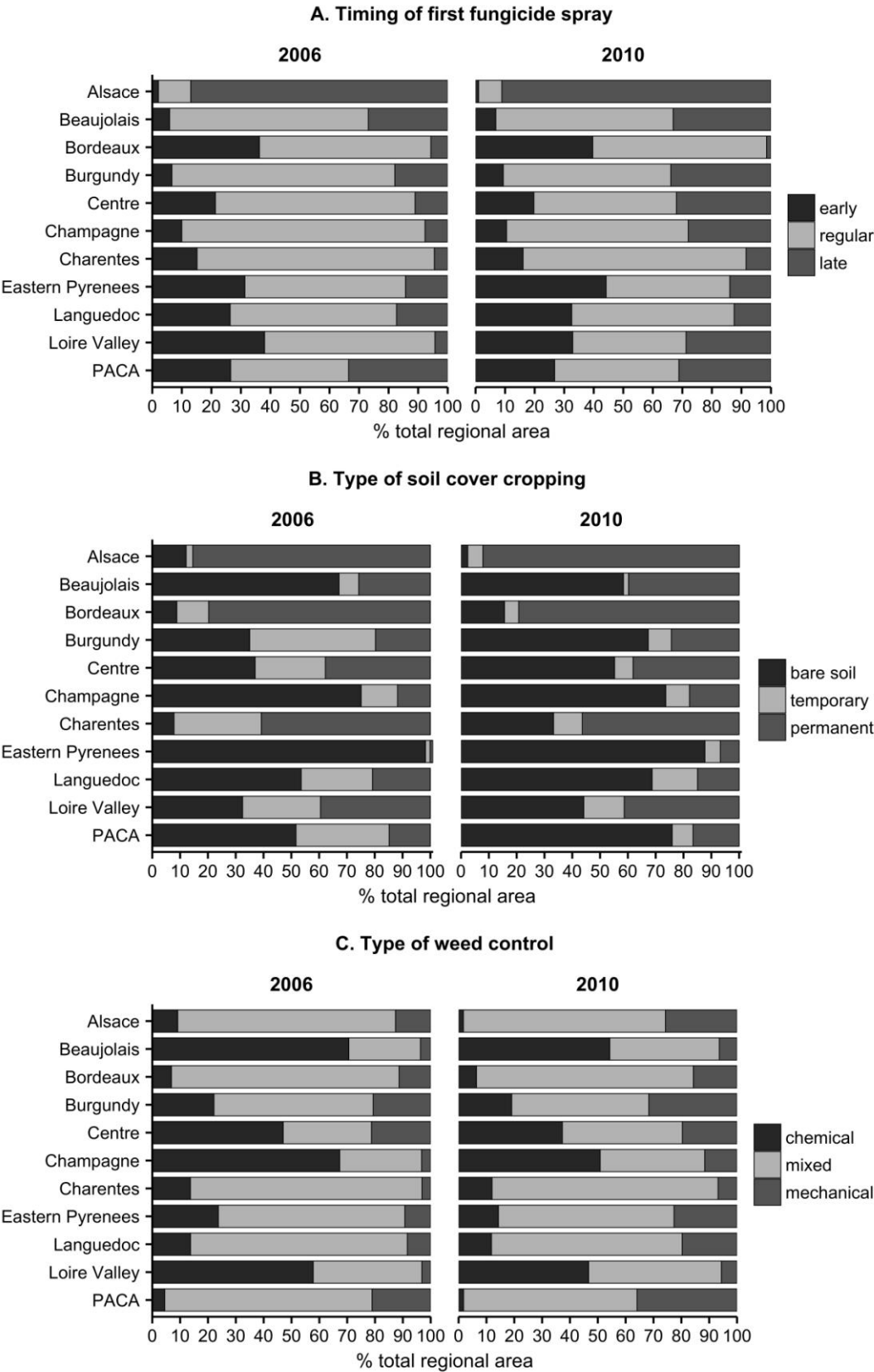


Table 1

Table 1. Characteristics of the variables potentially impacting pesticide use

Type of pesticide	Variable name	Variable description	Modality	Modalities description
Fungicides	first_fungi	timing of first fungicide spray	early	Early timing of first fungicide spray (i.e., before the regional median fortnight)
			regular	Regular timing of first fungicide spray (i.e., at the regional median fortnight)
			late	Late timing of first fungicide spray (i.e., after the regional median fortnight)
	mean_dose	mean fungicide spray dose	<i>quantitative variable (unitless: relatively to recommended dose)</i>	
Herbicides	total_fungi	Total number of fungicides spray in the field	<i>quantitative variable (number)</i>	
	weed_control	type of weed control	chemical	Chemical weeding only (alleyways and/or vine rows)
			mechanical	Tillage only (alleyways and/or vine rows)
			mixed	Chemical weeding associated with tillage in time or space (alleyways and/or vine rows)
	soil_cover	type of soil cover cropping	permanent	Soil of the vineyard covered by native or sowed grass during all the year
			temporary	Soil of the vineyard covered by native or sowed grass during part of the year only
			bare soil	Bare soil

Table 2

Table 2. Values of TFI_f (mean \pm standard deviation) related to the timing of first fungicide spray in 2006 and 2010 by wine-growing region.

