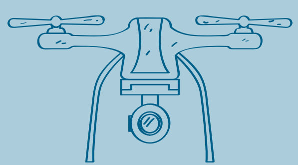
FARM EUROPE

LEVERAGING A TRANSITION

TOWARDS MORE SUSTAINABLE WINEGROWING SYSTEMS



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Farm Europe is a multi-cultural think tank founded in 2014 that aims to stimulate reflection on the EU's rural economies. Among the different departments of the think tank, the Wine Institute focuses its work on the coherence between the evolutions taking place within the wine ancesector and the public policies implemented at the European level.

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Executive summary

To address climate and environmental issues, the EU offers to establish a "Green Deal" for the European Union, with proposed measures targeting various economic sectors, including agriculture. To achieve climate neutrality by 2050, the Commission would like agriculture to be carbon neutral by 2035 and then compensate some of the emissions from other sectors.

In this context, the Farm 2 Fork and Biodiversity strategies encourage to reduce pesticide use by 50% and fertilizer use by 20% by 2030. They suggest that 25% of agricultural land should be farmed organically and that high-diversity landscape elements should cover 10% of agricultural land.

However, the strategies, as proposed by the Commission, would lead to an average drop in yields of 5%, a drop in European agricultural production of 10 to 15% depending on the sector, a reduction in exports of 20%, a drastic increase in imports and a drop in agricultural income of 8 to 16% (depending on the impact studies carried out). The study made by the Commission's research department (JRC) also confirms these results, even with the hypotheses of artificially limiting imports and 60% of farms using precision farming in 2030. The latter hypothesis suggests massive investments to be made by sectors that would see their revenues shrink. The The estimated environmental benefits are tenuous or non-existent at the cost of socially and economically onerous decrease.

Such consequences could be dramatic for the European wine sector, which employs more than 2.5 million people and occupies 5.6% of European agricultural land, particularly in areas where few other economies can develop.

Not only are they likely to jeopardize Europe's place on the world market, but they would have a significant impact on the living conditions of winegrowers and the economy of these regions.

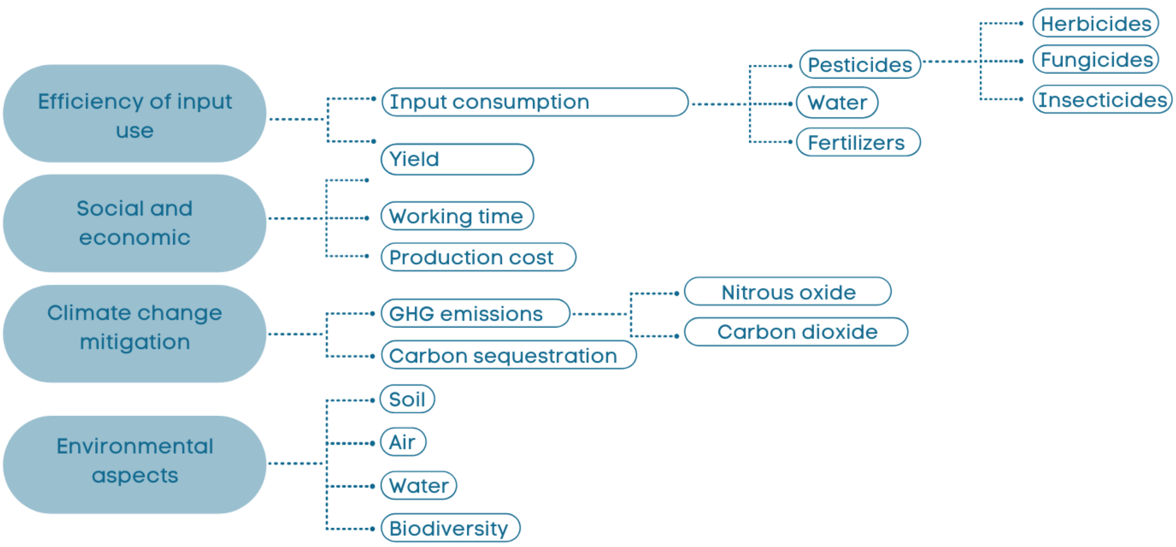
A wine sector restructuration scenario, including a reduction of the number of farms and an abandonment of land due to political decisions is not conceivable, especially as there is no real agricultural alternative for most of the wine-growing land.

These observations show the need to define another way to meet the principles of the European Green Pact and a responsible and effective ecological transition of agricultural sectors, including European viticulture.

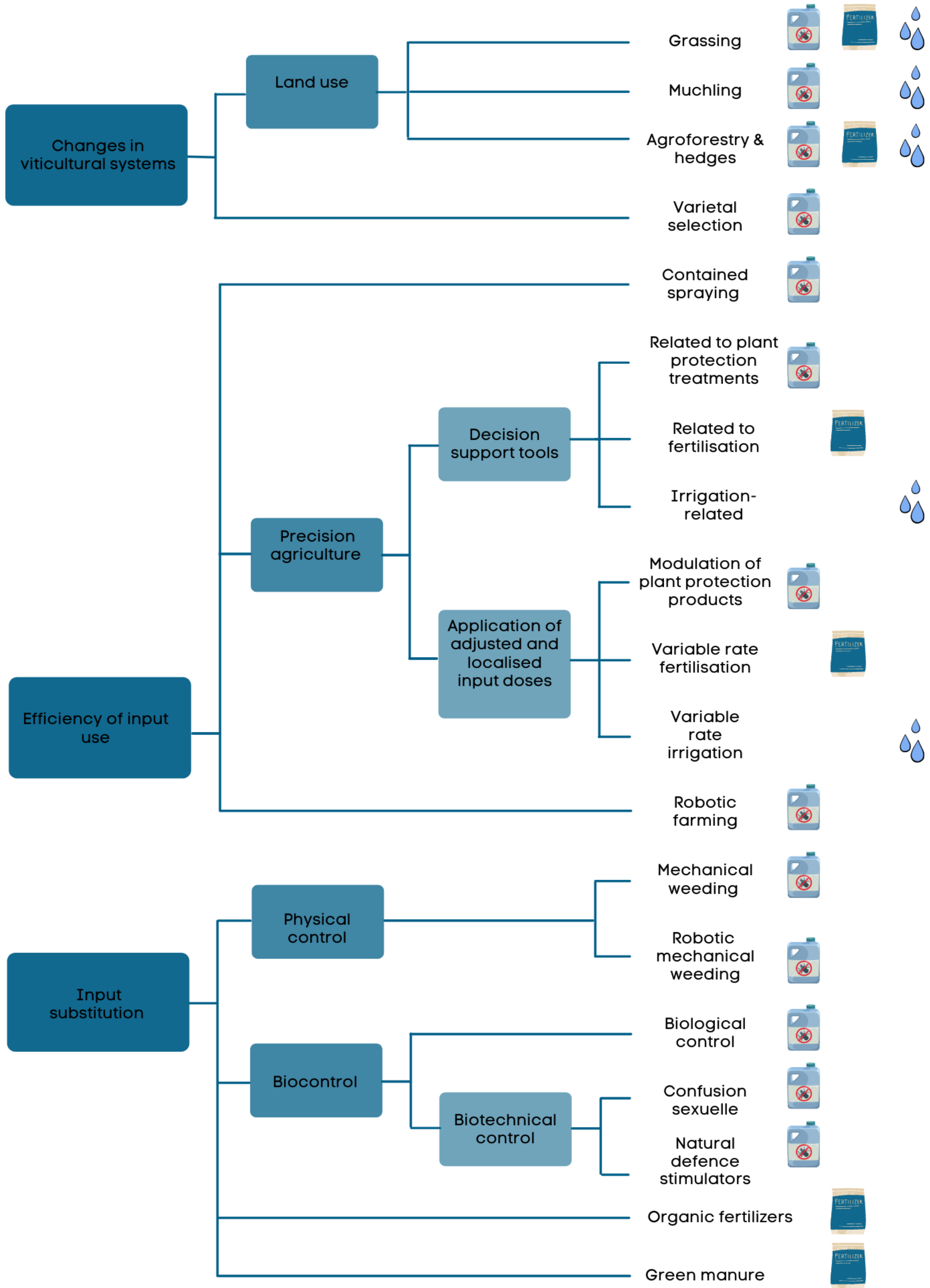
This report analyzes a set of practices that can be activated to reach the European objectives while fostering production capacities, revenues of the winegrowers and their working time.

Numerous European studies have evaluated and quantified the effect of various practices at the farm or plot level. Based on a review of this work, this study aims to quantify the effect of different practices to identify those with the best mix between environmental and climatic impact and economic and social impact.

The different data compared are given below:



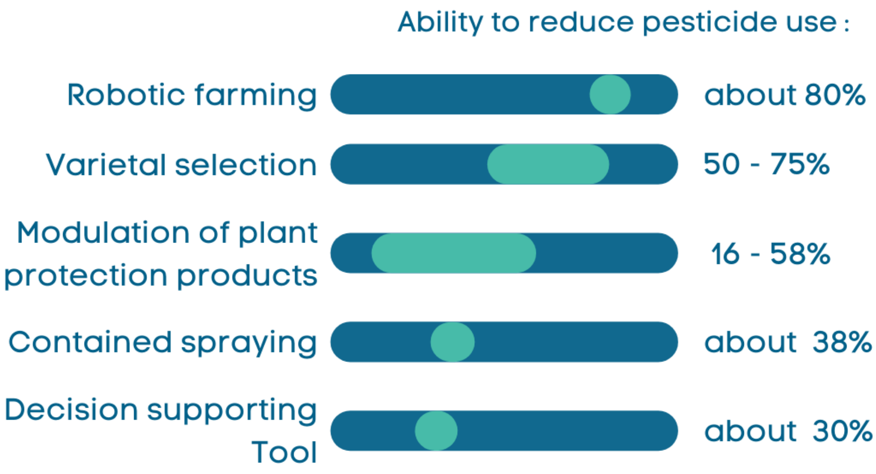
The practices studied and the inputs they affect are:



Results can be summarized as follows:

Effects of practices on pesticide use efficiency

Selected practices having beneficial effects on pesticide management generate the following results:



Effects of practices on fertilizer use efficiency

The use of decision supporting tools and variable rate fertilization seem the most interesting to promote. If most practices influence the quality of the musts, grassing, vitiforestry or green manures can lead to a quantitative decrease in yield. The difference in the type of fertilizer (synthetic, organic) has no impact on the efficiency of their use.

Effects of practices on water use efficiency

Practices such as grassing, organic and synthetic mulching and vitiforestry concern the efficiency of the use of water available in the soil and have effects that are observed according to the pedoclimatic contexts. They differ from practices related to the strategy of water use efficiency in irrigation, which include decision supporting tools, variable rate irrigation and fertigation. The latter seem to maintain or increase yields.

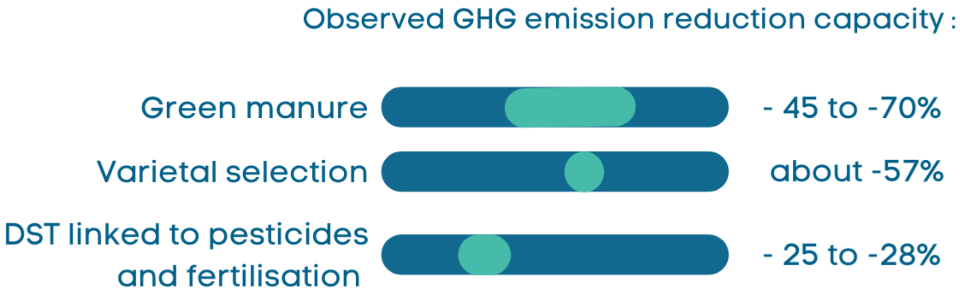
Effects of practices on socio-economic conditions

Varietal selection and the use of organic fertilizers are the practices that have a positive impact on yield, working time and production cost.

Decision supporting tools, adjustment of phytosanitary treatments, variable rate fertilization and variable rate irrigation may induce a slight increase in work time when learning how to use the tool but can generate positive returns in terms of economic profitability. Spontaneous weeding seems to be another interesting practice from a socio-economic point of view, as well as robotic mechanical weeding, whose investment is less than 40 000€.

The robotization of viticulture seems to be a promising technique in terms of work time, but it does not seem profitable today and is still in the experimental phase.

Among the practices studied, only grassing and agroforestry influence carbon sequestration. Practices that have a positive action on the different environmental components and whose capacity to reduce GHG emissions seems interesting are:



No practice is a silver bullet solution as they all have advantages and disadvantages. **Nevertheless, the most interesting to promote, whatever the input, seem to be the use of decision supporting tools, confined spraying, and varietal selection**.

Grassing, green manures, mixed mechanical weeding and biocontrol methods may compromise one of the social or economic dimensions. However, they remain interesting options for small vineyards or vineyards with low yield objectives.

Precision viticulture and robotization are the futures' solutions. To take full advantage of these technologies and decision supporting tools, training, support, and soil analysis are necessary.

Finally, the effectiveness of certain practices only occurs if the quantities of agricultural inputs are adapted to the sanitary pressure and the water and nitrogen requirements.

These conclusions are sometimes partial, particularly concerning carbon sequestration. The effects of the practices are in fact the result of the interaction of all the practices carried out on the plot and according to its pedoclimatic conditions. They cannot all be generalized on a European scale. Therefore, it seems necessary to compare these results with the feedback from winegrowers from different European regions and different types of farms.

Context

I. European wine production

A. Surface and geographical areas

Wine-growing areas occupied 3.2 million ha in 2015 in Europe. This corresponds to 5.6% of European agricultural land and 45% of the world's wine-growing area (European Commission 2017). As shown in Figure 1, the bulk of wine production is located on relatively poor land around the Mediterranean: 29% of these areas are in Spain, 24% are in France and 20% in Italy.

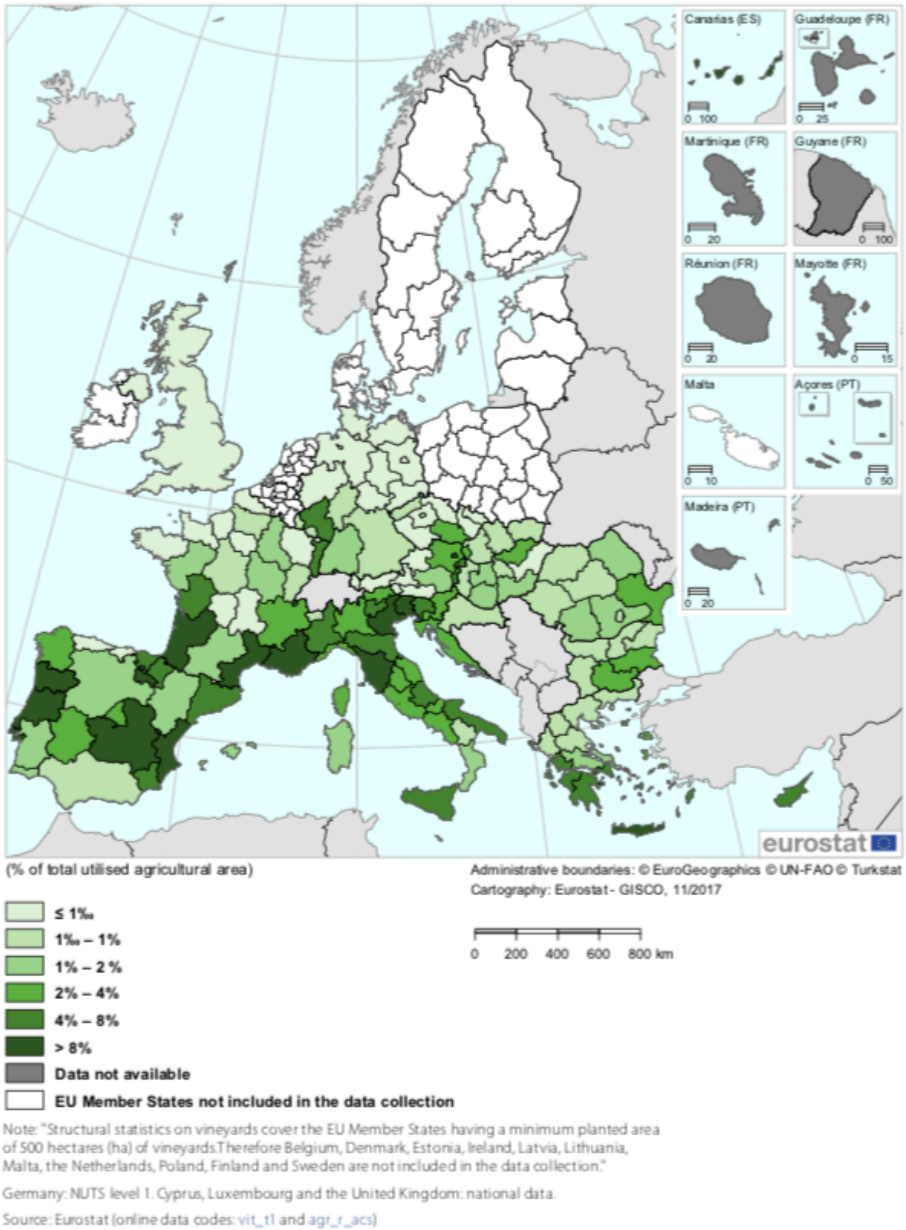


Figure 1 - European wine-growing areas in 2015 (% of total agricultural area), source: Eurostat (vit_t1)

B. Production

More than a third of the 2.5 million European winegrowers are in Romania. This represents 0.9 million holdings. Spain has 500,000 vineyards and Italy 400,000 vineyards. This corresponds to 20% and 15% of European winegrowers' holdings respectively.

