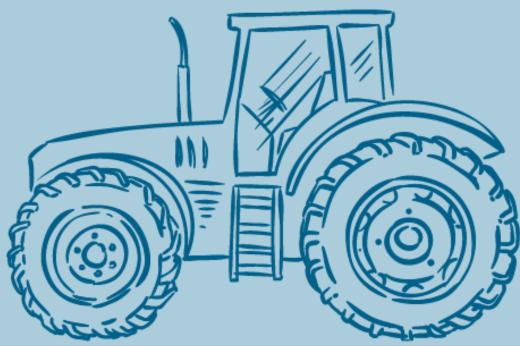
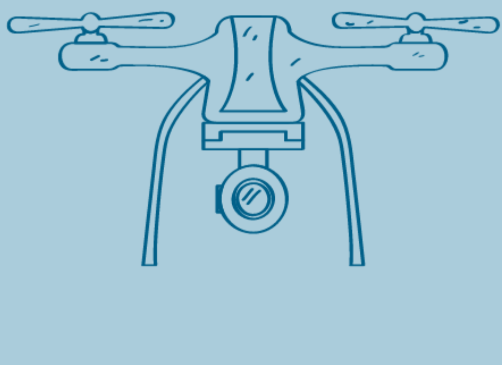
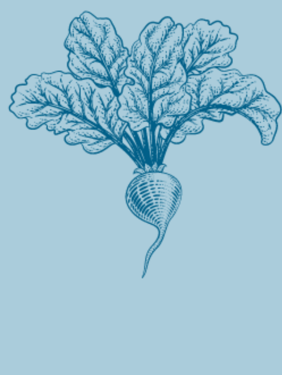
FARM EUROPE



LEVERAGING A TRANSITION

TOWARDS MORE SUSTAINABLE FIELD CROP SYSTEMS





Anaïs Levoir

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Farm Europe is a multi-cultural think tank founded in 2014 that aims to stimulate thinking about the EU's rural economies. The think tank, focuses on agriculture and food policies, particularly the Common Agricultural Policy (CAP), but also food standards, the food chain, environment, energy and trade issue.

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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 estimated environmental benefits are in total between held and nil at the cost of a socially and financially onerous decrease. Such consequences could be dramatic for the European agricultural sector, which employs more than 9.2 million people and occupies 38% of European territory. Field crop production is all the more exposed as it occupies more than two thirds of European arable land.

Not only would they jeopardize the ability of farmers to meet the needs of European population and contribute to the stability of world food markets, but they would also have a significant impact on the financial stability of farms, the associated sectors and the rural areas where they are located.

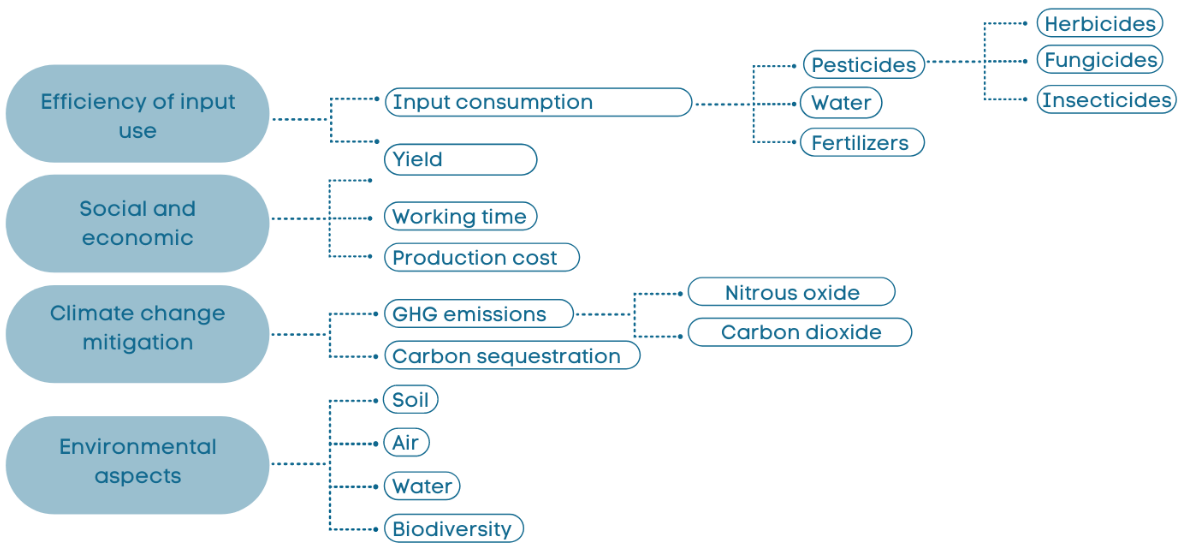
An agricultural sector restructuration that would reduce the number of farms and cause land abandon due to political decisions is not an option.