Wine-growing region	Year	<i>Early</i>	<i>Regular</i>	<i>Late</i>	<i>Regular versus early</i> pvalue	<i>Late versus early</i> pvalue	<i>Late versus regular</i> pvalue
National	2006	10.6 \pm 4.5	10.6 \pm 4.4	7.5 \pm 3.8	NS	***	***
	2010	11.3 \pm 4.1	11.0 \pm 3.8	9.2 \pm 3.5	NS	***	***
Alsace	2006	9.67 \pm 2.9	9.69 \pm 2.3	7.72 \pm 2.1	NS	***	***
	2010	9.36 \pm 2.7	9.86 \pm 2.7	8.64 \pm 2.5	NS	**	NS
Beaujolais	2006	13.8 \pm 2.7	13.6 \pm 2.6	11.8 \pm 2.5	NS	**	***
	2010	16.7 \pm 3.0	14.7 \pm 3.1	13.2 \pm 1.9	**	***	***
Bordeaux	2006	14.4 \pm 3.8	12.5 \pm 2.9	10.6 \pm 3.4	***	***	***
	2010	14.1 \pm 3.9	11.8 \pm 2.9	8.0 \pm 3.3	***	***	***
Burgundy	2006	15.1 \pm 3.5	14.8 \pm 3.2	12.7 \pm 3.1	NS	***	***
	2010	16.3 \pm 2.9	14.7 \pm 3.3	13.1 \pm 3.2	***	***	***
Centre	2006	9.7 \pm 3.7	8.0 \pm 3.0	4.9 \pm 2.5	*	***	***
	2010	10.9 \pm 4.1	10.9 \pm 3.7	9.1 \pm 3.7	NS	*	**
Champagne	2006	20.8 \pm 3.6	19.3 \pm 3.5	17.2 \pm 5.0	**	**	***
	2010	18.3 \pm 3.0	16.9 \pm 3.0	14.0 \pm 2.6	**	***	***
Charentes	2006	13.1 \pm 3.3	12.3 \pm 2.8	9.3 \pm 3.5	**	***	***
	2010	13.5 \pm 2.7	12.7 \pm 2.6	10.2 \pm 3.3	*	***	***
Eastern Pyrenees	2006	6.0 \pm 2.6	6.1 \pm 2.2	4.8 \pm 2.9	NS	*	**
	2010	6.7 \pm 3.3	6.2 \pm 2.3	5.8 \pm 1.8	NS	NS	NS
Languedoc	2006	8.8 \pm 2.7	8.2 \pm 2.9	6.5 \pm 2.6	NS	***	***
	2010	10.0 \pm 3.0	9.3 \pm 2.8	7.7 \pm 2.3	*	***	***
Loire Valley	2006	10.1 \pm 2.9	9.9 \pm 2.8	8.3 \pm 3.2	NS	*	*
	2010	9.4 \pm 2.3	9.2 \pm 2.3	8.9 \pm 2.1	NS	NS	NS
Provence	2006	7.0 \pm 3.7	6.5 \pm 2.9	5.1 \pm 2.4	NS	***	***
	2010	9.9 \pm 3.4	8.2 \pm 3.1	7.1 \pm 2.3	***	***	***

*p<0.05, **p<0.01 and *** p<0.001. NS: non-significant difference.

Table 3

Table 3. Values of. TFI_h (mean \pm standard deviation) related to soil cover cropping and weed management practices in 2006 and 2010 by wine-growing region.