There are great disparities in the size of the farms. The average size of winegrowing holdings is 1.3 ha. The smallest farms are located in Romania and the largest in France. The average size of Romanian and French farms are 0.21 ha and 10.5 ha respectively (European Commission 2017).

More than half of the production is under Protected Designation of Origin (PDO), i.e. 65%, 17% is under Protected Geographical Indication and 13% is considered as table wine (European Commission 2017).

European production in 2020 was 165 Mhl, with production mainly in Italy (49 Mhl), France (47 Mhl) and Spain (42 Mhl). Europe is the world's leading producer and exporter, its production corresponding to 63% of world production (OIV 2020).

C. Main inputs

The wine sector consumes substantial amounts of pesticides relative to the agricultural area it occupies (Pinto 2017). Few data are available at the European level or for other countries.

The most commonly used pesticides are fungicides. They correspond to 83% of the total TFI (Treatment Frequency index) [1] of pesticides used in viticulture. This represents a TFI of 12.7, or 16 treatments out of 21 on average in 2016. Insecticides correspond to 13% of the total TFI in viticulture, which represents about 1.9 TFI on average. Herbicides correspond to 5% of the total TFI in viticulture and correspond to 0.7 TFI on average. These figures are given as an indication, they vary depending on the years, the climatic and sanitary conditions, the regions and the choice of practices implemented in the vineyards (Simonovici 2019).

Nitrogen consumption

Grapes export 30 to 50% of the nutrients absorbed by the vines (Rousseau et al., n.d.). Nitrogen is the element to which the vine is most sensitive. An excess of nitrogen causes an exacerbated vigour, which translates into a too high yield and a decrease in berries 'quality. Conversely, a deficiency reduces yields and fermentability of musts, which also affects wine quality (Comifer 2012a).

Vine has modest needs. On average, they are around 20-60 kg of nitrogen per hectare per year for yields ranging from 6 to 10 t/ha and around 60 to 90 kg/ha for yields ranging from 10 to 25 t/ha (Gontier and Cahurel 2021; Comifer 2012a). Nitrogen management is primarily controlled by the mineralization of OM (organic matter) in the soil, which is dependent on climatic conditions, temperature, humidity, soil type and soil pH. If the latter is not sufficient and

[1] This is the ratio of the applied rate to the reference rate multiplied by the treated area.

deficiencies are diagnosed, the contribution of other forms of nitrogen can then be considered (Gontier and Cahurel 2021).

Water consumption

Irrigation is increasingly developed in the vineyards around the Mediterranean to mitigate climatic risks and to guarantee the yield and quality of the berries. More than 40% of the Spanish wine-growing areas are now irrigated and so are 10 to 15% of the areas in Portugal. These areas are tending to increase although restrictions on water use are imposed by regional legislation (Costa et al. 2020).

Interconnected inputs

Water availability and moisture influence the need for pesticides, as too much moisture may encourage weed development, which can lead to competition for nitrogen. An increase in fungal diseases may also occur under these conditions. Conversely, a reduction in nitrogen uptake can be observed during water stress as nutrients can only be absorbed in the presence of water ("Practising Total Grass Cover In Vineyards," n.d.).

II. The wine sector confronted to climate issues

Wine growing is dependent on the weather. Today it must deal with a shift in the seasons, as well as an increase in the temperature, frequency, and intensity of climatic hazards such as the risk of hot weather, drought, or heavy rainfall. These changes have a direct effect on the yields and organoleptic qualities of European wines, which are at the origin of their international reputation.

Little information is available on the share of GHG (greenhouse gas) emissions related to the European wine sector. Nevertheless, life cycle analysis studies on wine production have been carried out. They show that wine making, and marketing are much more emitting than the viticulture phase which emits between 1/5 and 1/4 of total emissions.

Winegrowing emits between 413 and 525 kg of eCO2 (carbon dioxide equivalent) per tonne of grapes. Emissions related to the combustion of diesel fuel for farm tractors and workers' transport account for almost half of the emissions. They range from 0.167 to 0.33 kg eCO2 per bottle of wine produced according to a study of seven French and Spanish vineyards. Emissions related to the production of phytosanitary treatments follow, but are very variable depending on the winery, ranging from 2 to 30%. They range from 0.017 to 0.355 kg eCO2 per bottle of wine produced according to this same study. N_2O (nitrous oxide) emissions and those related to the manufacture of fertilizer and diesel are less than 10%. They are all between 0 and 0.05 kg eCO2 per bottle of wine produced (KERNER, n.d.; Navarro et al. 2017).

To combat the effects of climate change, winegrowing, like all other sectors, must aim to reduce its GHG emissions. But it also has, like agriculture, the capacity to store carbon in its soils.

III. The wine sector and environmental issues

In addition to climate-related issues, agriculture is in constant interaction with abiotic natural resources (water, soil, and air), biodiversity and ecosystems. It is a beneficiary and provider of ecosystem services through the practices it implements. But it can also receive and emit negative impacts on these components. These include pollution of ecosystems by the inputs involved, pressure on water resources which are particularly vulnerable in Mediterranean regions, degradation of soil fertility and loss of biodiversity.

This observation is applicable to the entire agricultural sector. When also taking into account the negative externalities on health, as well as the role of farmers as managers of 38% of the European surface area, it has led to the implementation of environmental actions (requirements, incentives, remunerations, etc.) for agriculture.

IV. Policy responses to climate and environmental issues

To address climate and environmental issues, the EU is proposing a package of measures in its Green Deal:

The Commission has set itself the goal of achieving climate neutrality[2] by 2050 and a 55% reduction in emissions by 2030 compared to 1990. To achieve this, the LULUCF (Land Use, Land Use Change and Forestry) regulation, which covers GHG emissions and removals from land use, land use change and forestry, is being revised. In the proposed revision, agriculture must achieve climate neutrality by 2035 to be able to take over emissions from other sectors. In parallel, a European Carbon Farming Scheme is being developed.

The Farm to Fork Strategy (F2F) and the Biodiversity Strategy aim to reduce the use of chemical pesticides by 50% and fertilizers by 20% by 2030. They aim to achieve 10% of agricultural land with high-diversity landscape elements and 25% of land in organic farming.

[2] "A situation in which anthropogenic GHG emissions to the atmosphere are offset by anthropogenic removals over a period of time" (Matthews 2018).

V. The wine sector and the economic challenges

The F2F and biodiversity strategies could lead to a drop in production of at least 5% for the wine sector, a reduction in exports of around 20% and a drop in farm incomes of 8 to 16%, according to the impact studies carried out by the Commission and by the USDA-ESR (Farm Europe 2021)

These alarming trends are in addition to the climatic and environmental challenges facing the European wine sector. Beyond the place of the European wine sector on the world market, where competition is already tough, they call into question the living conditions of the farmers and the economy of the wine-producing regions. The idea of restructuring the wine sector, reducing the number of farms, and abandoning land is unthinkable, especially as there is no real agricultural alternative for most of the vineyard land.

Concrete actions ensuring an efficient use of inputs, a reduction of GHG emissions, an increase in carbon storage in the soil and the preservation of the environment while guaranteeing winegrowers good working conditions and a fair remuneration would make it possible to achieve the European objectives while protecting the production capacities of winegrowers.

Many studies have evaluated and quantified the effect of various practices on farms. The aim of this study is to select those practices whose effectiveness on the environment and the climate is recognized and which improve production capacity, farmers' revenues, and their working time.

Methodology

This report is based on a bibliographic review of studies, meta-analyses, articles, and practical sheets dealing with different viticultural practices. Most of these documents are feedback from European winegrowers, institutes, and European research centers.

The practices studied fall into three categories according to the ESR (Efficiency - Substitution - Re-design) concept (Gayrard and Delva 2015). They are given in **Erreur ! Source du renvoi introuvable.**together with the inputs whose use they affect.

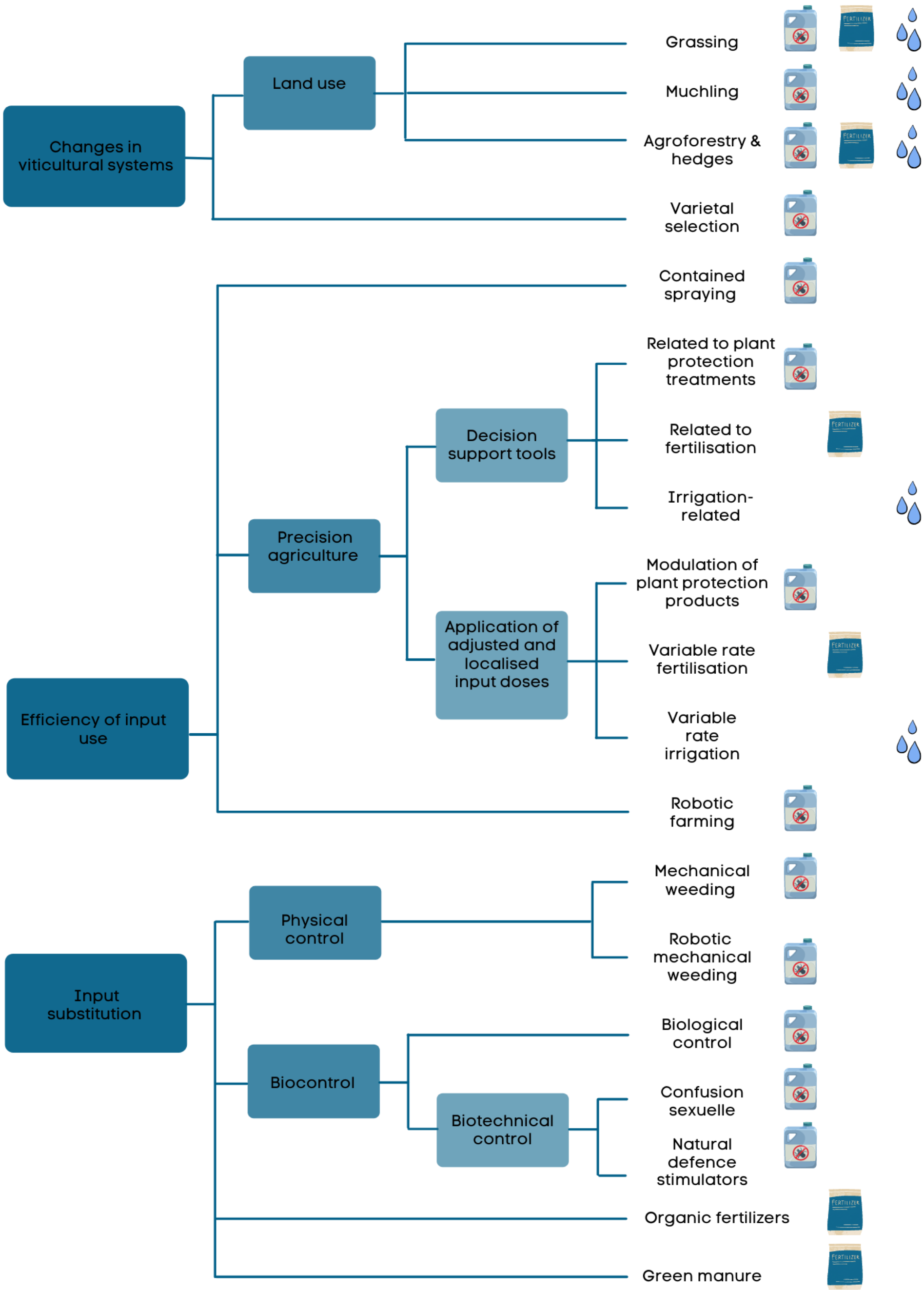


Figure 2 - Practices studied and the inputs they affect

These practices are common to all production systems. Other practices exist but have not been taken into consideration. Vineyard management (spacing of vine rows, choice of pruning type, orientation, etc.), for example, has not been studied, even though it allows for a reduction in water consumption, because too many factors need to be taken into consideration.

The effect of the practice on input use efficiency is analyzed from:

- Its effect on input consumption:
    - Pesticides (herbicides, fungicides and insecticides)
    - Nitrogen inputs
    - Water.
- Its effect on yields.

The effect of the practice on socio-economic dimensions was analyzed based on:

- Its effect on yields.
- Its effect on working time.
- Its effect on the cost of production. It accounts for the cost of inputs, including fuel, labor, traction and equipment, according to the information available.

The investments in machinery necessary to carry out the practice have not been considered because of the many ways in which it can be carried out (CUMA, EU financing, cooperative, third-party organization, oneself...). The economic outcome is difficult to calculate because it is specific to the characteristics of each farm.

The effect of the practice on climate change mitigation is studied from:

- Direct emissions of N_2O and CO_2 and, where data were available, indirect emissions of CO_2.
- The effect of practice on carbon sequestration.

The effect of the practice on the environment was studied quantitatively by the effect on the efficiency of input use and qualitatively on:

- Air quality which can be polluted by pesticides and NH3 (ammonia) emissions.
- The quality of the soil, which corresponds to :
    - Its chemical fertility: production/degradation of OM.
    - Its biological fertility: biodiversity of micro-organisms ensuring the biological activity of the soil.
    - Physical fertility: permeability, resistance to compaction, compaction, erosion and leaching.
- Water:
    - Water retention in the soil, fight against runoff.
    - Water quality: filtration and degradation of pesticides. Control of pesticide transfer, leaching and eutrophication.
    - The preservation of macro and microscopic biodiversity, fauna and flora.

The reference model and cross-sectional data

All these practices are compared to a "reference" system with chemical weeding. Pesticides (herbicides, fungicides and insecticides) account for about 490€/ha. Phytosanitary protection requires between 8 and 10 h/ha. The cost of fertilization is 190€/ha and requires between 3 and 5h/ha. Other practices related to pruning and plantation maintenance (disbudding, tying, pallissage, *etc.*) are not taken into account (Badier et al. 2019).

Whatever the practice, labour costs between 15 and 18€/ha. We can also consider that 1 kg of synthetic nitrogen fertilizer emits 2.6 to 3.7 kg of eCO2 and that 1% of the applied nitrogen is emitted as N2O. This information can be used to complement information on production costs or GHG emissions with information on labour time or fertiliser quantities applied (Nistor et al. 2019).

Highlighting of practices to be promoted

Many factors interfere with the trials carried out, such as the soil and climate context, the type of farm, the equipment available, the settings, the varieties, the history of the plot, etc. Other practices carried out on the plot should be added. The choice of analyzing by input and by practice is very simplistic. The aim here is to obtain orders of magnitude of the effect of the various practices to identify those with the greatest impact.

Results

I. Modification of the viticultural systems

A. Land use

1. Weed control

Grassing of vineyard plots is widely known in Europe. Nearly 50% of vineyards were so in France in 2010 (Garcia et al. 2018). These covers of legumes, grasses, crucifers, hydrophyllaceae can be spontaneous or sown (Gontier and Delpuech 2019; Frey 2016). They can be winter covers, planted after the harvest, until bud break, or semi-permanent covers if they are maintained until the next harvest. They are said to be permanent if the grass cover is not destroyed between two harvests (Frey 2016).

Among the different existing arrangements, the most common types of grassing are inter-row grassing, covering 50 to 60% of the soil surface, and under-row grassing, covering 25 to 30% of the soil surface. Total grassing is rarely practiced to limit the risk of reducing yields by 20 to 50% (Gontier and Delpuech 2019). It is not considered in this section.

Inter-row seeding can be done by broadcasting, with a direct seeder, or by planting in some cases (Frey 2016). Seeding under the row can be done with localized fertilizer spreaders, as little specific equipment is available today (Gontier and Delpuech 2019). Cover crop maintenance is done by mowing, shredding, grazing, or rolling. Cover destruction can take place by mechanical action (plowing, loosening, scratching, or hoeing), chemical action, or thermal action. This part concentrates on weed control as such. Its mechanical destruction is detailed on page 36and its chemical destruction by robots on page 34.

a. Results obtained

Effects on input use

Pesticides

Weed management

The primary purpose of grassing is to control weeds (Varray and Le Roux 2012). It allows to limit weeding to the rows of vines, which reduces the quantities of herbicides used per hectare by two or three (Benoit 2010). However, herbicides generally represent only 5% of phytosanitary treatments, making the effect of grassing on pesticides very low.

Disease management

Grass cover has no direct effect on diseases. Indirect effects observed on powdery mildew, grey rot or downy mildew are related to a decrease in vine vigour, caused by the competition of the cover for water and nutrients (INRAE 2021). Grass cover can also increase the biological activity of the soil, leading to a more rapid decomposition of residues, which are sources of inoculum. Others, on the other hand, believe that grassing maintains high humidity near the vines. This humidity associated with the rise in temperatures, in spring, would favor the risk of fungal disease development (Garcia et al. 2018).

Pest management

The effect of grassing on pests is not clearly documented. Some authors claim that inter-row and cavaillon grassing increases the presence of pests while others observe their reduction (Garcia et al. 2018). For example, according to a study conducted in Beaujolais between 2004 and 2012, the presence of a grassed strip every five rows reduces the use of insecticides (Varray and Le Roux 2012).

Water

Grass cover promotes soil water storage in winter but can compete with vines from spring onwards (Froger 2020). Water stress at the beginning of the cycle or bud break can lead to a decrease in vegetative growth, which can be beneficial for vigorous and early vines. If it occurs between flowering and veraison, it can lead to a decrease in yield.