These observations suggest the **need to define another path to meet the principles of the European Green Deal and a responsible and effective ecological transition of the agricultural sectors**.

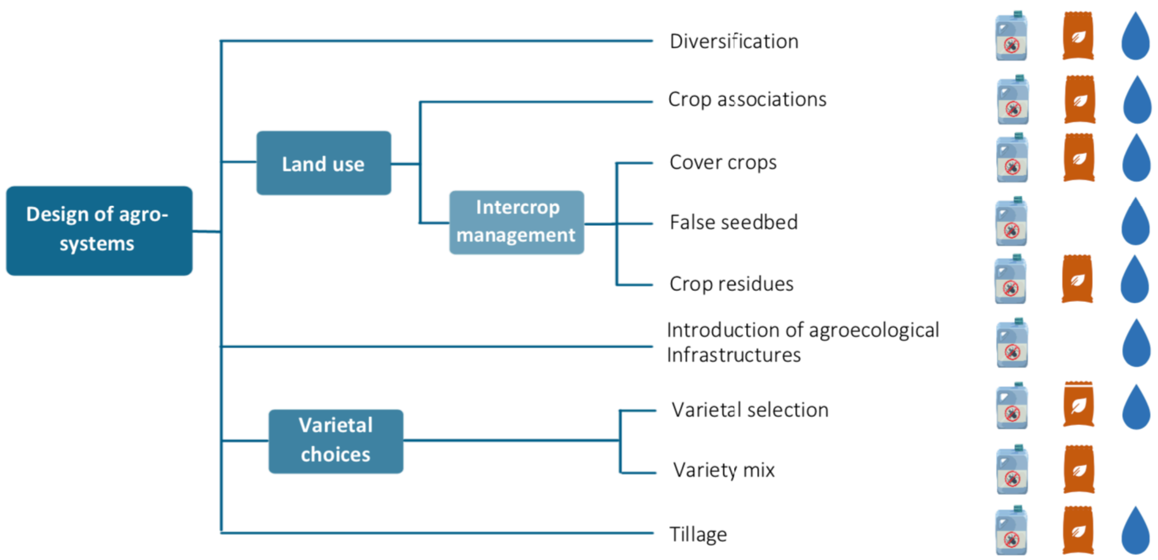
This report analyzes a set of practices that can be activated to reach the European objectives while fostering production capacities, farmers' revenues and their working time.