Wine-growing region	Year	Soil cover						Weeding			
		<i>bare soil</i>	<i>permanent</i>	<i>temporary</i>	<i>permanent versus temporary</i> p.value	<i>permanent versus bare soil</i> p.value	<i>temporary versus bare soil</i> p.value	<i>chemical</i>	<i>mecanical</i>	<i>mixed</i>	<i>mixed versus chemical</i> p.value
National	2006	1.1 \pm 1.0	1.0 \pm 0.7	1.2 \pm 1.0	**	NS	***	1.6 \pm 0.9	0.0 \pm 0.1	1.0 \pm 0.7	***
	2010	1.0 \pm 0.9	0.7 \pm 0.6	0.6 \pm 0.7	***	NS	***	1.6 \pm 0.8	0.0 \pm 0.1	0.7 \pm 0.6	***
Alsace	2006	1.3 \pm 1.0	0.8 \pm 0.6	0.7 \pm 0.9	NS	NS	NS	1.5 \pm 0.8	0	1.0 \pm 0.5	***
	2010	0.2 \pm 0.4	0.4 \pm 0.4	0.0 \pm 0.1	NS	NS	NS	-	0	0.5 \pm 0.4	-
Beaujolais	2006	1.7 \pm 0.8	1.2 \pm 0.8	1.3 \pm 0.9	NS	***	*	1.7 \pm 0.8	0.0 \pm 0.1	1.3 \pm 0.7	***
	2010	1.7 \pm 0.8	1.2 \pm 0.8	0.6 \pm 0.9	*	***	**	1.8 \pm 0.7	0	1.3 \pm 0.7	***
Bordeaux	2006	0.8 \pm 1.2	1.2 \pm 0.8	1.4 \pm 1.2	NS	***	**	1.8 \pm 1.0	0.0 \pm 0.1	1.3 \pm 0.8	***
	2010	1.1 \pm 1.1	0.7 \pm 0.6	0.5 \pm 0.5	NS	NS	NS	1.7 \pm 0.9	0.1 \pm 0.2	0.8 \pm 0.6	***
Burgundy	2006	1.3 \pm 0.9	0.9 \pm 0.7	1.1 \pm 0.9	NS	***	*	1.5 \pm 0.7	0	1.4 \pm 0.8	NS
	2010	1.0 \pm 1.0	0.8 \pm 0.7	0.6 \pm 0.8	NS	NS	*	1.5 \pm 0.8	0	1.2 \pm 0.8	**
Centre	2006	1.1 \pm 0.9	0.5 \pm 0.4	0.9 \pm 0.8	NS	***	NS	1.2 \pm 0.8	0	0.8 \pm 0.4	***
	2010	1.4 \pm 1.1	0.7 \pm 0.6	0.5 \pm 0.8	NS	***	**	2.0 \pm 0.9	0	0.8 \pm 0.5	***
Champagne	2006	1.6 \pm 0.8	0.8 \pm 0.7	1.3 \pm 0.7	***	***	*	1.6 \pm 0.8	0	1.2 \pm 0.7	***
	2010	1.4 \pm 0.8	0.8 \pm 0.8	1.0 \pm 0.8	NS	***	**	1.5 \pm 0.7	0.0 \pm 0.1	1.2 \pm 0.7	***
Charentes	2006	1.3 \pm 0.8	1.0 \pm 0.5	1.6 \pm 1.0	***	NS	NS	1.9 \pm 0.9	0	1.1 \pm 0.6	***
	2010	1.2 \pm 0.8	0.7 \pm 0.6	0.6 \pm 0.5	NS	***	***	1.6 \pm 0.8	0.0 \pm 0.0	0.8 \pm 0.6	***
Eastern Pyrenees	2006	0.9 \pm 0.8	0.7 \pm 0.7	-	-	-	-	1.2 \pm 0.7	0	1.0 \pm 0.8	NS
	2010	0.6 \pm 0.6	0.5 \pm 0.9	0.1 \pm 0.1	NS	NS	***	1.3 \pm 0.6	0	0.6 \pm 0.6	***
Languedoc	2006	0.9 \pm 0.8	0.8 \pm 0.6	1.2 \pm 1.0	***	NS	***	1.5 \pm 1.0	0.0 \pm 0.2	0.9 \pm 0.7	***
	2010	0.7 \pm 0.8	0.5 \pm 0.5	0.6 \pm 0.7	NS	NS	NS	1.7 \pm 0.9	0.0 \pm 0.1	0.6 \pm 0.6	***
Loire Valley	2006	1.7 \pm 0.8	1.0 \pm 0.6	1.7 \pm 0.8	***	***	NS	1.7 \pm 0.8	0	1.2 \pm 0.7	***
	2010	1.7 \pm 0.9	0.9 \pm 0.5	1.1 \pm 0.7	NS	***	***	1.7 \pm 0.8	0	1.0 \pm 0.6	***
Provence	2006	0.6 \pm 0.6	0.6 \pm 0.5	0.6 \pm 0.5	NS	NS	NS	0.9 \pm 0.6	0.0 \pm 0.0	0.8 \pm 0.5	NS
	2010	0.3 \pm 0.5	0.4 \pm 0.4	0.2 \pm 0.3	NS	NS	NS	0.9 \pm 0.7	0	0.5 \pm 0.5	NS

“-“ less than 5 individuals were in this modality

*P<0.05, **P<0.01 and *** P<0.001. NS: non-significant difference.

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