The influence of grass cover on vineyard yields varies according to climate, soil type, grass type and grape variety. In rainier climates, grass cover is much less competitive for water. Water stress results in reduced nitrogen uptake. The competition of grass for nitrogen will therefore be higher in the Mediterranean area than in more humid regions ("Pratiquer l'enherbement Total En Vigne," n.d.).

Fertilizers

The effect of grass cover on nitrogen availability for vines is discussed according to the type of grass cover. Legume-based cover crops can provide nitrogen inputs. Their effects are detailed in the section on green manures, page 51. A risk of competition for these nutrients can occur for grass coverings other than flower strips or green manures ("L'enherbement de La Vigne En 10 Questions Réponses" 2020). It can be avoided by regular mowing.

The establishment of grass cover requires the application of about 30 kg N/ha, which is relatively low, to initialize grass cover growth (Comifer 2012a).

Effects on yield

Grassed areas compete with the vines for water and nutrients. This has an impact on the yield, which can decrease by 9% on average compared to chemical management. This decrease remains variable. It is very marked in the second year and tends to decrease in the following years. One solution to limit this competition is to reduce the surface area of the grass ("Grassing the Vine in 10 Questions Answers" 2020).

While weed control may reduce yields, it maintains or even increases the quality of some wines (Gontier and Delpuech 2019).

Effects on working time

Grassing techniques require three times more work than chemical management. Two to five time-consuming annual interventions take place, depending on the chosen layout and the equipment used. According to other sources, the implementation of grass strips in the inter-rows in viticulture requires a total of 1 hour to grass one row every eight rows on a 0.4 ha plot (Varray and Le Roux 2012).

Effects on the cost of production

Taking into account the cost of products, labour and traction, the cost of grassing varies from 800 to 1,000 €/ha/year and that of chemical management amounts to 100-140 €/ha/year according to Christophe Gaviglio (2018). If weed control is spontaneous, it would save 15 to 26 €/ha/year (INRA 2019). The time spent per hectare is the first factor influencing the cost of production. Winegrowers who accept that grass develops at a reasonable level reduce the number of mowings and have a cost per hectare close to chemical weeding, but this might impact the yield (Delpuech 2014).

Effects on climate change mitigation

Vineyard grassing allows for the storage of between 0.18 and 1.76 tons of carbon per ha per year (INRA 2019). This practice emits about 1 tonne of CO_2e per year and per hectare (Chenu et al. 2014).

Other effects on soil, water, air and biodiversity

Grassing encourages biological activity in the soil, maintains biodiversity and produces organic matter. The grassing of the inter-rows structures the soil, reinforcing the resistance to compaction and restores compacted soils. Soil stability and bearing capacity are also maintained. Soil porosity is increased, thus fostering water retention in the soil. Runoff, erosion, and pesticide transfer through rain and into groundwater are reduced ("L'enherbement de La Vigne En 10 Questions Réponses" 2020; Garcia et al. 2018).

b. Remarks

The impact of grass strips on pests and their effectiveness in biological control depends on their type and proportion (Jeanneret et al. 2017). Their capacity to infiltrate and attenuate molecules also depends on the nature of the soil (Gril, Carluer, and Le Hénaff 2011). This is why a diagnosis of the soil situation of the plot and the specific processes taking place there must be made before their implantation (Gril, Carluer, and Le Hénaff 2011).

Grassing can reduce yields, which is the main fear of winegrowers regarding this practice. This practice is suitable for production systems with moderate production objectives, such as in Protected Designation of Origin (PDO), where the yields to be achieved are low (Gaviglio 2018a). Regular weeding limits the competition of the canopy on water and nitrogen, thus reducing the impact on yield. Robotic weeding would allow to reach a correct yield without increasing the workload.

c. Appraisal

Grass cover increases the cost of production due to the increase in work time. The species planted can compete with the vines for water and nitrogen resources. While yields may be affected, the quality of some wines may be improved. This is a recommended practice for vigorous and early vines to improve harvest quality.

Herbicides can be reduced, but they represent only a small portion of the total phytosanitary treatments. If canopy management is technically feasible, the choice of species to be planted and the type of layout is strategic so as not to have a negative impact on the gross margin. This practice does not seem to allow efficient use of inputs today. The advent of robotization, which reduces labour time and provides better control of the canopy, could lead to a review of this conclusion.

If the amount of carbon stored per year is greater than the GHG emissions linked to their management, grassing appears to be an interesting solution to mitigate climate change. This practice preserves biodiversity, soil and water.

2. Mulching

In viticulture, mulches are used to control weeds. They are an alternative to chemical weeding when they are applied under the row and to mechanical work when they are applied in the inter-row. They also have the property of keeping the soil moist and cool, which is good for the water available to the vines.

A 5 cm thick organic mulch can be made in mature plots from shredded plot weeds or pruned vine parts. Cereal straw, hemp stalks or bark can also be used (Gontier and Gaviglio 2018; Manzone et al. 2020). The establishment of a new vineyard plot can be carried out on tarpaulins or textiles covering the interplant areas (Gaviglio and Delpuech 2019; Agrobiofilm Consortium 2013). Among these synthetic mulches, only biodegradable tarps are considered. These solutions of organic or synthetic origin are currently little used by winegrowers.

a. Results obtained

Effects on input use

Herbicides

Organic or tarpaulin mulches have a limited effect over time. Organic mulches decompose quickly and are only effective on weeds two years after their installation. The first degradations of the covers are generally observed after 4 to 5 months in Mediterranean climate, in particular because of the UV. Nevertheless, they have a lifespan of 2 to 4 years (Gontier and Gaviglio 2018; Agrobiofilm Consortium 2013).

Table 1shows that, during this period, their effectiveness against weeds is average and variable depending on the materials used in the organic mulch.

Table 1 - Percentage effectiveness of different mulches on weeds

Mulching	Percentage efficiency	Source
Cereal straw	25-30%	(Gontier and Gaviglio 2018)
Crushed hemp fibres	60-80%	(Gontier and Gaviglio 2018)
Crushed chestnut bark	60-80%	(Gontier and Gaviglio 2018)
Crushing of weeds in the inter-weed bed	70%	(Manzone et al. 2020)

Water

Trials in French vineyards have shown higher water levels in soils covered with organic mulch compared to the control. Temperatures in mulched soils were up to 5°C lower than in the control. These differences vary between years, climates, seasons and mulch types (Gontier and Gaviglio 2018).

According to a Spanish study, organic mulch reduces vine evapotranspiration more than synthetic mulch, but it increases vine transpiration. According to their results, organic mulch reduces water consumption by 37% compared to plastic mulch (López-Urrea et al. 2020).

Greater root growth of the vines was observed under plastic mulch compared to the control, resulting in better water uptake. This statement made for plastic mulches was not verified for organic mulches.

Effects on yields

A 20-25% decrease in yield was noted for organic mulches in a 2010-2012 trial. The reason for this yield decrease was not clearly identified. Thus, the correlation between yield decline and organic mulch implementation is not clear (Gontier and Gaviglio 2018).

The vines are more vigorous in the first three years after planting when a tarpaulin covers the inter-planted soil compared to bare soil. Early yields are increased 11-fold (4.24 kg/head) compared to yields obtained on bare soil (0.39 kg/head) in extremely dry conditions. They can be reduced by 30% under milder conditions (Agrobiofilm Consortium 2013).

Effects on working time

The use of mulch varies the working time between -20% and +17% compared to chemical weed control, as shown in Table 2. This variation is due to the type of mulch and the tools available. After installation, a simplification of the work takes place, especially for organic productions (Gontier and Gaviglio 2018).

Table 2 - Labour time per hectare with different mulches or chemical weed control

Type of mulch	Working time (h/ha)	Source
Cereal straw	2	(Gontier and Gaviglio 2018)
Shredding of weeds in the inter-weeds with a vine shoot shredder	2,92	(Manzone et al. 2020)
Chemical weed control	2,48	(Manzone et al. 2020)

Effects on the cost of production

The installation of an organic mulch or a tarpaulin is two to six times more expensive than mechanical weeding, which costs about 320€/ha/year according to IFV references. An estimate of the costs is given in Table 3. The contribution of organic matter or the purchase of tarpaulins represent the major part of the investment. Labour and mechanization costs only amount to about 60€/ha. The biennial renewal of the mulch generates a cost that is compared to the savings in fuel and herbicides made compared to chemical weeding (Gontier and Gaviglio 2018).

Table 3 - Estimated cost of different types of mulch

Type of mulch	Estimated cost	Source
Organic	730 to 1830/ha/year when amortized over 3 years	(Gontier and Gaviglio 2018)
Biodegradable tarpaulin	Three times higher	(Gontier and Gaviglio 2018)
Crushing of weeds in the inter-weed bed	+7% compared to chemical weed control	(Manzone et al. 2020)

The margin obtained with mulching is likely to be lower than that obtained with chemical weed control (Gontier and Gaviglio 2018). The cost of using biodegradable plastics would be compensated by the better yields they allow, according to studies conducted by Agrobiofilm Consortium(2013).

Effects on climate change mitigation

A 3% reduction in CO_2 emissions was found when organic mulches were applied, due to lower herbicide and fuel consumption (Gontier and Gaviglio 2018; Manzone et al. 2020).

Life Cycle Assessment (LCA) of biodegradable plastic mulches estimates that CO_2 emissions and non-renewable energy consumption double when using biodegradable plastic sheeting compared to bare soil (Agrobiofilm Consortium 2013). The data are detailed in Table 4.

Table 4 - Non-renewable energy consumption and CO2 emissions when managing inter-planting with a biodegradable tarp or bare soil tillage, source: Agrobiofilm Consortium 2013

	Non-renewable energy use (GJ/ha)	CO2 emissions (T eCO2/ha)
Biodegradable tarpaulin	30	1,4
Bare ground	15	0,7

Other effects on soil, water, air and biodiversity

These organic or synthetic mulches protect the soil against erosion, compaction, leaching and the risk of eutrophication. They ensure the availability of nitrogen and water for the vines and create conditions conducive to the proper biological functioning of the soil and the breakdown of organic matter. Nevertheless, a cereal straw mulch can lead to crusting after the first rain (Gontier and Gaviglio 2018; Manzone et al. 2020). Soil moisture is maintained, limiting evapotranspiration. Some experiments report a drop of about two degrees Celsius at the foot of mulched vines compared to ambient air (Gontier and Gaviglio 2018; Agrobiofilm Consortium 2013). The induced herbicide reduction improves air quality and limits the risks of transfer to water (Gontier and Gaviglio 2018).

b. Appraisal

This is an easy practice to implement when establishing vines, but is much more complex to implement on vines already present (Gontier and Gaviglio 2018). It facilitates maintenance, maintains humidity at the foot of the vines in dry periods but provides only average weed management. Energy costs are reduced for organic mulches but increase per hectare when using biodegradable plastics. The investment is important, whatever the type of mulch. Their effective duration is much too short to be economically profitable. This practice should be combined with other low-cost practices, such as grassing of inter-rows and/or inter-plant areas (Gontier and Gaviglio 2018).

3. Agroforestry and hedges

The introduction of fruit trees (almonds, peaches, figs, apples and olives) or timber (ash, oak, poplar, etc.) into vineyard plots has attracted renewed interest in recent years. These systems, which have long been cultivated around the Mediterranean from Spain to Greece, have been abandoned by the last generations of wine growers because of mechanization (Trambouze and Goma-Fortin 2013; Lang et al. 2019). Today technical institutes and some vineyards are studying their potential for climate change mitigation, carbon sequestration, biodiversity preservation.

Planting trees in a vineyard can be carried out in a very diverse way depending on the choice of species planted, their position in and around the plots, their density and maintenance (Bourgade et al. 2020) ... The choice of vineyard management system is also important, as shown by some farmers who have successfully reintroduced trees while maintaining mechanical work (Canet 2018).

Few technical and scientific references document vitiforestry and agroforestry in viticulture. This section details the results obtained in projects carried out in the south-west and south-east of France, as well as in eastern Germany, in conventional and organic plots. These studies involve the introduction of rows of trees every 4 to 40 rows of vines. These trees are 5 to 10 years old and have not yet reached maturity.

c. Results obtained

Effects on input use

Insecticides

The main interest of reintroducing trees in vineyards is to stimulate biological control (Trambouze and Goma-Fortin 2013). Nevertheless, effects on pest control have been observed (Bourgade et al. 2020).

Water

One of the main fears of winegrowers is that the presence of trees will lead to water competition. No significant difference in water stress was observed in the various studies, despite the sometimes very dry conditions in summer. These observations were made for trees that had not reached their maximum size and should be verified on older plots (Trambouze and Goma-Fortin 2013; Bourgade et al. 2020).

Fertilizers

As with water stress, growers are concerned that the presence of trees will compete with the vines for nitrogen. The results differ according to the studies. According to some, such competition exists because the assimilable nitrogen content decreases by 8 to 20% (Trambouze and Goma-Fortin 2013). Conversely, a correlation between the presence of trees and an increase in available nitrogen and its assimilation by vines is put forward by (Lang et al. 2019). For others, the presence of 8-9 year old trees does not seem to influence vine vigor or nitrogen status (Bourgade et al. 2020).

Many factors such as grape varieties, tree species, age, tree and vine management systems, soil type and climate may explain the heterogeneity of the findings.

Effects on yields

Light interception from trees does not affect grapevines, even for shady species (Trambouze and Goma-Fortin 2013). High-density tree plantings should be avoided because of their impact on wine production.

The presence of 8 to 10 year old trees can induce a punctual cooling of 2.5°C maximum. A decrease in the time spent in temperatures above 30°C, the maximum limit for photosynthesis, is occasionally observed (from 1 hour to 3.5 hours less on average) compared to the other vines. This decrease in temperature, maintaining photosynthetic activity, is linked to a phenomenon of convection and to the shading of the crops. The vines that were with lower temperatures during flowering have the highest yields of the plot and the highest acidities. Plots exposed to high nighttime heat have the lowest yields and acidities (Bourgade et al. 2020). Conversely, in winter, the presence of compact tree hedges and wooded strips can increase the risk of frost (Dufourcq and Rocque 2021).

No significant effect of the presence of trees close to the vines on their vigour and yield was observed compared to vine rows further away from the trees (Bourgade et al. 2020). Conversely, a reduction of 9 to 31% was observed in southeastern France when rows of trees were placed parallel to the vines every 3 to 4 rows at a distance of about 3 meters from the vines (Trambouze and Goma-Fortin 2013).

Wine quality was not significantly affected by the presence of trees (Bourgade et al. 2020; Lang et al. 2019).

Effects on working time

The presence of trees in vineyards requires an increase in labour. Their planting requires about 13h/ha and their maintenance about 6h/ha/year for the first three years (Bourgade et al. 2020). This increase in time required makes this technique obsolete today (Trambouze and Goma-Fortin 2013).

Effects on the cost of production

The introduction of trees in vineyard plots is associated with organizational constraints, significant long-term costs and uncertain profits. Few studies have examined the profitability of agroforestry systems, and even fewer in viticulture. Only one reference on the investment linked to the planting of trees in a vineyard exists. It estimates the planting of 100 Cormier trees per hectare at 1 074 €/ha in 2000. It should be noted that this cost varies according to the density planted, the species chosen and the protection system adopted. Other agroforestry systems implemented in other crops are estimated over 30 years at €4,580/ha or €43 per linear metre of hedge in the border (Bourgade et al. 2020).

At 75 trees per hectare, labour is the most expensive item, accounting for 85% of the total. Maintenance of trees or shrub hedges is the most expensive activity. It represents 77% of the funds, compared to planning (3%) and planting (20%). The maintenance of the trees must be adapted according to the objective assigned to them. These operations are costly but necessary for efficient management of agroforestry plots (Bourgade et al. 2020).

There may be additional costs associated with changes in vineyard operations. For example, the change from mechanical to manual harvesting due to the shape and size of the trees. On the other hand, the testimony of certain farmers shows that the straddle carriers manage to pass over pruned trees. Their presence improves, according to them, the passage of the machines during harvesting because the berries fall more easily (Canet 2018).

Planting trees in place of vines reduces the yield targets of the vines per hectare. Once mature, they could compete more for light, water and nutrients, which could have a negative impact on vine yields. The revaluation of their production (fruit or wood) varies according to the species. The outlets for wood production are still not clear, especially since the density of trees in the vineyard plots is lower than in other agroforestry systems. Bourgade et al(2020). The cost of the system is not compensated by an increase in income (Trambouze and Goma-Fortin 2013).

Effects on climate change mitigation

The presence of 30 trees/ha sequesters between 0.45 and 0.9 tC/ha/yr and tree hedges store about 0.1 tC.ha/yr for 100ml/ha (Bachevillier et al. 2015). No data accounting for emissions related to the maintenance of trees planted in viticulture were found.

Other effects on soil, water, air and biodiversity

Planting trees in vineyards has positive externalities on biodiversity, although studies are still too recent to draw conclusions. The presence of trees reduces the risks of soil erosion and compaction. They enrich it. An added value for consumers, local residents and tourists in terms of landscape is created (Bourgade et al. 2020; Trambouze and Goma-Fortin 2013).

d. Appraisal

The presence of trees in viticulture increases carbon sequestration in the soil. They have a variable effect on the control of vineyard pests. There is no competition for water in this type of system. However, there is some debate about nitrogen competition. Trees are interesting during hot weather because they provide a cool microclimate, which improves the quality of the wines under these conditions. On the other hand, in winter, they can favour frosts. They have contrasting effects on yields. Their maintenance leads to an increase in work time and production costs. They can also lead to additional costs for vine maintenance. Profits can be obtained from the use of their production but are not yet well evaluated.