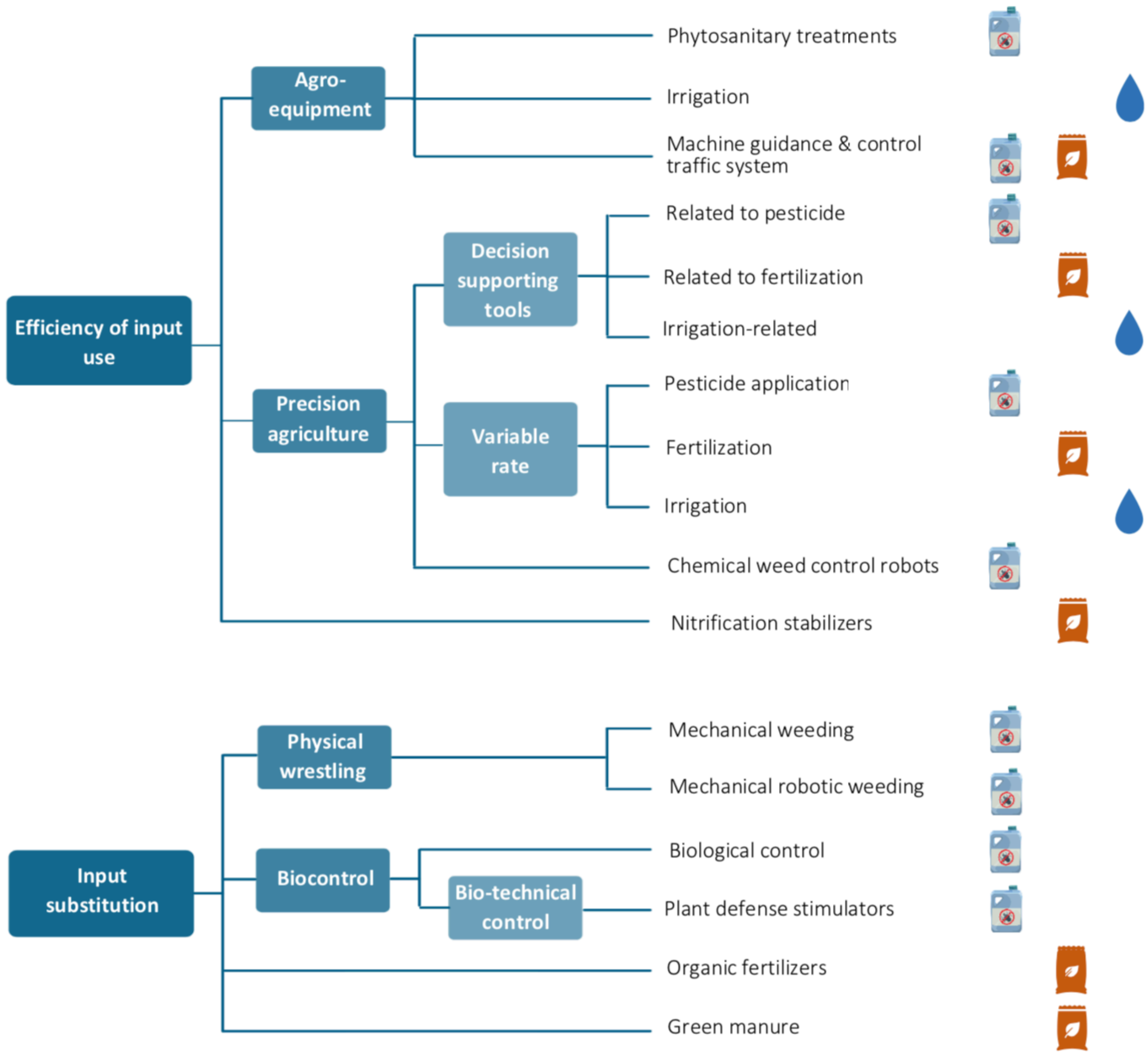
Numerous European studies have evaluated and quantified the effect of various practices at the farm or plot level. Based on a review of this work, this study aims to quantify the effect of different practices to identify those with the best mix between environmental and climatic impact and economic and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

The different data compared are given below:



The practices studied and the inputs they affect are:





Results can be summarized as follows:

Practices that seems to achieve the better outcomes in line with the objectives of GHG net zero and economical use of inputs are, at the system re-design level:

- Diversification of rotations and maximum soil cover, especially during the intercropping period;
- Alternating tillage and shallow tillage;
- The selection of resistant varieties, either early or late ones.

In addition to these solutions, there are different ways to improve the efficiency of pesticides, fertilizers, and irrigation use, such as

- Modernization of agricultural equipment,
- DST recommendations
- Local and adjusted application of inputs.

Some of these solutions can be costly, others, such **as DST or replacement of certain parts,** are affordable alternatives.

Practices that seek to replace pesticides do not generally allow for complete removal of them. They are preventive or complementary alternatives. The substitution of synthetic fertilizers by green or organic fertilizers appears to be an interesting solution to reduce GHG emissions. However, the use of green fertilizers can be complex and the use of organic fertilizers depends on the ability to obtain organic matter.

Choosing the right practices depends on many factors which will then determine the efficiency of input use, climate, environment and socio-economic conditions. Certain practices can thus have beneficial or negative effects depending on the region of Europe that is being considered.

Local or even regional support for farmers seems useful to help them identify the sets of practices that are tailored to their situation. **Training is necessary** to enable them to quickly take control and use the maximum potential of their agricultural equipment. **The recommendations of DSTs must also be adjusted to local conditions**.

In addition to supporting farmers**, it is essential to ensure the accessibility of agricultural equipment and DST while fostering the modernization of equipment to improve the efficiency of input use**. This is a priority that public policies should focus on.

Robotics, on the other hand, is too new and too expensive. In 15 or 20 years, it could be a promising additional solution.

Context

I. European arable crops

A. Surface and geographical areas

Arab land areas represent 99 million ha in 2019 in Europe. This corresponds to 60% of European agricultural land (composed of arable land, areas dedicated to perennial crops and permanent grassland) and 6% of the world's arable and permanent crop land (Harrison 2002). More than half the arable lands area is located in France (18%), Spain (12%), Germany (12%) and Poland (11%). Two-thirds of the arable lands are cultivated on farms specialized in field crops.

Cereals, oilseeds, and protein crops are the main crops grown on this land, followed by roots and tubers, field vegetables and fiber crops.

B. Production

There are great discrepancies in terms of farm size. The average size of farms specialized in cereals, protein crops and oilseeds is 60 ha. The smallest farms are in Greece and the largest in the Czech Republic. The average size of Greek and Czech holdings is 8 ha and 167 ha respectively (Eurostat 2021a).

More than 85% of farms specialized in cereal, oilseed and protein crop production are in Romania (441 000 farms), Poland (393 000 farms) and Italy (173 000 farms) (Eurostat 2021a).

Europe exports about 20% of its wheat production. Large quantities of oilseeds and animal feed or rice are imported (European Commission 2021).

C. The main inputs

Pesticide consumption

The three main pesticides are fungicides, pesticides, and insecticides. Pesticide consumption varies greatly according to soil and climate conditions, crops and the choice of practices implemented. However, it is estimated for a standard field crop that 10% of the pesticides applied are insecticides and that the remaining 90% correspond to herbicides and insecticides (ADEME 2021).

Fungicides appear to be the most used pesticides in Europe, averaging 1.14 kg/ha in 2019. Fungicide use is 0.64 kg/ha on average in 2019. Large disparities exist between countries for fungicides and pesticides. Insecticides appear to be the least used pesticides at 0.24 kg/ha on average. They are mainly used in the southern half of Europe. Their sale is lower in the northern half (Eurostat 2021d; 2021c).

Nitrogen consumption

Nitrogen requirements vary depending on crops. For example, whole plant nitrogen exports from oilseed rape are around 250 kg nitrogen (N) per hectare (ha), beet crops around 230 kg N/ha, potato crops around 218 kg N/ha, maize crops around 185 kg N/ha, wheat crops around 170 kg N/ha and barley crops 146 kg N/ha. The nitrogen input is calculated from the yield targets of the crops and the nitrogen residues of the previous crop (UNIFA 2021).

According to Hourcade *et al.*, (2015), a nitrogen application of 160 kg/ha is applied on average to wheat, which amounts to about 20-25% of the operational costs. He estimates that 50-70% of the applied nitrogen is assimilated by the crop. Other authors state that 50-70% of the applied nitrogen is lost due to leaching, volatilization, or denitrification.