There is a lack of experience with this practice. Studies on plots with older trees still need to be carried out. Technical, economic and environmental analyses must also be carried out. The adaptation of the vine and forestry systems to mechanization, making them economically viable, is necessary for their diffusion. This system could be completed by grassing to preserve soil quality and biodiversity (Canet 2018).

B. Varietal selection

In order to be marketed or exchanged, all seeds of the main agricultural species are registered in the official catalogue of species and varieties, according to European regulations. The VATE (Agronomic, Technological and Environmental Value) is one of the tests carried out to register new varieties in the catalogue. The new variety must meet these criteria and perform better than the control varieties of the species. However, the criteria for this assessment are not harmonised between the Member States.

No variety systematically combines all the criteria of interest (resistance to abiotic stress, yield capacity, resistance to bio-aggressors, nutritional and gustatory quality, etc.). To take advantage of varietal resistance, the choice of varieties should be based on the main risks present on the plots in which they are grown.

1. Results obtained

Effects on input use

Pesticides

The majority of varieties resistant to known pests and diseases are disease resistant. Some weed resistant or tolerant varieties exist. Competitive, they produce chemical exudates that inhibit the development of other plants or provide better soil cover. Few varieties are currently resistant to pests (Guyomard et al. 2013).

In viticulture, the use of resistant varieties requires 0 to 3 treatments against oidium and mildew, compared to 6 or 7 treatments for traditional varieties. This represents a saving of 60 to 90% of the cost of treatments and spraying against these diseases. Regions, vintages and grape varieties are factors influencing these results, as is the type of production (conventional or organic) (Pinto 2017).

Water

With regard to water management, the aim is to find varieties that are tolerant to water stress in order to minimize the consequences of drought on yield. Although the environmental criteria of VATE mention assessing the adaptation of the variety to technical itineraries with limited access to water, some feel that this is not well taken into account (Quenin 2020).

Some grape varieties adapt their physiology, to resist drought (Carbonneau and Ojeda 2013). The choice of rootstock and its root depth is important to anticipate the water stress of the vines (Marguerit et al. 2011).

Effects on yields

The use of varieties resistant to bio-aggressors and the adaptation of the treatment program makes it possible to improve the yields in terms of quantity and quality (Guyomard et al. 2013).

In viticulture, many studies show that resistant grape varieties obtain yields of 10t/ha to 20t/ha, which are generally higher than the yields obtained for traditional control grape varieties. The agronomic aptitudes of the grape varieties are not the only factors influencing the yield. Vintage, soil characteristics, management system and technical itinerary also play a role in yield (Pinto 2017).

The use of varieties that are better adapted to drought minimizes yield losses.

Effects on working time

In viticulture, 4 to 5 hours of treatments can be avoided by using resistant grape varieties (Pinto 2017).

Effects on the cost of production

The cost of resistant grape varieties in viticulture is 1.5 to 2 times higher than that of traditional plants (Pinto 2017). Compared to the use of traditional grape varieties, their use in conventional production induces a saving in production cost of 21% per hectare of vines. A saving of 15% of the total production cost per hectare of vineyard is observed in organic production (Pinto 2017).

Effects on climate change mitigation

A reduction in the number of phytosanitary treatments induces a reduction in fuel consumption related to the use of a sprayer. Indirect energy consumption related to the manufacture of pesticides is reduced (Guyomard et al. 2013). In viticulture, the use of resistant grape varieties can reduce GHG emissions by up to 57% compared to traditional grape varieties (Pinto 2017).

Other effects on soil, water, air and biodiversity

In the same way, a reduction in the number of farm vehicles used for treatment reduces the risk of settling. If the quantities of nitrogen spread are reduced, the risk of leaching is reduced. A reduction in the number of treatments also reduces the risk of polluting the water table and increases the presence of biodiversity. Such varieties are less sensitive to natural hazards and the effects of climate change (Guyomard et al. 2013).

2. Remarks

Resistant varieties can be the source of additional costs, despite the reduction in production costs and the good yields they allow. No planting premium is given for these varieties, unlike some traditional varieties. The wineries also seem less interested in resistant varieties than in traditional varieties and therefore pay them less. These new varieties need communication to gain recognition by the general public, which generates a cost (Pinto 2017). The use of new genomic technologies could be decisive in this area to synthesize the characteristics of traditional varieties and the desired resistances. In this respect, the work of adapting the European regulations launched by the Commission is an essential step.

3. Appraisal

The use of pest resistant or tolerant varieties would reduce the incidence of pests and thus prevent the use of pesticides, if the protection programs are adapted to the pest pressure. This would also reduce the cost of production. The yields obtained are equal to or greater than those measured for a more sensitive variety. The effects of using resistant varieties on working time and on the reduction of greenhouse gases are still debated. This method should be combined with other means of control to prevent possible circumvention of resistance by pests (Guyomard et al. 2013).

The use of resistant grape varieties seems to be a way to increase the efficiency of pesticide use, although the risk of increasing production costs is not negligible.

Varieties that are drought tolerant or that can adapt their production cycle to water constraints are of great interest for coping with climate change. However, these criteria are not sufficiently considered during the registration process.

II. Efficiency of input use

A. Contained spraying

A variety of types of sprayers exist in viticulture, the most common being pneumatic canopies, face-to-face sprayers and aeroconvectors (Adrien Vergès 2020). Recovery panel sprayers have existed for many years, formerly used in winter to fight against wood diseases. This technique has recently been adapted to carry out roofing treatments, face by face. The use of recovery panel sprayers for foliar treatments is still not widespread (Adrien Vergès 2020).

Different models of skimmer panels exist, such as pneumatic skimmer panels or airblast panels. The latter seem to be the most efficient in terms of spray quality and drift control (Auvergne et al. 2021; Carra, Codis, Delpuech, Vergès, et al. 2017).

The choice of nozzles is also important. Air injection nozzles reduce the risk of drift compared to conventional turbulence nozzles (Adrien Vergès 2020). Finally, the choice of speed also influences spray performance (Carra, Codis, Delpuech, Montegano, et al. 2017).

1. Results obtained

Use of pesticides

Thanks to the sprayers

Sprayers with recovery panels can recover an average of 40% of the sprayed products. This saving varies according to the season. It can approach 70% during the first treatments because of the low coverage of the foliage and reduces with the growth of the plant. When the vegetation is fully developed, 10 to 15% of products are saved. A trial conducted on a 1000 ha estate found a 50% reduction in the consumption of phytosanitary products thanks to the acquisition of 25 sprayers with recovery panels (Adrien Vergès 2020; Auvergne et al. 2021). These results also vary according to the model of the recovery panel equipment (Carra, Codis, Delpuech, Montegano, et al. 2017).

The devices with recovery panels increase the amount of product deposited on the leaves. The application of products on the vegetation is also more homogeneous. These sprayers provide more reliable crop protection than air-convector or air canopy sprayers (Carra, Codis, Delpuech, Montegano, et al. 2017).

Thanks to the nozzles

The choice of nozzle type also has an impact on the amount of spray that is applied to the vines. Air injection nozzles form larger drops than conventional turbulence nozzles. They ensure equivalent or even higher deposits than conventional turbulence nozzles, a better distribution of the product within the plant canopy and a lower risk of drift (Carra, Codis, Delpuech, Montegano, et al. 2017).

Effects on yields

There is little information on the effect of confined spraying on yields. Treatments are applied to achieve targeted yields. It is therefore assumed that these technologies that seek to increase pesticide use efficiency have no effect on yields.

Effects on working time

A loss of working time is noted when using sprayers with recovery panels. These sprayers treat a maximum of two rows of vines per pass. Other techniques can treat four rows per pass, thus increasing their work rate (Carra, Codis, Delpuech, Montegano, et al. 2017; Adrien Vergès 2020).

Particular attention must be paid to the maintenance of the recuperator panel devices and nozzles. The cleaning of air injection nozzles and associated equipment recommended (filters, filter pumps...) is 1h30, which represents a significant constraint (Carra, Codis, Delpuech, Montegano, et al. 2017).

Nevertheless, trials have shown that on undisturbed terrain, reclaim panels provide good spray quality for forward speeds of up to 9 km/h compared to the usual 5 km/h (Carra, Codis, Delpuech, Montegano, et al. 2017; Adrien Vergès 2020). This increase in forward speed can in some cases compensate for the loss of field time.

Effects on the cost of production

Sprayers with recovery panels have a higher purchase cost than commonly used sprayers. This increase was between €10,000 and €50,000 in 2017 depending on the model and options. In addition to this purchase cost, there is an increase in labour costs due to the higher cleaning time and a potential increase in field time.

Air injection or anti-drift nozzles cost up to twice as much as conventional turbulence nozzles, depending on their other characteristics, such as material and spray angle.

The economic balance of contained spraying depends on the characteristics of the farm. In case of numerous treatments to counter a high sanitary pressure, the additional costs are compensated by the saving of products which is on average 40%. In the opposite case, only the environmental benefits will compensate the costs (Carra, Codis, Delpuech, Montegano, et al. 2017; Adrien Vergès 2020).

Effects on climate change mitigation

Contained spraying has little impact on GHG emissions and carbon sequestration. Its main effect is the reduction of indirect CO_2 emissions related to the reduced use of pesticides.

Other effects on soil, water, air and biodiversity

Sprayers with recovery panels reduce spray losses caused by drift to the ground and air by 15 to 30 times compared to conventional spraying (Adrien Vergès 2020; Carra, Codis, Delpuech, Montegano, et al. 2017). Application drift is divided by 3 when using airblast sprayers equipped with air injection nozzles (Carra, Codis, Delpuech, Montegano, et al. 2017). Less drift reduces soil and air contamination from plant protection treatments. The quality of these compartments is preserved, which benefits groundwater and surface water quality as well as biodiversity.

2. Remarks

The practicality of these sprayers is debated. They are known to be complex to use. Although they are adaptable, their maneuverability in the plots can vary according to the chosen management and the width of the inter-rows. Their interest also depends on the topography of the farm as they are limited to low slope plots (Adrien Vergès 2020; Carra, Codis, Delpuech, Montegano, et al. 2017).

If the increase in forward speed is put forward to reduce the time of work, it is to be dosed with caution. A speed that is too high can disadvantage product recovery and therefore environmental performance (Carra, Codis, Delpuech, Montegano, et al. 2017).

Confined air blast sprayers with air injection nozzles seem to perform best in terms of input efficiency and environment. The small orifice size of this type of nozzle increases their risk of clogging compared to conventional nozzles (Carra, Codis, Delpuech, Montegano, et al. 2017).

The section closure exists but not the individual nozzle closure.

Given the lack of development of other technologies, such as individual nozzle closure in viticulture, confined spraying seems an interesting alternative. It is recommended to use these sprayers with the support of advisors and/or DSTs (decision supporting tools) such as Optidose (Adrien Vergès 2020).

3. Appraisal

Panel sprayers with airblast recovery panels seem to be the most efficient in terms of spraying quality (efficiency and homogeneity of spraying) and in environmental terms (reduction of drift). They are even more effective when equipped with air injection nozzles. The impact of confined spraying appears to be zero on yields and minimal on GHG emissions. These technologies have a higher purchase cost and are described as complex to use. They can increase labour time because of longer field and clean-up times. These disadvantages can be partially or totally compensated by a saving of pesticides and an increase in the speed of progress. Their economic balance depends on the characteristics of the vineyard.

B. Precision agriculture

Precision agriculture, through DSTs, offers an adjustment of agricultural practices according to measured conditions (soil, climatic conditions, type of crop, etc.). DSTs can be associated with dose modulation tools or automatic robots. Dose modulation tools correspond to the methods of applying variable doses of inputs and power steering of tractors. They adjust the doses and their location according to the needs of the crops (Farm Europe 2019).

As shown in Figure 3, digital tools related to crop production can be classified into 5 levels according to their degree of accuracy, the equipment required and their cost. DATs processing information from sensors, weather stations, satellite images and cameras are present at each level. They are detailed on page 25. From the third level, these tools are associated with dose modulation tools. They are discussed on page 29. Levels 4 and 5 add to the tools of the previous levels robotization as an alternative to pesticides for pest and disease management and irrigation. The tools are discussed on page 34(Farm Europe 2019).

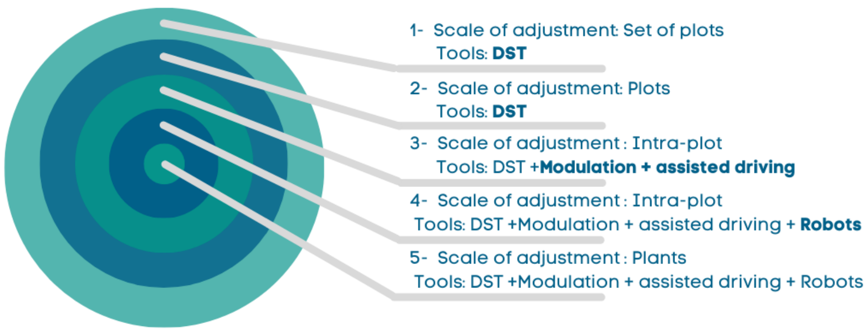


Figure 3 - The five levels of digital agriculture

1. Decision supporting tools

Decision supporting tools (DST) are diagnostic, risk assessment or advisory tools that offer solutions adapted to the agronomic and pedoclimatic context of the plot on:

- Product selection (doses, concentrations, choice of active substance, product mixtures)
- The treatment (date, location, choice of equipment and settings)
- Complementary practices (varietal choice, rotations, preventive methods, etc.) (Arvalis 2019).

This section focuses on DSTs that help reason the use of inputs (pesticides, fertilizers and water). The manual adjustment of inputs on the different zones of the plot, based on maps, is also detailed.

To estimate the risk of sanitary, nutrient or water pressure and to adapt their recommendations, DSTs are based on the history of the plot, the type of soil and the climate. This information is provided by the winegrowers, measured by satellite images, or in real time via sensors, cameras, and weather stations (Farm Europe 2019).

a. Results obtained

Use of inputs

Pesticides

Many DSTs map the vineyard or adjust fungicide treatment programs to phytosanitary risks based on weather stations (Zébic 2016). This is notably the case of Optidose® which allows a reduction of fungicide doses by an average of 30%, varying from -15 to -50% depending on the year, the location and the grape variety (Dubois 2018). Another tool developed by the ICV, Décitrait®, ensures reductions of between 20 and 35% according to the ICV (Montigaud 2020). This French average is supported by another Italian study that obtains a 25% reduction in the quantities of pesticides applied from a prescription card without compromising yield (Román et al. 2020).

Fertilizers

One study accounted for a 20-30% fertilizer saving in French vineyards through the use of DSTs in viticulture compared to traditional methods (Sawyer, Oligschlaeger, and Nikolay Khabarov 2021). A reduction between 33 and 45% of nitrogen and potassium fertilizers has been observed in Greece (A. T. Balafoutis et al. 2017).

Water

Irrigation can be adjusted manually from the prescription maps of the DST. Such an adjustment is done uniformly by zone or even on the whole plot. A finer adjustment can be done automatically, with the variable rate irrigation (VRI) techniques, described on page 32. The irrigation prescriptions of the DSTs are compared to irrigated systems without DSTs.

The use of micro-irrigation, drip irrigation, can lead to an increase or decrease in water consumption depending on the sectors of the plot, compared to standard consumption. Only a minority of vineyards are irrigated today in Europe. For example, less than 10% of French vineyards have such systems (Sawyer, Oligschlaeger, and Nikolay Khabarov 2021). However, there is a renewed interest in Mediterranean regions due to the increase in temperature and the reduction in rainfall.

Among the various irrigation methods available, there is a renewed interest in fertigation - or fertirrigation or fertilizing irrigation. Fertigation ensures a better assimilation of nutrients, which can only be absorbed in the presence of water. This allows for higher yields than with fertilizer alone.

Irrigation of the vines has the sole objective of limiting the hydric constraint and essentially impacts the composition of the berries, which will become waterlogged. This affects their volume, which is however strongly linked to the genetics of the grape varieties (Deloire 2019). The quantities of water and their inputs vary according to the grape varieties, the stages of the vegetative cycle, the water constraints encountered, the terroir and the targeted objectives. Irrigation adjustments ranging from -16% to +8% compared to a control plot, observed in fertigation trials, illustrate these variations (A. T. Balafoutis et al. 2017).

DSTs can help to control irrigation and increase its efficiency. These are essentially models linked to weather stations, probes or humidity sensors. But *in situ* measurements with a pressure chamber are still essential to ensure that the model used matches reality (Deloire 2019).

Effects on yields

Input management DSTs such as fertilizers and pesticides, as well as those that help with harvest planning, will improve the quality of clusters rather than their quantity, thereby increasing the value of the wines produced (Sawyer, Oligschlaeger, and Nikolay Khabarov 2021). Generally no yield reduction is observed when following the pesticide and fertilizer reductions advocated by these DSTs (Dubois 2018; Sawyer, Oligschlaeger, and Nikolay Khabarov 2021). Although there is no correlation between irrigation and yields, some experiments have obtained yield increases of more than 50% when 50 to 100 mm of water were applied under Mediterranean conditions (Zébic 2016). In contrast, a reduction in irrigation has no impact on yield according to the trial conducted by Ortuani et al.(2019. The study by (A. T. Balafoutis et al. 2017) in Greece is an example, obtaining a 16% yield increase under fertigation by manually adjusting fertilizer amounts on two areas. No information on the quality of the grapes from these yields is specified.

Effects on working time

Producers of DSTs claim the simplicity of the interfaces and the time savings they bring by reducing fertilizer and pesticide applications (Sawyer, Oligschlaeger, and Nikolay Khabarov 2021). Some studies show, however, that the use of DSTs that recommend crop protection treatment doses leads to an additional cost of 60€ per treatment for some providers. They did not, however, report any additional difficulties (Dubois 2018).

Effects on the cost of production

The cost of DSTs is about 25-35€/ha or 250-500€/year (Montigaud 2020; Sawyer, Oligschlaeger, and Nikolay Khabarov 2021). DSTs depend on climatic and meteorological data. Depending on the type of DST used, growers may have to set up weather stations. Weather stations require an investment of between €400 and €2,000 (Weenat 2020). These stations can be managed and benefit organizations following the farmers, an isolated farmer or a group of farmers geographically close enough. To this can be added an increase in work time (Dubois 2018).

Effects on climate change mitigation

It is recognized that the use of input requirements mapping allows for more efficient management of inputs and therefore lower GHG emissions related to pesticide, fertilizer, fuel, and electricity consumption (Sawyer, Oligschlaeger, and Nikolay Khabarov 2021).

In fertigation, the increase in yields allows an increase in energy efficiency of around 20% (Stamatiadis 2013).

Irrigated crops emit more N_2O than non-irrigated crops. This increase is between 50 and 140%. Precision irrigation would reduce these emissions by adjusting the amount of water irrigated to crop needs (Soto et al. 2019).

A reduction of 25% to 28.3% in GHG emissions was achieved in viticulture based on a carbon footprint analysis of two Greek vineyards. This carbon footprint considered GHG emissions related to fertilizer production, direct and indirect N_2O emissions, pesticide production, crop residue management, as well as energy consumption (A. T. Balafoutis et al. 2017). But according to other studies, the use of satellite imagery provides limited assistance in the adaptation of viticulture to climate change (Sawyer, Oligschlaeger, and Nikolay Khabarov 2021).

Other effects on soil, water, air and biodiversity

A reduction in surface water and groundwater pollution is observed in viticulture when using DSTs related to fertilizer management. However, the contribution of satellite imagery remains limited in preserving biodiversity and limiting air and soil pollution (Sawyer, Oligschlaeger, and Nikolay Khabarov 2021).

b. Remarks

The use of DSTs whose recommendations are based on satellite images is still not widespread today. As an example, such DSTs are used in 1% of vineyards in France (Sawyer, Oligschlaeger, and Nikolay Khabarov 2021). The multiplication of similar services and competition will drive down prices in the coming years, leading to their democratization.

These DSTs are limited because they do not consider the variability of clusters and microclimate. A solution to be developed in the future to remedy this would be to have automated field sensors (Zébic 2016).

c. Appraisal

In viticulture, many DSTs recommend the doses of pesticides and fertilizers to be applied based on soil maps and weather stations. Suggesting when to act, they help manage inputs and change practices. They ensure their efficient use by reducing input doses without compromising yield. These reductions vary according to location, year, soil and climatic conditions, and sanitary pressure. DSTs mainly improve the quality of yields and have little influence on quantity. Still underdeveloped, DSTs related to water management also seek to improve water efficiency. Their main objective is to adjust water supply to limit water stress and its consequences on berry composition.

The impact of any DST on working time is difficult to quantify. The work time could increase when they are used. A return on investment occurs through the increase in gross margin linked to a reduction in input consumption and a potential increase in berry quality. Their contribution to adapting to and combating climate change and to preserving the environment is limited to a reduction in GHG emissions and a decrease in water pollution. These tools, which are not yet widely available, represent a further step towards compliance with environmental regulations.

2. Application of adjusted and localized doses of inputs

In viticulture, some fertilizer spreaders adjust the quantities of soil improvers, manure or fertilizer according to measured needs. Precision spraying, which adapts the opening and closing of its nozzles based on a mapping of needs or on data from onboard cameras, is very little developed and has not gone beyond the experimental stage.

Adjustment of the amount of water irrigated, in Variable rate irrigation (VRI) systems, can be achieved by automatically controlling the triggering and duration of opening of nozzles or multiple sections of the irrigation network from a recommendation map. Water pressure adjustment is another alternative (Soto et al. 2019).

These techniques are slowly appearing in the vineyard machinery fleet. They have a higher cost than their standard counterparts (Zarco-Tejada, Hubbard, and Loudjani 2014).

a. Results obtained

i. Modulation of plant protection products

Effects on pesticide use

The use of sprayers to modulate input doses is much less developed in viticulture than in field crops. DSTs that adjust the amount of pesticides in real time using on-board sensors or remote sensing are still in the experimental phase and can save 16 and 58% of pesticides (Lorriette 2019; Soto et al. 2019; Raynal 2019). The only way to modulate doses in viticulture is to adapt the speed. The current boom in sprayers with recuperator panels, detailed on page 22, may explain the lack of interest in intra-plot modulation (Personal communication with Thomas Crestey, Bruno Tisseyre and Jacques Rousseau 11/01/2021).

Effects on yields

Little information exists on the effect of adjusting pesticide treatments on yield. In general, yields are maintained or even increased if modulation of pesticide doses allows more targeted action against pests (Soto et al. 2019).

Effects on working time

Few studies specific to viticulture quantify the effect of precision spraying on working time.

In general, adjusting the amount of pesticide to be applied can save time when preparing spray doses and applying the treatment, if pest pressure is lower. However, the training required to master this technique and the calibration of the system are time-consuming and compensate for this time saving, ultimately leading to an increase in work time (Soto et al. 2019).

Effects on the cost of production

According to the review by A. Balafoutis et al(2017), the economic gains enabled by precision sprayers are proportional to:

- Weed pressure and weed stubble distribution.
- The amount of pesticide applied, which is related to weed competition and crop tolerance and resistance.
- The cost of pesticides.
- The number of applications per year.
- The type of system used: the risk of errors increases for a system without assisted guidance.

Herbicide savings reduce production costs. In addition, there are the labor and fuel costs associated with these technologies. A saving of 20% is possible according to data from experiments presented by Raynal (Lorriette 2019).

Although precision sprayers are becoming more and more accessible, they still have a higher investment cost than conventional sprayers. Variable and fixed costs are estimated to be on average 4.5€/ha higher for precision sprayers. Other studies estimate the investment in precision sprayers to be profitable if it leads to a pesticide saving of more than 14€/ha (A. Balafoutis et al. 2017). In Europe, experts estimate that investments made in precision sprayers using recommendation maps linked to their GPS can be amortized in 3 to 4 years (Soto et al. 2019).

Effects on climate change mitigation

Reducing the use of pesticides does not have a significant direct impact on GHG mitigation in relation to total agricultural emissions. The emissions related to pesticides that can be reduced occur mainly during their manufacture. Applied in much smaller quantities than other inputs (fertilizers, seeds, fuel), their impact on GHG emission is very low at the farm level (A. Balafoutis et al. 2017).

Other effects on soil, water, air and biodiversity

Decreasing the use of pesticides through precision spraying improves water and air quality. More natural habitats are preserved and an increase in the diversity of living organisms is observed (Soto et al. 2019).

ii. Variable rate fertilization

Effects on fertilizer use

In viticulture, as for precision plant protection, the development of fertilizer spreaders that modulate doses is in its infancy. A few fertilizer spreaders that have been tested can save 25 to 30% of fertilizer (Aubert 2020; Alexandre Abellan 2014; Personal communication with Thomas Crestey, Bruno Tisseyre and Jacques Rousseau 11/01/2021).

Effects on yields

The use of precision spreaders in viticulture improves the homogeneity of the harvest, which improves the quality of the yield (Aubert 2020).

Effects on working time

Few studies specific to viticulture have quantified the effect of real-time modulated fertilisation on working time. As these technologies are similar to those used in field crops, we can estimate that their effect will be of the same order of magnitude.

In arable farming, the time spent spreading fertiliser is reduced by an average of 1.56% when precision spreaders are used. However, the training required to master this technique and the system settings are time-consuming. They increase working time by an average of 2.19% and 2.29% respectively. Farmers see an increase in total working time of 2.82% on average (Soto et al. 2019).

Effects on the cost of production

In viticulture, the savings in fertilizer made possible by the fertilizer spreaders tested translates into a saving of €9/ha. Nevertheless, this saving achieved does not make the equipment investment profitable (Gaviglio 2018c).

Effects on climate change mitigation

Reducing the amount of fertilizer leads to a decrease in direct and indirect N_2O emissions. Coupled with lower fuel use, this reduces direct and indirect CO_2 emissions. Ammonia emissions are also reduced.

Variable rate fertilization could reduce GHG emissions by 5% compared to emissions from nitrogen fertilizer application. According to a study modelling their effects on GHG emissions at the European scale, these technologies can reduce between 3805 and 6567 kT eCO_2/year, which corresponds to 1.5% of the total GHG emissions of the agricultural sector in 2015 (Soto et al. 2019).

Other effects on soil, water, air and biodiversity

Fertilizer application adjusted to crop needs also reduces the risk of leaching and eutrophication. Ammonia emissions are also reduced (Soto et al. 2019).

iii. Variable rate irrigation

Effects on water consumption

Few data quantifying the effects of VRI techniques on water consumption, productivity and production costs exist today at European level. This finding is even more pronounced for precision micro-irrigation alone (Soto et al. 2019). As described in the section on DSTs, page 25, a minority of vineyards are irrigated today. Drip irrigation and fertigation of vineyards is however booming, especially around the Mediterranean. The aim of these techniques is to combat water stress by adjusting the quantities of water.

The evolution of the quantities of water consumed (increase or decrease) varies according to the locations, the years, the pedological and climatic conditions as well as the sanitary pressure. The efficiency of VRI micro-irrigation is therefore difficult to quantify. Nevertheless, it can be estimated that with the automation of the section cuts, the efficiency of this technique is equal to or greater than what is possible with the DSTs linked to irrigation management.

Effects on yields

As described in the ADO section on page 25, irrigation in viticulture influences berry composition, and thus yield quality rather than the quantity of berries produced (Sawyer, Oligschlaeger, and Nikolay Khabarov 2021; Deloire 2019).

Research conducted in fertigation shows a better assimilation of fertilizers in the presence of water, thus leading to an increase in yields. The results obtained with VRI fertigation should be of the same order of magnitude or even higher than those obtained by manually adjusting fertigation based on DST prescriptions.

Effects on working time

In general, the automation of VRI irrigation ensures time savings in the field. However, the training required to master this technique and adapt it to the soil context of the soils on which they are planted, as well as the calibration of the system, are time-consuming (Soto et al. 2019).

Effects on the cost of production

The cost of adopting precision irrigation from pre-existing drip irrigation systems is estimated at €40/ha (Soto et al. 2019). To this must be added the cost of recommendations by DSTs. The automation of work time reduces the costs related to irrigation management. In viticulture, up to 170€/ha/year can be saved (Paysan and Dufourcq 2018). This offsets a potential increase in labour time. The reduction in water and fertilizer consumption obtained by fertigation induces a decrease in production cost. Coupled with an increase in yield, the gross margin increases.

Effects on climate change mitigation

Irrigated crops emit more N2O than non-irrigated crops. This increase is between 50 and 140%. IRV would further reduce these emissions by adjusting irrigated water amounts to crop needs compared to uniform application of DST-prescribed water amounts (Soto et al. 2019).

Other effects on soil, water, air and biodiversity

IRV minimizes leaching risks and improves groundwater quality. Oxidation of SOM is reduced, thus promoting soil quality (Stamatiadis 2013).

b. Remarks

The possibility of using these technologies depends on the type of vineyard configuration. As shown in Figure 4, the use of these technologies is possible in the majority of vineyards. However, there are regions where the possibility of implementing these technologies is between 1 and 29% (Ghiglieno 2020).

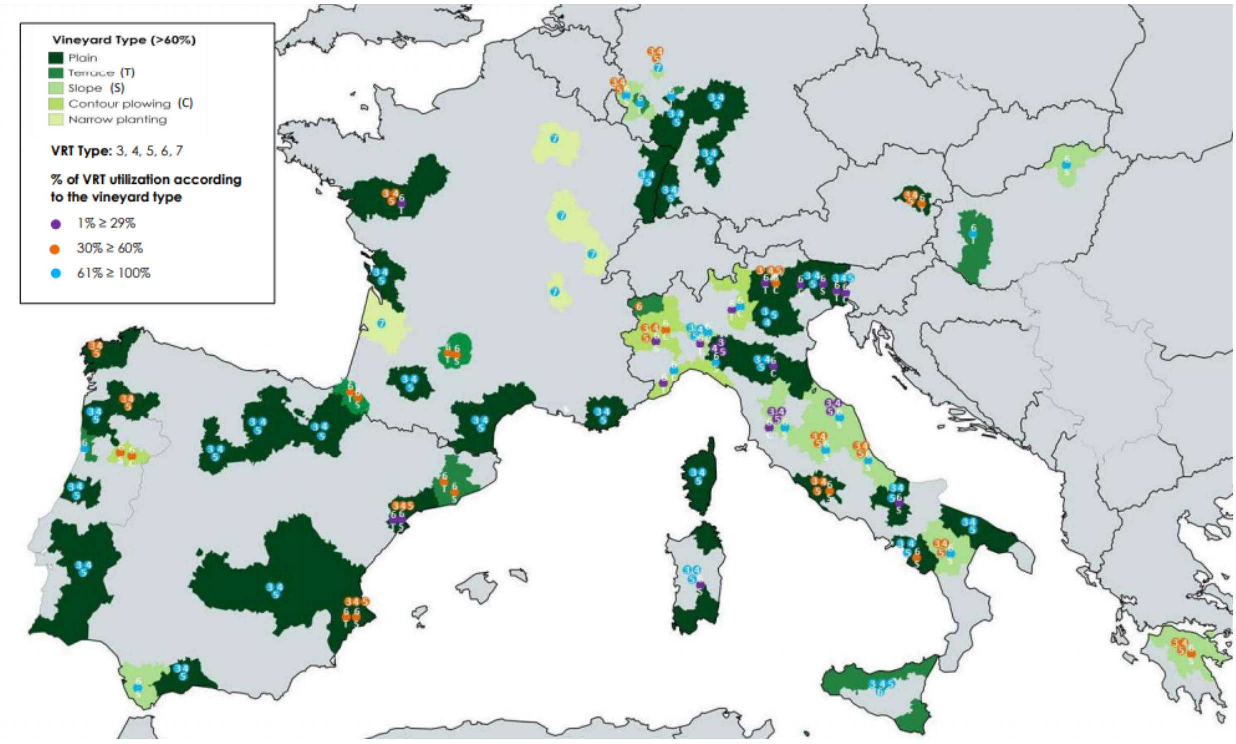


Figure 4 - Percentage of use of dose modulation tools according to type of vineyard, source: Ghiglieno 2020

Although these technologies represent an investment, their cost is decreasing year after year and they are appearing in more and more agricultural equipment. It is now estimated that 70 to 80% of equipment on the market is equipped with them. These costs, as well as the effects on input efficiency and production costs, vary from one country to another, depending on the size of the farms, their type and their technologies

Investments can be made at the level of individual farms or by collective entities, as is done by GAIA in Greece, particularly in regions where farms may be smaller.

In addition to investment support, these tools require good broadband coverage in European rural areas, which is below 50% for 14 member states (Ivanova et al. 2018). Finally, better interoperability of tools would make them more accessible to farmers (Zarco-Tejada, Hubbard, and Loudjani 2014).

c. Appraisal

Technologies for adjusting the quantities of pesticides and fertilizers in real time are being tested in viticulture. Variable rate pesticide treatments are struggling to develop in the face of competition from confined spraying. The effects of these techniques on efficient water management are much more complicated to analyse.

Precision plant protection maintains or even increases yields. The quality of the yields is superior thanks to the homogenization of the yield that variable rate fertilization allows. An improvement in the composition of the berries is also obtained in VRI.

Whatever the inputs, the gain in treatment time is offset by the calibration of the system and the appropriation of the technique. A return on investment and a reduction in production costs is possible, by choosing tools adapted to the sanitary pressure and to the nitrogen and water requirements. This choice must also consider the size of the users (farm or group of farms) or by using third party organisations.

While variable rate fertilization has the potential to reduce GHG emissions, precision irrigation may increase GHG emissions if it increases the volume of water irrigated.

These technologies improve water, air and soil quality and help preserve biodiversity. They can be used to complement other levers, such as disease control, soil management or mechanical management.

3. Robotic farming

Robotisation in viticulture is less developed than in other agricultural sectors but seems promising. Robots are nowadays thought to maintain the soil, to help during harvesting and pruning, to collect data on the condition of the vines or even to carry loads (Gaviglio 2018c). While some robots are beginning to be commercialized, most are still in the experimental stage.

As with other agricultural sectors, robotics in viticulture is being developed primarily to deal with weed management (Gaviglio 2018c). Numerous robots configured to attach inter-row or cavaillon tillage tools are currently being developed ("La Bataille Des Robots Viticoles Est Lancée?" 2018). The use of robots for mechanized soil maintenance is detailed on page 40. This section focuses on the use of robots applying adjusted doses of pesticides.