Water consumption

Agriculture uses 33% of the water consumed on average in Europe. This figure rises to 80% in the Mediterranean region. The main irrigated crops are maize, rice, potatoes, and sugar beet. Irrigation is used above all in France, Spain and Italy (Eurostat 2021b). Besides irrigation, certain agricultural practices can influence the volume of water in the useful reserve.

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 under water stress as nutrients can only be absorbed in the presence of water.

II. The agricultural sector and the challenges of production and food security

The agricultural sector must produce enough to cover the needs of a growing population while human resources are falling (Gaba et al. 2016).

The number of farmers in Europe fell by 25% between 2005 and 2015 and the number of farms reduced by 20% between 2007 and 2013. This trend is likely to increase with more than half of farmers being over 55 years old and only 6% being under 35 years old (European Committee of the Regions, 2018).

Maintaining production despite the decline in the number of farmers means increasing the productivity of farms. This implies, among other things, investments and raises concerns over financial resources available on farms to do so, and therefore over the profitability of agricultural activity, which has been struggling over the last two decades. Also considering the trend towards lower prices for agricultural raw materials and the growing volatility of world markets, farmers' position within the supply chain should be strengthen and they should be given the means to generate a decent income and the capacity to invest in the future. This income must ensure remuneration for work and the sustainability of their business (investments, anticipation of hazards....) (European Commission 2019).

The agricultural sector has a major role in establishing and maintaining food security. The production, availability and storage of sufficient food are its responsibility. Beyond physical access to food, economic access must be guaranteed, by maintaining affordable prices in relation to consumers' income. Food security is achieved when food is available and economically accessible to all people at all times, at national, European and international levels (FAO, IFAD, WHO, 2021).

III. The agricultural sector and the climate challenge

The agricultural sector 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.

This sector is both the only economic sector capable of storing carbon and a sector that emits GHGs (greenhouse gases). In 2019, agriculture emitted about 386 million tons of CO_2 equivalent (eCO_2), which corresponds to 10% of total European emissions. Almost 40% of these emissions, i.e. 152 million tons of eCO_2, were related to nitrous oxide (N_2O) emissions, with the remainder mainly corresponding to methane (CH_4) emissions and livestock manure management.

Field crops have a negligible role on CH_4 emissions (Guyomard*et al.*, 2013). On the other hand, nitrogen fertilization is responsible for 50 to 60% of N_2O emissions, which are estimated to rise by 35 to 60% between 2007 and 2030 at the global level (IPPC 2007). Other GHG emissions occur indirectly during the manufacture of synthetic fertilizers. Various sources estimate that the total GHG emissions associated with the application of one kg of N are equivalent to emitting between 2.6 and 8 kg of eCO_2 (IPPC, 2007; Stagnari*et al.*, 2017;*Whealbi*, 2021). Indirect CO_2 emissions also occur during the manufacture and application of pesticides. These emissions are by default estimated to be 9.2 kg eCO_2 per ton of active ingredient (ADEME 2021).

To mitigate the effects of climate change, agriculture, like all other sectors, must aim to reduce its GHG emissions. It also has the capacity to store carbon in its soils. The objective assigned to it under the Green Deal is to achieve emission neutrality by 2035.

IV. The agricultural 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 biodiversity losses.

V. Policy responses to climate and environmental issues

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

The Commission has set itself the goal of achieving climate neutrality 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 changed. 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 proposed by the Commission 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 features and 25% of land in organic farming.

VI. The agricultural sector and economic issues

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

Such impacts are stacking up to climatic and environmental challenges faced by the European agricultural sector. The idea of restructuring the agricultural sector, drastically reducing the number of farms, and abandoning land is not an option. Farmers are, because of the goods and services they provide, vital to the survival and development of our societies.

The aim is therefore to foster their resilience, enabling them to overcome crises related to both global markets and climate issues, so that they can meet the needs for supply within the EU and stability in global food markets (European Committee of the Regions, 2018).

Concrete actions should be taken. They should ensure the efficient use of inputs, a reduction of GHG emissions and increase of carbon storage in soils. They should also foster the preservation of the environment, while guaranteeing good working conditions and fair remuneration for farmers. Finally, they should secure the capacity for this sector to develop. All these would make both the European objectives and the economic, environmental, European and global food security challenges compatible.

Many studies have evaluated and quantified the effect of various practices on farms.

The aim of this study is to list the practices whose effectiveness on the environment and the climate is recognized and which support the production capacities, farmers' income, and their working time.

Methodology

This study compiled information on the effect of agricultural practices on input use efficiency, on the socio-economic dimensions and on climate change mitigation and the environment. It is based on a literature review of studies, meta-analyses, articles and practical sheets dealing with different practices related to arable farming. Most of these documents come from agricultural journals, European institutes, and research centers.

The practices studied take place at the level of agricultural plots. These practices are transversal to all production systems and are implemented during the design of rotations or between soil preparation and harvesting. Practices related to crop storage are not concerned.

They are divided into three categories following ESR (Efficiency - Substitution - Re-design) principles (Gayrard and Delva 2015). They are given in Figure 1 together with the inputs whose use they affect.

Efficiency analyzes the relationship between the yield obtained and the consumption of inputs (pesticides, fertilizers, or water) necessary to obtain it. The lower the input consumption, the better the efficiency

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

- 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 and labor), and the cost of traction and equipment. It is evaluated according to the information available.

Investments in the machinery needed to carry out the practices have not been considered because of the many this can be approached (CUMA, EU financing, cooperative, third-party organization, self-financing, etc.). The economic balance sheet 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 from the manufacture and transport of inputs.
- The effect of practice on carbon sequestration.

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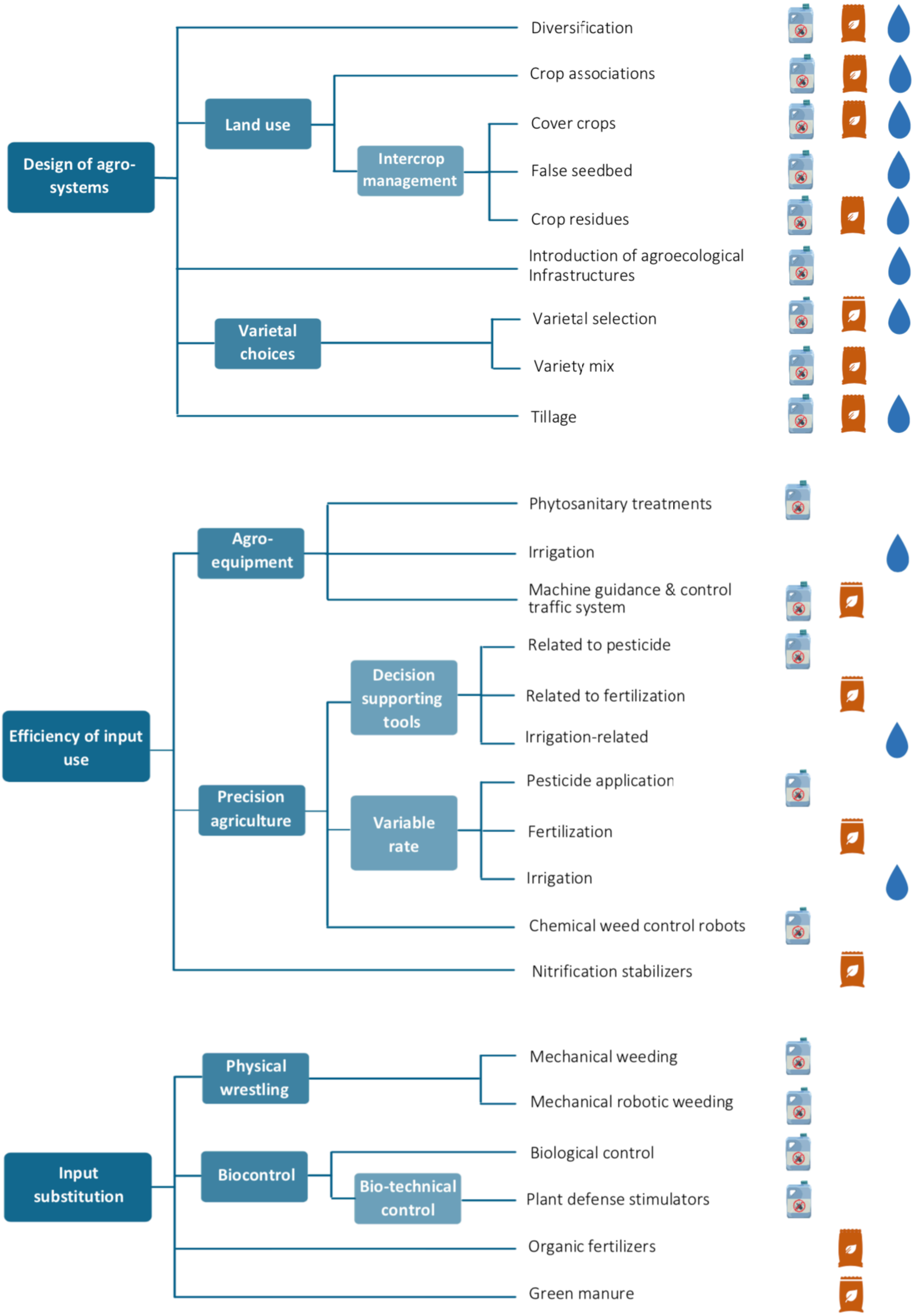