Very little data quantifying the performance of these robots is available today, as none of them have gone beyond the experimental phases.

a. Results obtained

Effects on pesticide use

Although it is assumed that a localized and pressure-adjusted pesticide application leads to a reduction in the use of phytosanitary products, few data quantifying this reduction are available. An ongoing study seeks to recover 80% of the sprayed product, which corresponds to the amount of pesticide that is not generally retained by the foliage ("La Pulverisation Confinée Vitibot" 2021).

Mechanical management of the cavaillon and the inter-row seems to be preferred to the spraying of herbicides by robots modulating the doses.

Effects on yields

No information on the impact of spray robots on yields is given. If weed, disease and pest detection is accurate, they would logically have no or positive impact on yields.

Effects on working time

While some believe that spraying robots would remove some work time constraints, this reduction in work time is not quantified. According to others, robots would simplify the drudgery of work but their use requiring the presence of someone would not affect working time (Gaviglio 2018c).

Effects on the cost of production

A saving linked to a lower use of inputs reduces the cost of production. No study quantifies this rate of reduction, which depends on the phytosanitary pressure. This saving does not allow to amortize the cost of the robots, which is between 40 000€ and 150 000€ (Gaviglio 2018c). The cost of the service per hectare varies from 1,500 to 3,500 €/year/ha. This price today is very high and will tend to decrease in the coming years with the diversification of the offer.

Effects on climate change mitigation

In addition to the potential reduction in GHG emissions related to less pesticide use, a reduction in fuel items compared to existing tractors would be observed (Gaviglio 2018c).

Other effects on soil, water, air and biodiversity

The risks of drifting are limited, thus reducing air, soil and water pollution which plays in favour of biodiversity preservation. The weight of the robots being lower than current tractors, they avoid problems of compaction (Gaviglio 2018c).

b. Remarks

The use of robotics in viticulture is interesting to deal with weed pressure, especially in the cavaillon where mechanical control risks damaging the vines.

c. Appraisal

The use of robotics in viticulture could be an interesting solution against diseases and weeds of the cavaillon (Gaviglio 2018c). However, the technical and economic model of viticultural robotization is not yet found. The cost of these solutions, the number of robots today on the market and those still in the development stage make it a future solution rather than a current one.

III. Input substitution

A. Pesticides

1. Physical Wrestling

Physical control targets weeds. It is seen as an alternative to herbicides. Among the different means available, mechanical weeding, robotic mechanical weeding and thermal weeding are distinguished. The latter, whose main methods are flame, steam or hot water weeding, was not considered in this study. Indeed, their use is harmful to the biodiversity of the first centimeters of the soil, costly, and emits greenhouse gases. It can be a source of fire outbreaks (Guyomard et al. 2013).

a. Mechanical weeding

In viticulture, different mechanical weeding tools are used for the row and the inter-row. The most common tools for inter-row weeding are: the de-caulper, inter-row weeders with weeder blades and rotary tools that pull up and disperse weeds. Mixed weeding combines mechanical weeding of the inter-row with chemical weeding under the row. The inter-row management can be carried out by disc or tine tools. Mowing can also be carried out if it is grassy. All these modalities, row/inter-row, mixed weeding or not, type of weeding (total or partial) influence the number of tool passages, as shown in Table 5 and Table6. The average number of passes for chemical weed control is 1.7. The number of passes in mixed or mechanical weed control is three to four times higher (Jacquet et al. 2019).

Table 5 - Average number of passes for mechanical weeding alone, source: Jacquet et al. 2019

	Treatment	Without weed	Weed control	Half grassing
Rank	Chemical	0	0	0
	Mechanics	3,1	2,5	2,7
Inter-row	Mechanics	3,6	1	1,7
	Mowing	0	2,4	1,6
Total		6,7	5,9	6

Table 6 - Average number of passes for mixed weed control, source: Jacquet et al. 2019

	Treatment	Without weed	Weed control	Half grassing
Rank	Chemical	1,5	1,8	1,8
	Mechanics	0,7	0,3	0,3
Inter-row	Mechanics	3,1	0,4	1,4
	Mowing	0	3	1,7
Total		5,3	5,5	5,2

iv. Results obtained

Effects on herbicide use

Mechanical weed control makes it possible to do without herbicide. A 33% reduction in herbicide dose can occur with mixed weed control (Jacquet et al. 2019).

Effects on yields

The impact of the tools on the superficial root network and the injuries caused to the stumps can lead to a drop in yield of 5 to 20% in extreme cases. Yield reductions are mainly observed in the first five years of mechanical weeding. Stump age and conformation, soil type and root establishment also influence yield (Jacquet et al. 2019).

Effects on working time

Mechanical and mixed weeding have a much longer work rate than mechanical weeding. The work time increases on average from 6.3h/ha to 10.7h/ha with mechanical weeding, depending on whether the vineyard is narrow or wide and whether the inter-row is grassed, semi-grassed or not grassed. Table 7details these methods. This increase is less for mixed weeding, varying from 3.4h/ha to 6.8h/ha depending on the row spacing and weed control, as shown in Table 8.

Table 7 - Additional work time for mechanical weeding compared to chemical weeding (h/ha), source: Jacquet et al. 2019

Type of vines	Without weed	Weed control	Half grassing
Narrow	10,7	11,5	6,3
Large	9	6,3	8,4

Table 8 - Additional work time for mixed weed control compared to chemical weed control (h/ha), source: Jacquet et al. 2019

Type of vines	Without weed	Weed control	Half grassing
Narrow	4,9	4,7	3,4
Large	6,8	5	5

Effects on the cost of production

Inputs (herbicides and fuels), traction, labour, depreciation, and equipment repairs are considered in the cost of production. The cost of labour and mechanisation are higher than the cost of pesticides, which increases the cost of production. It increases on average from 124 to 636 € in mechanical weeding, depending on whether the vineyard is narrow or wide and whether the inter-row is grassed, semi-grassed or not grassed. Table 9details these methods. This increase is less for mixed weeding, varying from 38 to 241 € depending on the row spacing and weed control, as shown in Table 10.

Table 9 - Additional production cost of mechanical weeding compared to chemical weeding (€/ha), source: Jacquet et al. 2019

Type of vines	Without weed	Weed control	Half grassing
Narrow vines	333	445	636
Wide vines	282	124	246

Table 10 - Additional production cost of mixed weed control compared to chemical weed control (€/ha), source: Jacquet et al. 2019

Type of vines	Without weed	Weed control	Half grassing
Narrow vines	241	205	38
Wide vines	196	109	180

Effects on climate change mitigation

The higher number of passes in mechanical weeding and mixed weeding than in chemical weeding, raises fuel consumption by an average of 5.7 and 3.4 times respectively (Jacquet et al. 2019). Mechanical weeding will consume one to five times more energy than chemical weeding depending on the assumptions, which translates into as many additional direct CO_2 emissions (Gaviglio 2020).

Other effects on soil, water, air and biodiversity

In viticulture, the reduction in herbicide use made possible by mechanical weeding improves water quality.

v. Remarks

Mechanical weeding is highly dependent on rainfall. It must be carried out under favourable climatic conditions, over periods that can be very limited (Guyomard et al. 2013). Weed cover, development stage and soil condition impact the type of tool needed and the date of intervention. Curves and slopes increase the risk of erosion in viticulture (Gaviglio 2020).

Weeding tools require an investment that can be made by a group of winegrowers, a cooperative or a CUMA. Such sharing can be complicated if the periods when climatic conditions allow mechanical weeding are limited. Investing in such tools requires that favourable soil and climatic conditions be met (Guyomard et al. 2013). An understanding of the soil and flora dynamics is required to limit the risks of erosion and yield loss. Training and regular monitoring are recommended to practice mechanical weeding (Gaviglio 2020).

The use of these tools should be rationalized. Mechanical weeding is not very effective against perennials, which are multiplied and disseminated by the tools that fragment them (Garnica et al. 2020).

The effectiveness of treatments combining mechanical and chemical control depends greatly on the effectiveness of the herbicides used and the stage of the crop at which they are applied (Garnica et al. 2020).

vi. Appraisal

Mechanical weeding requires specific tools depending on the location of the weeding in vineyards. This solution is effective if it is repeated regularly or combined with herbicide treatments that can be applied in reduced doses or locally. Under certain conditions, it allows you to do without herbicides.

Profitability may be reduced by increased fuel and time consumption, and potential impact on yield quality and quantity. The GHG balance of this solution is worse than chemical weed control due to direct CO_2 emissions from fuel.

b. Robotic mechanical weeding

Robotic mechanical weeding is one type of precision farming. These are tools such as hoes, harrows, rotary, or interceptors that incorporate assisted driving and weed recognition technologies to be autonomous.

Weed control robots are mainly developed for high added value crops with a wide row spacing, such as in horticulture or viticulture. Their use is in full development: several robots are available on the market and many prototype projects are underway. The shape of the robots varies according to their use (pulling, mowing, etc.) and their ability to attach tools that are specific to them or tools usually used by the winegrower.

Mechanical weeding of the inter-row is already efficient and effective. The challenge of robotization is therefore focused on the maintenance of the cavaillon, where the difficulty is not to injure the vines or pull up the stumps (Gaviglio 2018c). While their performance is known qualitatively, very little quantitative information is available (Gaviglio 2018c; Lowenberg-DeBoer et al. 2020).

Mechanical weeding robots are different from robots that spray herbicides in an ultra-precise manner, which are described in detail in the section on dose modulation, page 29. Some farmers combine mechanical and chemical weeding robots to perform mixed weeding.

i. Results obtained

Effects on herbicide use

The autonomy of the tools makes multiple interventions possible. The frequency and regularity of robot passes increase weed control (Gaviglio 2018a).

Mechanical weeding robots have an efficiency on weeds ranging from 65 to over 82% (Fountas et al. 2020). A reduction of chemical treatments is observed although cavaillon maintenance is difficult (Gaviglio 2018c).

Effects on yields

No information regarding the effect of robots on yields is given except by the manufacturers, according to whom the impact is zero (Naïo Technologies 2016). If the efficiency of the weeding robots is satisfactory, i.e. above 80%, no impact on the quantity and quality of the yield takes place. Regular mowing by a mowing robot prevents weediness from inducing hydro-nitrogen stress on the vines. Crop damage can be observed in viticulture, when robots work along the cavaillon (Lowenberg-DeBoer et al. 2020).

Effects on working time

Although the use of robots requires a human presence, they reduce working time by about 20% (Barbière 2020). They allow an adjustment of the organization to focus on higher value-added operations and reduce the drudgery of work (Gaviglio 2018a).

Effects on the cost of production

A synthesis of studies conducted between 1990 and 2018 argues the lack of research regarding the economic impact of robotization in agriculture (Lowenberg-DeBoer et al. 2020).

The cost of mechanical weeding remains substantial although it is reducing year by year (Gaviglio 2018a). A weeding robot remains more expensive than chemical weeding, with the necessary investment ranging from €25,000 to €80,000 (Farm Europe 2019). Studies estimate that investing up to €40,000 in a weeding robot will still be more beneficial in the long run than mechanical weeding. In viticulture, the purchase of a robot represents about 90% of the cost of weed control (Lowenberg-DeBoer et al. 2020).

Effects on climate change mitigation

According to Lowenberg-DeBoer et al(2020, assumptions about environmental benefits have been made but not quantified. The reduction in the use of herbicides leads to a reduction in indirect CO_2 emissions related to their manufacture. This statement must be qualified, as the construction of robots also emits CO2. A reduction in fuel is observed compared to the use of towed implements or sprayers, thus reducing direct CO2 emissions (Lowenberg-DeBoer et al. 2020; Farm Europe 2019; A. Balafoutis et al. 2017).

Other effects on soil, water, air and biodiversity

Robots that are smaller than a tractor reduce the risk of soil compaction compared to a tractor towing an implement or sprayer (Lowenberg-DeBoer et al. 2020). They have the ability to work in the presence of and in close proximity to natural features such as trees, rocks, waterways (Lowenberg-DeBoer et al. 2020). Less herbicide use improves water and air quality.

ii. Remarks

Given the investment cost of a robot, solutions such as weed control services and contracts reduce the cost of use and make robots profitable on larger surfaces (Lowenberg-DeBoer et al. 2020). The versatility of robots, especially in viticulture, would make them more profitable (Gaviglio 2018a). A final alternative would be to help with the investment of robots, as their use is a lever to reduce the use of herbicides and plays in favour of the environment. However, the ability of weed control robots to achieve environmental objectives compared to other alternative solutions is not unanimous (Lowenberg-DeBoer et al. 2020).

iii. Appraisal

Although weed control robots are increasingly used and their performance is recognized, little quantitative data on their performance is available today. They make it possible to reduce or even do without herbicides. Yields are generally not affected, although a reduction can sometimes be observed when using mechanical weed control within the row. The laboriousness of work is reduced, making it possible to reorganize priorities. They potentially reduce CO_2 emissions and improve air, water and soil quality. Despite all these advantages, weed control robots lack competitiveness compared to other methods because of their cost. Alternatives that make them more accessible are being developed.

2. Biocontrol

Biocontrol is the set of plant protection methods based on the use of natural preventive or curative mechanisms. It is a regulation of living organisms induced directly or indirectly by the use of microorganisms and macro-organisms predators, parasitoids, pathogens or competitors of the bio-pest. Substances of microbial, plant, mineral and animal origin, which are natural or synthesized in the same way as nature, can also be used. Chemical mediators such as pheromones are also used. Microorganisms, substances of natural origin, and chemical mediators are considered as plant protection products and are subject to a marketing authorization.

Within biocontrol, biological control, which is based on the use of living organisms, is distinguished from biotechnical control, which uses biological phenomena or products of organic origin but not living beings. Biotechnical control can include products that do not systematically meet the criteria to be registered as biocontrol (Dumoulin et al. 2019; Meyer 2018).

a. Biological control

Biological control can be achieved through the introduction and acclimation of a new species, mass releases, or by inoculating small quantities of organisms that predate the target pests. Manipulating the environment to foster the pest's enemies is also part of the biological control process. This can be done, for example, by inserting agro-ecological elements (Aubertot et al. 2005). The effects of some of these elements are detailed in the sections on grassing and agroforestry, pages 9and 16.

Biological control is highly developed in arboriculture, market gardening, horticulture, and viticulture, but is much less common in field crops.

i. Results obtained

Effects on pesticide use

In viticulture, many biocontrol products are used to control fungal diseases such as downy mildew, grey rot, powdery mildew and against pests (mites, leafhoppers, thrips, flies...). Biocontrol products can reduce the presence of bio-aggressors by 20 to 60% compared to controls without control (Winetwork 2020; Rotolo et al. 2018; Calvo-Garrido et al. 2019). It is often recommended to couple them with synthetic plant protection (Dumoulin et al. 2019; Rotolo et al. 2018). According to Rotolo et al.(2018), such a combination allows an efficiency of 96%, which is higher than the efficiency of synthetic pesticide treatments alone (87%).

Biocontrol agents against weeds are not well developed today. Solutions based on the principle of allelopathy, seed predation by beneficials such as carabids or rhizobacteria are beginning to be studied. Research on the formulation of bioherbicides or mycoherbicides is underway. This is a complex alternative to synthetic herbicides (Bailey 2014).

Effects on yields

Biocontrol agents do not have a direct effect on yield. They can be used to ensure yield if pest levels are below the maximum threshold for biocontrol effectiveness. The yield obtained with the use of such products is generally higher than the control without control. But their effectiveness is low when used alone and can lead to a yield loss of up to 50 or 60% compared to the targeted yields.

Effects on working time

Most biocontrol agents have a very similar dosage to conventional crop protection products when they are to be sprayed. Other disposal methods, such as larval sachets, exist. The positioning of some must be adjusted according to the points of contamination, which increases the time of placement (Dumoulin et al. 2019).

Effects on the cost of production

The price range for biocontrol products is between 45 €/ha and 250 €/ha in viticulture (Winetwork 2020). The costs can vary from simple to double for a couple of biological agent/bio-aggressor, depending on the formulation of the different products. A product is said to be as profitable as a conventional phytosanitary treatment up to about 40€/ha and more expensive beyond that. The frequency of treatments can also increase, thus raising the cost of production. These products do not require large mechanization. Those in sachets can be dispersed manually, which generates an additional cost related to labour and equipment, if done with drones (Dumoulin et al. 2019; Aubertot et al. 2005).

The use of a half-dose of fungicide calls into question the economic interest of this solution, which is already expensive and to which the cost of an additional treatment is added (Dumoulin et al. 2019).

Effects on climate change mitigation

Regardless of the type of crop production, the introduction of biological agents to control weeds, diseases and pests does not affect the soil condition. It therefore has no effect on N2O emissions and carbon sequestration. These practices are generally inexpensive in direct and indirect energy, thus limiting $_{CO2}$ emissions (Guyomard et al. 2013).

Some biocontrol agents, such as bacteria or fungi can produce NH3 (Khan, Bano, and Babar 2020).

Other effects on soil, water, air and biodiversity

The reduced use of pesticides, made possible by biocontrol products, improves air and water quality and promotes biodiversity. Some biological agents act as PDS. Other products, such as sulfur, can be used as fertilizers (Dumoulin et al. 2019).

ii. Remarks

Most biocontrol products claim to have no harmful effects on the environment. This claim is qualified by the fact that the natural origin of biocontrol products does not remove their toxicity. It does, however, accelerate their recognition and degradation by biochemical processes in the ecosystem, when they are not inherent or persistent. The use of certain biological agents such as Spinosad is debated because of their toxicity to pollinators and their persistence. On the other hand, the introduction of predators or parasites must be done with knowledge of the environment, at the risk of seeing certain species become invasive. The case of Asian ladybirds is a good example (Dumoulin et al. 2019).

Biocontrol products that have living organisms as their active ingredient see their effectiveness vary according to climatic conditions (Meyer 2018; Guyomard et al. 2013; Dumoulin et al. 2019). In order to ensure effective control of bio-pests, it is sometimes advisable to combine them with a half dose of pesticides (Rotolo et al. 2018). This combination is not always possible because some biological agents are sensitive to pesticides. The use of low pesticide doses can lead to the creation of resistance phenomena and impact the different components of the environment (water air and biodiversity) as well as the health of the user (Guyomard et al. 2013).

Their development faces technical difficulties in product formulation, partly due to the large-scale multiplication of biological agents and the narrow spectrum of targeted pests. Added to this is the difficulty of estimating their curative and/or preventive effects. Their survival involves cumbersome logistics and storage conditions, both at the distribution and farm levels (Bailey 2014).

iii. Appraisal

Biocontrol products mainly concern diseases and pests. Their effectiveness is not always equal to that of conventional pesticides and depends on many factors, including climate. Yields are uncertain. Combined with the significant cost of biocontrol products, these alternatives can compromise the economic performance of farms.

Biocontrol products can reduce CO_2 emissions from the use of synthetic inputs. Water quality, air quality and biodiversity are improved if the use of pesticides is reduced. However, their impact on the environment must be qualified because the introduction of organisms into the ecosystem can potentially induce unintended imbalances linked to the toxicity or predation of the biocontrol agents used. R&D efforts can help develop more effective products and identify potential negative effects.

b. Biotechnical control

Biotechnical control is the use of chemical mediators. The use of pheromones for sexual confusion is the best known example. Other chemical mediators, such as natural defence stimulators, have the capacity to induce resistance mechanisms in plants against bio-aggressors.

i. Sexual confusion

The use of pheromones only concerns certain insects and is specific to the targeted bio-pest. Sexual confusion disorients males and females following a saturation of pheromones in the environment (Guyomard et al. 2013). It is a technique widely developed in viticulture and arboriculture.

1) Results obtained

Reduction of insecticides

Up to four treatments of insecticides specific to the targeted insects can be avoided with mating disruption. In some years, it is even possible to avoid the use of these insecticides (Thiéry, Delbac, and Laurence 2019).

Effects on yields

Yields are not affected by the use of mating disruption. It is a preventive method that can be used alone or coupled with a curative insecticide treatment depending on the pressure observed to ensure yield maintenance (Le Bars et al. 2019).

Effects on working time

This method requires technical skills and therefore observation to place the devices at the right time and in the right place. Pheromone dispensers are renewed annually, and require between 0.5 and 5 hours of installation per hectare per year. It is necessary to count between 4 and 6 hours per hectare and per year of observation to put the devices at the right time, in the right place and to react if the pressure is too strong. In return, there is a reduction in the workload associated with chemical treatments. A better distribution of work during the season is observed despite an increase in work time (Herbin 2011; Le Bars et al. 2019).

Effects on the cost of production

Setting up pheromone dispensers costs between 150 and 350€/ha, depending on the number of generations and insects that one wishes to control (Herbin 2011; INRA 2018). This cost is higher than that of synthetic insecticides. To this must be added the cost of the labour required for the installation of the devices and the observations. A reduction in the cost of plant protection products, mechanization and fuel takes place if the number of insecticide treatments is reduced (Le Bars et al. 2019).

Effects on climate change mitigation

The energy cost of pheromone production is lower than that of pesticides, which reduces indirect CO_2 emissions. Sexual confusion does not require mechanized interventions in viticulture, which reduces direct CO_2 emissions. If the number of insecticide treatments decreases, a reduction in CO_2 emissions is observed (Guyomard et al. 2013; Le Bars et al. 2019).

Other effects on soil, water, air and biodiversity

The safety of pheromones and their potential to reduce the use of insecticides is beneficial to biodiversity. However, there is a risk of secondary pests, such as leafrollers, emerging if there is less use of broad spectrum insecticides. An improvement in water and air quality is also noted (Le Bars et al. 2019).

2) Remarks

The ability of mating disruption to control the third generation of pests is sometimes questioned. Although this technique tends to become more widespread, some farmers refuse to use this already expensive solution if they have to carry out additional insecticide treatments (Goinere 2020).

3) Appraisal

In viticulture, mating disruption makes it possible to reduce the number of insecticide treatments without compromising yield. The economic performance is variable. This solution is more expensive than synthetic insecticides and increases the need for manpower. Nevertheless, there is a reduction in the costs of fuel, mechanization and insecticides. Biodiversity is thus preserved and GHG emissions are reduced, improving water and air quality.

ii. Natural Defences Stimulators

Natural defense stimulators (NDS) or plant defense stimulators (PDS) correspond to any substance or non-pathogenic living microorganism that, once in contact with the plant will induce a state of vigilance or defense against bio-aggressors (Aubertot et al. 2005). These are preventive treatments that activate the plant's defense mechanisms against bio-pests causing fungal diseases (Faessel et al. 2014).

1) Results obtained

Effects on pesticide use

Their effectiveness varies from 0 to 100%. Numerous scientific references point to a lack of correlation between promising results from controlled experiments and randomized results obtained in the field (Daire, Aveline, and Bidaut 2018; Faessel et al. 2014).

Their effectiveness is partial and limited in time. It depends on the interaction with the variety, the development stage of the plant, the environment (temperature, luminosity, available nutrients) and the formulation of the products. This is why several applications are generally recommended, in association with a phytosanitary treatment (Aubertot et al. 2005). Some research has shown better efficacy when SDPs are combined with fungal treatments in half-doses, rather than alternating fungal and SDP treatments in full-doses (Daire, Aveline, and Bidaut 2018).

Effects on yields

Yields and their quality are, due to the variability of action of NDS, lower or equal to yields obtained using pesticides (Guyomard et al. 2013; Faessel et al. 2014).

Effects on working time

SDPs are usually applied by spray, similar to fungal treatments (Dusserre et al. 2018). Treatments must be repeated every 7 to 14 days (Daire, Aveline, and Bidaut 2018; Petit, Aveline, and Molot 2020). The workload is even greater if they are coupled with fungicide treatments.

Effects on the cost of production

PDSs have a cost comparable to or much higher than fungicides in viticulture. An increase in production cost may occur if they are combined with pesticides or if the occurrence of treatments is important (Guyomard et al. 2013; Petit, Aveline, and Molot 2020).

Effects on climate change mitigation

NDS do not consume more energy than pesticides. GHG emissions are equal if they are applied alone (Gayrard and Delval 2017). They increase if they are combined with fungal treatments (Guyomard et al. 2013).

Other effects on soil, water, air and biodiversity

The effect of PDS on water quality, air quality and biodiversity depends on the eco-toxicology of the molecule used (Gayrard and Delval 2017).

2) Remarks

The energy cost of activating plant defenses may reduce yield performance (Dusserre et al. 2018). In addition, the combination of SDPs with a half-dose fungicide may increase the risk of resistance.

3) Appraisal

SDPs have a set of economic constraints (potentially lower yields, additional labour costs and equal or higher production costs), with variable efficiency and mixed environmental benefits.

c. Effectiveness of biocontrol

To be as effective as possible, biological and biotechnical control must be part of a larger-scale prophylactic approach by combining with longer rotations, the use of resistant varieties, crushing crop residues, ensuring better soil cover... (Guyomard et al. 2013).

B. Fertilizers

1. Organic fertilizers

In viticulture, nitrogen plays an essential role in the functioning of the vine and in its yields, both in terms of quality and quantity. Nitrogen management is primarily managed through soil OM. These are substances and carbon compounds of animal or plant origin in decomposition which constitute the litter and the stable humus. These OMs ensure, among other things, the storage and availability of minerals for plants. They have tended to decrease in wine-growing soils over the last few decades, except in grassed plots or where pruning wood is returned (Gontier 2021).

Maintenance and increase of soil OM stock is achieved by amendments. These are large inputs made every 3-4 years (Comifer 2012a). Other nitrogen inputs in the form of organic or synthetic fertilizers are only made if OM management is correct and deficiencies are diagnosed.

a. Results obtained

Effects on fertilizer consumption

Application rates vary greatly depending on the target yield, soil type and soil maintenance. They can be zero if the yield objective is low or up to 90 kg N/ha if the yield objective is high. These quantities are much lower than the quantities of nitrogen made available at planting. The latter vary from 150 to 250 kg N/ha for an input of 30 to 50 tons of manure compost per hectare and from 500 to 550 kg N/ha for an input of 60 tons of green waste compost per hectare (Comifer 2012a).

Effects on yields

A fine characterization of the fertilization potential of organic amendments and fertilizers as well as the availability of nutrients to the canopy is essential to meet soil needs (Guyomard et al. 2013). The application of a well-characterized organic amendment or fertilizer adjusted to the soil and crop needs should allow to reach the targeted yields (Gontier and Cahurel 2021).

Effects on working time

The amendments take place every 3 or 4 years and lead to a punctual increase in the workload. The time and effort involved for the winegrowers is the same for both organic and synthetic fertilizers.

Effects on the cost of production

The cost of acquiring and applying organic soil improvers or fertilizers is considered to be lower than that of synthetic fertilizers (Guyomard et al. 2013).

Effects on climate change mitigation

For a theoretical application of 50 kg/ha, organic amendments divide N2O emissions by 6 compared to organic and organo-mineral fertilizers and by 4 compared to mineral fertilizers. During their use, CO_2 emissions are 3 to 5 times lower than for fertilizers with organic fractions (Galbrun 2012).

According to Navarro et al.(2017), N2O emissions from organic fertilizers are on average 0.023 kg CO2e per 75 cL bottle, or per kg of grape bunch. Knowing that one hectare of vineyard produces on average 8 tons of grapes, this corresponds to approximately 184 kg CO2e/ha. Synthetic fertilizers emit an average of 0.017 kg of CO2e of N2O per 0.75 cL bottle, i.e. per kg of grapes, and their production corresponds on average to emissions of 0.012 kg of CO2e per 0.75 cL bottle, i.e. per kg of grapes. Knowing that one hectare of vineyard produces an average of 8 tons of grapes, the manufacture and application of synthetic fertilizers emits an average of 232 kg CO2/ha. Thus, according to their study on 18 French and Spanish vineyards, the use of organic fertilizer emits 20% less CO2e than the use of synthetic fertilizer.

Other effects on soil, water, air and biodiversity

Organic amendments improve the physical, chemical and biological fertility of the soil (Galbrun 2012). However, these sometimes substantial quantities of organic nitrogen have little impact on the nitrogen flows lost because the products used generate little available and therefore leachable nitrogen (Comifer 2012b). Maintaining or improving soil OM ensures the retention and degradation of organic micropollutants and pesticides, which improves water quality (Gontier 2021). The application of organic amendments and fertilizers can be accompanied by increased NH3 emissions (Guyomard et al. 2013).

b. Appraisal

The availability of nutrients, especially nitrogen, is ensured by the presence of OM in the soil. OM can be maintained or increased through soil amendments. Organic or synthetic fertilizers are used later, if a deficiency is observed. The quantities of amendments are relatively small. They are adapted to the needs of the soil and the targeted yields. The amendment is applied every 3-4 years, leading to an occasional increase in work time. The work time is equivalent for organic and synthetic fertilizers. The acquisition of synthetic fertilizers is more expensive than for organic fertilizers and amendments. The amendments emit less CO_2 and N_2O than organic or synthetic fertilizers. Organic fertilizers emit more N_2O than synthetic fertilizers. The GHG balance of the latter, combining CO_2 emissions linked to their manufacture and N_2O emissions, reverses the balance. Soil improvers are good for soil fertility, biodiversity, and water quality, but NH_3 emissions that compromise air quality can occur.

2. Green manure

Green manures are crops containing legumes that are sown to provide nitrogen for the following crop. They assimilate atmospheric nitrogen through their biological nitrogen fixation (BNF) capacity if they are grown for more than 60 days. They are thus self-sufficient in nitrogen and reduce the use of nitrogen fertilizers during their cultivation (Véricel et al. 2018; Thromas, Bompard, and Giuliano 2018). During the degradation of their residues, part of the nitrogen they contain is mineralized by soil microorganisms and made available to the next crop.

They are perennial or annual plants generally planted in mixtures with other legumes, brassicas or cereals rather than alone. In viticulture, they are established for a few months to a few years in the inter-rows (Baddeley et al. 2017).

a. Results obtained

Effects on fertilizer consumption

In viticulture, the presence of green manures containing legumes in the inter-rows restores between 35 and 45kg N/ha (IFV 2019). These quantities are similar to the nitrogen needs of the vine, which are on average 20 to 30 kg N/ha for an average yield objective. For high yield objectives, they can meet part of the vine's nitrogen requirements, which can be as high as 70 kg N/ha. Studies have shown that vines benefit from the nitrogen provided by green manures. However, the use of green manures as an alternative to nitrogen fertilizers is very little developed in Europe. This could partly be explained by the risks of competition of leguminous crops on water and nitrogen resources (Garcia et al. 2018; MATRAY 2019).

Effects on yields

The impact of green manures on yields is discussed in viticulture. Several trials show no significant difference between yields obtained with green or mineral fertilizers (MATRAY 2019; Zanzotti and Mescalchin 2019). Others show that competition for water and nitrogen resources by green manures during flowering and berry formation can lead to lower yields (MATRAY 2019). Late destruction of green manures can also delay the availability of nitrogen for vineyard needs. When nitrogen is available at the time of bunch closure and veraison, an increase of 19 to 65% in the nitrogen content of musts has been observed (Ivaldi 2014).

The type of destruction also influences the yields. Burying green manures can increase vigour by more than 30% and increase the rate of bud break the following year, compared to a simple shredding-rolling.

Effects on working time

In viticulture, soil preparation, sowing, maintenance and destruction of green manure cover crops require between 5.5 and 8.5 hours per ha per year (Arino 2009).

Effects on the cost of production

The installation of green manures on all the inter-rows of a vineyard plot in autumn costs between 90 and 290€/ha approximately. This price includes the cost of labour, traction and seeds. Its destruction costs about 35€/ha and its burial 55€/ha (IFV 2019; Arino 2009).

Effects on climate change mitigation

A study carried out in Sicily estimates that the presence of green manure reduces the carbon budget by 45% compared to conventional management. The quantified GHG emissions per hectare per year are given in Figure 5. The use of green manures in alternate rows reduces GHG emissions by up to 70% compared to conventional management. All the practices carried out (tillage, fertilization, pest management, harvesting and management of pruning residues), as well as the pedoclimatic characteristics were taken into account (Novara et al. 2020).

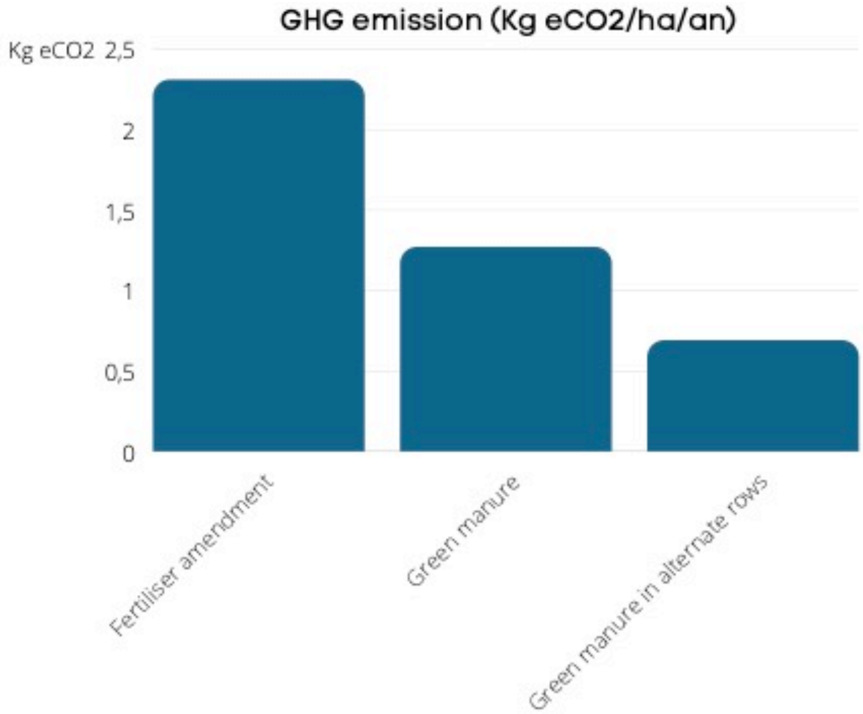


Figure 5 - GHG emissions by type of nitrogen application, source: Novara et al (2020)

Other effects on soil, water, air and biodiversity

The inclusion of other crop species in the rotation increases crop biodiversity. The succession of different root types improves the soil structure and its permeability to air and water. The risks of compaction and erosion are reduced. Leaching phenomena are reduced if the nitrogen supplied by the green manure matches the needs of the following crop (Verdier et al. 2019; Preissel et al. 2017). Biological activity is stimulated and the amount of OM increases (IFV 2019; Thromas, Bompard, and Giuliano 2018).

b. Remarks

Managing green manures can be tricky to get the benefits without causing water and nitrogen stress or increasing leaching risks. Increased ammonia volatilization following the implementation of green manures is a consequence more specific to Mediterranean climates (Baddeley et al. 2017). Support may be required.