Figure 1 - Practices studied and the inputs they affect

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 NH_3 (ammonia) emissions.
- The soil quality, 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, 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.

Cross-sectional data

Whatever the practice, labor costs between 15 and 18€/ha. It can also be considered that 1 kg of synthetic nitrogen fertilizer emits 2.6 to 8 kg of eCO2 and that 1% of the applied nitrogen is emitted as N2O (IPPC, 2007; Stagnariet al., 2017;Whealbi, 2021). These informations can be used to complement data on production cost or GHG emissions thanks to those given on labor time or fertilizer quantities applied (Nistoret al., 2019).

Highlighting practices that should be promoted

Many factors interfered 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 were carried out on the plot and cause interferences too. Moreover, sorting analyzes by input and by practice is, in fact, reductive. The aim here is to identify practices that would make it possible to achieve the European transition objectives while maintaining or improving the working conditions and remuneration of farmers.

Results

I. Changes in agrosystems

A. Diversification of rotations

Any crop re-introduced into a rotation is considered a diversification crop as soon as it is not part of the standard rotation. The most common diversification crops are legumes, sorghum, rye, brassicas and flax. Crops that are usually part of rotations, such as sunflower or maize, are considered as diversification crops when they are planted in basins where they are not present in typical rotations. In areas close to livestock, grassland species may be used (Carpentier 2014; Jabran et al. 2015; Martin-Monjaret 2019). These crops can be cash crops, cover crops or combined crops. They make it possible to lengthen rotations, to vary planting periods and methods, and to increase soil cover.

1. Results obtained

Effects on input use

Pesticides

The effect of diversifying rotations can decrease weed occurrence by up to 40% by introducing species that break their cycle (Mayerová, Madaras, and Soukup 2018; Philips 2017; Wozńiak et al. 2019). Rotations considered diversified[1] correspond to the least pesticide-consuming rotations, in contrast to simple rotations (Lechenet et al. 2014; Mayerová, Madaras, and Soukup 2018). Depending on authors, crop protection adapted to the observed pressure allows a saving of one to two pesticide treatments, i.e. saving up to 50€/ha per crop, or reducing the TFI by 40% (Preissel et al. 2017; Verdier et al. 2019).

Fertilizers

The results obtained by Lechenet et al.(2014) suggest that diversified rotations reduce the amount of nitrogen fertilizer to be applied. Less fertilizer use is even more marked for rotations including legumes compared to their control (Lechenet et al. 2014). These crops have the ability to fix atmospheric nitrogen, through their symbiosis with bacteria of the genus Rhizobium. Their ability to provide nitrogen to the following crop is detailed in the section on green manures, page 103.