Nematicidal effects have been observed for some green manures such as perfume tagela, oats or crotalaria. However, these effects are specific to certain nematode genera and do not concern, for example, those that transmit short-knot.

Some vineyards where the grapes are harvested manually have abandoned green manures for social reasons. Indeed, green manures bother the workers and favour the presence of ticks.

c. Appraisal

Although not very developed in European viticulture, green manures can replace up to all nitrogen fertilizers, depending on the yield objectives set.

This compensation takes place provided that the nitrogen supplied by the green manure is available when the vine needs it. No significant difference in yield was observed compared to the use of fertilizer. The creation of hydric stress by green manures can be a source of yield reduction for the following crop.

Input costs are reduced, but labour time is increased, but the implementation of green manures has a cost. Green manures reduce N2O and CO2 emissions and improve SOC levels. Biodiversity, soil structure and water quality are improved.

IV. Results

A. Effects of practices on input use efficiency

1. Effects of practices on pesticide use efficiency

Table 11compiles the average results obtained by the different practices compared to the use of pesticides in the conventional way. These are averages or results observed in studies.

Practices that can influence the amount of herbicides consumed are considered satisfactory when their effectiveness on weeds is around 80%.

Practices that have a positive effect when coupled with a pesticide dose, whose effect on total pesticide consumption is less than 10%, or whose effectiveness is highly variable are shown in orange.

The practices, represented in green, which seem to induce a reduction in the consumption of pesticides are interesting:

- Robotic farming can reduce the number of animals by up to 80%;
- Varietal selection can allow a reduction of 50 to 75%;
- The Modulation of plant protection products can allow a reduction of 16 to 58%;
- Contained spraying can achieve a reduction of up to 38%;
- Phytosanitary DSTs can allow a reduction of around 30%.

One of these practices is part of the system redesign strategy, the others are part of the efficiency strategy.

Table 11 - Effects of surveyed practices on pesticide use

	Fungicides 83% of pesticides	**Insecticides** 13% of pesticides	**Herbicides** 5% of pesticides	**Total pesticide consumption**
Grassing			↘ 50% to 67%	1,7% to 2,5%
Mulching			↘ 25% to 80% weeds	↘ 0% to 5%
Agroforestry & hedges		Disparate effects not quantified		
Varietal selection	↘ 60% to 90%			↘ 50% to 75%
Contained spraying	↘ 40%	↘ 40%		↘ 38%
Decision supporting tool				↘ 30%
Modulation of plant protection products				↘ 16% to 58%
Robotic farming				↘ 80%
Mechanical weeding			↘ 33% to 100%	↘ 1,5% to 5%
Robotic mechanical weeding			↘ 65% to 82% weeds	
Biological control	↘	↘ • 20 to 60% of bio-aggressors compared to the control • 96% if combined with plant protection treatments*.		↘
Sexual confusion		↘ up to 4 treatments of insecticides **		↘ 13% max
Natural defence stimulators	↘ 0% to 100%	↘ 0% to 100%		↘ 0% to 96%***

*Effectiveness superior to the chemically treated control (87%)
**May allow to dispense with herbicides herbicides
***It is very unlikely to reach the maximum reduction because SDN are pest specific and several pests are present in the vineyards

2. Effects of practices on fertilizer use efficiency.

Fertilizers are applied to meet targeted yields in terms of quantity and quality. Thus Table 12presents the effects of fertilizer use and yield practices.

Table 12- Effects of study practices on fertilizer use and yield

	Use of fertilisers	Yields: Quantity	Yields: Berry quality
Grassing	• Requires + 30 kg/ha at planting • Risk of competition	↘ variable, 9% according to a study	= or ↗
Agroforestry & hedgerows	Mixed effects: • ↘ by 8% to 20% of the available nitrogen • No influence of trees on vine vigour	Mixed effects: = or ↘ by 9% to 31%	No effect
Decision supporting tool	↘ by 20 to 45%		↗
Variable rate fertilisation	↘ by 25 to 30%		↗
Organic fertilizers	• Variable, from 0 to 90 kg/ha • Less than the quantities applied during planting	Fertiliser use depends on target yields	
Green manure	Can meet 50 to 100% of nitrogen requirements	Risk of competition for water and nitrogen during flowering and berry formation	• ↗ from 19% to 65% the nitrogen content of wine musts • ↗ vigour and budburst

Most practices influence the quality of the musts. Some of them, such as grassing, vitiforestry or green manure, can lead to a quantitative decrease in yield. The difference in the type of fertilizer (synthetic or organic) has no impact on the efficiency of their use. The increase in vigour and bud break linked to green manures can have positive or negative externalities depending on the context of the plots and the pedoclimatic conditions.

Practices related to the use efficiency strategy, i.e. the use of DSTs and variable rate fertilization, seem to be the most interesting to promote in terms of fertilization management.

3. Effects of practices on water use efficiency

Water has a direct effect on the uptake of fertilizer by the vines and therefore affects the quantity and quality of yields. Table 13presents the effects of the practices on water consumption and yields compared to non-irrigation.

Table 13- Effects of study practices on water use and yield

	Water consumption	Yields: Quantity	Yields: Berry quality
Grassing	Varies according to season, climate, soil type and grass cover	↘ variable, 9% according to a study	= or ↗
Organic mulching	↘ by 40% for organic mulch compared to synthetic mulch	↘ 20% to 25%	
Synthetic mulching		Various effects : • ↗ up to 11 times in extremely dry conditions • ↘ by 30% in mild conditions	
Agroforestry & hedges	No water constraints	Various effects: = or ↘ by 9% to 31%	No effect
Decision supporting tool	↘ by 16 to 8% in fertigation	No correlation ; • = or ↗ • ↗ from 16% to 50% in fertigation compared to no irrigation in the Mediterranean	
Variable rate irrigation	Irrigation efficiency : = or ↗ than what DSTs related to irrigation and fertigation management allow		

Practices such as grassing, organic and synthetic mulching and vitiforestry concern the efficiency of the use of the water available in the soil. If they help to maintain soil moisture or if they do not cause water constraints, they have either observed or negative effects depending on the pedoclimatic context.

These practices are distinct from practices related to the irrigation water use efficiency strategy, which include DSTs, variable rate irrigation and fertigation. The latter appear to maintain or increase yields.

B. Effects of practices on socio-economic conditions

The effects of practices on socio-economic conditions are summarized in Table 14. Practices with more than two negative effects on yield, working time or production cost were not retained. Practices leading to a quantitative reduction in yield or an increase in working time of more than 3 hours were also excluded.

Varietal selection and the use of organic fertilizer are the practices that have a positive impact on yield, labour time and production cost.

DSTs, crop protection treatment modulation, variable rate fertilization and variable rate irrigation can lead to a slight increase in work time when learning how to use the tool.

Spontaneous weeding seems to be another interesting practice from a socio-economic point of view, as well as robotic mechanical weeding whose investment is less than 40 000€.

The robotization of viticulture seems to be a promising technique in terms of work time, but it is not profitable today.

Table 14 - Effects of the practices studied on yields, labour time and production costs

	Yields Quantity	Berry quality	Working time compared to chemical management	Effects on the cost of production
Grassing	↘ variable, 9% according to a study	= or ↗	↗ time 2,5	• ↗ 6 to 10 times (660 to 900 €/ha/year more) • Savings of 15 to 26 €/ha/year possible with spontaneous grassing
Organic mulching	↘ by 20% to 25%		↘ by 20%	↗ 5 to 18 times (640 to 1830 €/ha/year more)
Synthetic mulching	Various effects: • ↗ up to 11 times in extremely dry conditions • ↘ by 30% in mild conditions		↗ 17%	↗ 3 times
Agroforestry & hedges	Various Effects = or ↘ from 9% to 31%	No effect	Time consuming: • Planting : ↗ time 5 ; • Maintenance in the first three years : ↗ par 2	• Plantating: ≈1000€/ha • Cost over 30 years estimated at 4600€/ha or 43€/mL
Varietal selection	Yields of 10 to 20t/ha which are generally higher than the yields of traditional grape varieties		↘ 4 to 5 hours of treatment per year	↘ by 15 to 21%
Contained spraying			No consensus: • ↗ of site time and cleaning • ↘ time through increased speed	↘ 40% of outputs in case of high pest pressure
Decision supporting tool	• No correlation : • = or ↗ • ↗ 16% to 50% in fertigation compared to no irrigation in the Mediterranean	↗ thanks to DSTs linked to fertilisation	Variable : • ↗ time required to master this technique • ↘ working time	• +25 to +35€/ha or • +250 to +500€/an
Modulation of plant protection products	= or ↗		Variable : • ↗ time required to master this technique • ↘ spraying time	• Cost-effective if pesticide savings are greater than 14€/ha • ↘ 20% of pesticides achievable • Amortized over 3 or 4 years

Variable rate fertilisation		↗	↗ by 2,82%	• ↘ €9/ha of pesticides achievable (without taking into account the amortisation of the equipment)
Variable rate irrigation		= or ↗ of irrigation efficiency	Variable : • ↗ time required to master this technique • ↘ working time	Potential savings of 130€/ha
Robotic farming			↘ arduous work	• Unquantified pesticide savings, which are not enough to compensate robot's costs yet
Mechanical weed control	↘ by 5% to 20% in extreme cases		↗ from 3.4h/ha for mixed weed control to 10.7h/ha for mechanical weed control alone	↗ from 40 to 640€ depending on the type of weeding and the configuration
Weed control mechanical robotic	Not quantified = if efficient weed control : above 80%.		↘ 20% of working time	• Higher than chemical weed control (between 25 000 and 80 000) • Profitable if < €40,000
Biological control	↘up to 60% if used alone with many pests		= to ↗ depending on how it is implemented	• ↗ by 45€/ha to 250€/ha compared to a chemical treatment
Sexual confusion	• Preventive method • No impact on yield		• ↗ 4.5h and 11h per ha/year • Better distribution of working time	• ↗ 4 to 8 times • Higher workload
Natural defence stimulators	Less than or equal to pesticide use		↗	
Organic fertilizers	Variable depending on targeted yields		=	Lower than synthetic fertilizers
Green manure	Risk of competition for water and nitrogen during flowering and berry formation	• ↗ by 19% to 65% of the nitrogen content of musts • ↗ vigour & budburst	↗ by 5h30 to 8h30 per ha/year	= to 2 times more

C. Effects of practices on environmental and climatic performance

The effects of the practices on the balance of GHG emissions and on the various ecosystem compartments (water, soil, air, and biodiversity) are given in Table 15. For each practice, the quantities of carbon sequestered are converted into eCO2 and subtracted from the emissions linked to the practice. Each environmental component is analyzed qualitatively as described in Methodology, page 6.

Among the practices studied, only grassing and agroforestry have an effect on carbon sequestration. The practices whose capacity to reduce GHG emissions has been quantified and which have a favourable action on the various environmental components are

- Green manures, which have been shown to reduce GHG emissions by between -45 and -70%;
- Varietal selection, which has been shown to reduce GHG emissions by approximately -57%;
- DSTs related to pesticide and fertilizer management, whose observed GHG emission reduction capacity varies between -25 and -28%;

However, the GHG emissions linked to viticulture remain much lower than those linked to wine-making.

Table 15 - Effects of studied practices on climate change mitigation and environmental components

	Effects on climate change mitigation (on GHG emissions)	**Other effects on :** Soil	Water	Air	Biodiversity
Grassing	GHG balance : CO_2 emissions between -1.8 and +0.34 de CO_2/ha/year	● Physical, chemical and biological fertility	●	○	●
Organic mulching	↘ by -3%	● Physical, chemical and biological fertility	●	●	●
Synthetic mulching	↗ by 200% (ACV)	○	○	○	○
Agroforestry & hedges	• 30 trees per ha sequester between 0.45 and 0.9 tC/ha/year • 0.1 tC/ha/yr for 100ml/ha of hedges • No information on maintenance-related emissions	● Physical fertility	○	○	●
Varietal selection	↘ 57% in GHG emissions compared to traditional grape varieties	● Physical fertility	●	○	●
Contained spraying	↘ unquantified	○	●	●	●
Decision supporting tool	• ↘ by 25% to 28% for phytosanitary treatments and fertilisation ; • ↗ by 50% to 140% N_2O in irrigated crops compared to non-irrigation	○	●	○	○
Modulation of plant protection products	Identical	○	●	●	●
Variable rate fertilisation	↘ by 5%	○	●	○	●
Variable rate irrigation	↗ by 50% to 140% N_2O in irrigated crops compared to non-irrigation	● Chemical fertility	●	○	○

Robotic farming	↘ assumed but unquantified	● Biological fertility	●	●	●
Mechanical weeding	• ↗ 1 to 6 times more fuel consumption; • ↗ 1 to 6 times more energy consumption ; • ↘ herbicide use (unquantified)	○	●	○	○
Robotic mechanical weeding	↘ unquantified	● Physical fertility	●	●	○
Biological control	↘ unquantified	○	●	● ↗ NH3 emissions depending on the products used but ↗ air quality	●
Sexual confusion	Unquantified: • ↘ if applied alone • ↗ if applied with pesticides	○	●	●	● Preservation of fauna and flora but risk of emergence of secondary bio-aggressors
Natural defence stimulator	• = if applied alone • Higher if applied with pesticides	○	●	● Depends on the ecotoxicology	●
Organic fertilizers	↘ by 20% compared to synthetic fertilizers	● ↗ of the physical, chemical and biological fertility of soils but little impact on leaching	●	● ↗potential of NH3 emissions	○
Green manures	↘ by 45% to 70%	● Physical, chemical and biological fertility	○	○	●

V. Discussion

A. Interesting practices to be promoted at European level

The practices that were highlighted for their beneficial effects on input consumption, socio-economic conditions and environmental and climatic aspects are summarized in Table 16.

Table 16- Summary of the most beneficial practices on input use efficiency, socio-economic conditions and environmental and climatic performance

	Effects on consumption :			**Effects on socio-economic situation :**	**Effects on environmental & climate performance**
	Pesticides	Fertiliser	Water		
Grassing	○	○	○	🟠	○
Mulching	○	○	○	○	●
Varietal selection	●	○	○	●	●
Contained spraying	●	○	○	●	●
Decision supporting tool	●	●	●	🟠	●
Modulation of plant protection products	●	○	○	●	○
Variable rate fertilisation	○	●	○	●	○
Variable rate irrigation	○	○	●	●	○
Robotic farming	●	○	○	○	○
Robotic mechanical weeding	○	○	○	🟠	○
Organic fertilizers	○	○	○	●	○
Green manure	○	○	○	○	●

No practice is a key solution, they all have advantages and disadvantages. In view of Europe's climatic and environmental objectives, the most interesting practices to promote without compromising the socio-economic performance of winegrowers seem to be the use of **DSTs**, **contained spraying** and **varietal selection**.

However, other practices remain as alternatives with other effects. Among those that have not been highlighted, many lead to a reduction in yield, an increase in labour and production costs. These include grassing, green manures and mixed mechanical weeding. These practices can be interesting to implement in small vineyards with low yield objectives such as PDOs. The same applies to preventive practices such as biological control, which can be combined with pesticides if the pressure of bio-aggressors is too strong.

Precision viticulture (adjustment of input doses) and robotization could be future solutions due to their current cost and state of development.

Some of these practices, especially those using recent technologies (DAS, precision farming, robots, etc.) require training, support and soil analysis to get the most out of their potential. The use of resistant grape varieties is only effective if the treatments are adapted to the phytosanitary pressures.

B. Limitations and prospects

This is a review carried out at European level based on the results of experiments. It seems necessary to compare these results with feedback from wine growers.

For certain practices, the results obtained under specific conditions cannot be generalized to all European wine regions. Indeed, the choice of practices is strongly dependent on the context of the farm and the plot. In addition to the soil and climate conditions and the topography of the vineyard, the age of the vines, the vineyard management system, the possibility of pooling equipment or using manure from neighbouring farms, and the proximity of urban areas all affect the practices that can be implemented. The size of the farms is important to ensure that DSTs, the adjustment of input quantities and robotization produce tangible results, particularly at the environmental level (A. Balafoutis et al. 2017).

The conclusions of the studies included in this review may sometimes be too hasty, especially concerning the effect of practices on soil quality and carbon sequestration. Indeed, the effect of a change in practice on the soil can be observed after seven years.

The results of the studies on which this review is based are analysed according to the elements studied (input consumption, yield, production cost, etc.). These results are in fact the result of the interaction of all the practices carried out on the plot and according to its pedoclimatic conditions. To take into account all these practices, it would be necessary to show the complementarity of the practices.

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List of acronyms

LCA: Life Cycle Assessment

PDO: Protected Designation of Origin

C: Carbon

CO_2: Carbon dioxide

CO2e: CO2 equivalent

ESR : Efficiency - Substitution - Re-design

F2F: Farm to Fork Strategy

BMF: Biological Nitrogen Fixation

Ha: Hectare

IFT: Indice de fréquence des traitements

LULUCF: Land use, land change and forestry

Mhl: million hectolitre

OM: Organic matter

N: Nitrogen

N_2O: nitrous oxide

NH_3: Ammonia

DST: Decision support tool

NDS: Natural defences stimulator

PDS: Plant defence stimulator

VATE : Agronomic, technological and environmental value

VRI: Variable rate irrigation