[1] whose crop frequency in the rotation is low and their effects on pests, soil structure and nitrogen availability are positive for the next crop (Lechenet et al. 2014).

Water

Water consumption depends on the crops in the rotation and the soil and climate conditions (Guyomard et al. 2013). Crop diversification makes it possible to reduce the presence of a highly water-consuming crop in the rotation by inserting other less water-consuming crops. For example, 100% irrigated maize can be replaced by dry cereals or other less water-consuming irrigated crops. Attention must be paid to the water needs of the crops when choosing diversification species.

The avoidance strategy seeks to avoid coinciding the critical or sensitive phases of the crop cycle with periods of water deficit. Crops that can be sown early, in autumn or late winter, are to be favored so that these water-sensitive phases take place before summer. These include winter cereals and oilseed rape, which are among the most commonly planted crops (Aspar 2019).

Effects on yields

The effect of diversification and lengthening of rotations needs to be assessed at the scale of rotations. The insertion of legumes, for example, which have a lower yield than cereals, explains why a reduction in productivity can occur between two rotations of the same duration (Lechenet et al. 2014). Nevertheless, legumes can improve the yields of next crops. This phenomenon is described in the section on green manures on page 103.

Effects on working time

Some scientists estimate that lengthening rotations increases labor time per hectare by half an hour to two hours per year (Hunt, Hill, and Liebman 2017; Davis et al. 2012; Verdier et al. 2019). Others argue that there is no correlation between workload and rotation diversification (Lechenet et al. 2014).

Crop diversification allows for a more even distribution of peak workloads for farmers due to the greater diversity of sowing and harvesting periods. This increases flexibility at the farm level (Lechenet et al. 2014).

Effects on the cost of production

The effect of rotation lengthening and diversification on production costs is mixed and depends on the crops planted. For some, lengthening rotations increases fuel consumption. This increase is even greater for rotations without legumes than for those that include them (Lechenet et al. 2014). But reductions in fertilizer and pesticides can offset this increase in fuel consumption.

The difference in gross margin between rotations with and without legumes varies from one country to another. In the best cases, the introduction of legumes allows an increase in gross margin of an average of 22 €/ha/year. A decrease in gross margin of up to 108 €/ha/year was observed for irrigated crops following the introduction of legumes. Agronomic and environmental conditions are the source of this high variability. In forage production, the introduction of legumes allows an increase in gross margin of between 4 €/ha/year and 103 €/ha/year, throughout Europe. Inter-regional differences in gross margin are also reduced (Preissel et al. 2017).

The more diversified the rotations, the lower the sensitivity to price volatility (Lechenet et al. 2014).

Effects on climate change mitigation

Legumes emit 5 to 7 times less N_2O than other crops (Stagnari et al. 2017). When introduced in successions, a reduction of N_2O ranging from 8 to 35% per year is observed in Germany, Italy, Sweden, Romania as well as in the United Kingdom (Preissel et al. 2017; Véricel et al. 2018).

The more diversified the rotations, the more energy consumption - and thus direct CO_2 emissions - seem to decrease (Lechenet et al. 2014).

This reduces the GHG balance of rotations by an average of 9% (Verdier et al. 2019).

Other effects on soil, water, air and biodiversity

The risk of increased leaching fluxes varies depending on how diversification crops are introduced, their place in the rotation and the scale at which it is accounted for (Véricel et al. 2018). There is an increase in autumn leaching following pea or oilseed rape without regrowth compared to wheat, as shown in Table 1. Autumn leaching after oilseed rape with regrowth is much reduced or even lower than leaching after wheat. Table 2shows that a decrease in leaching occurs following wheat preceded by oilseed rape or peas, compared to wheat. An inter-annual compensation is observed at the rotation scale, compared to cereal-based successions as shown in Table 3(Beillouin et al. 2017).

Table 1 - Changes in autumn leaching following a pea or oilseed rape crop, compared to a cereal crop (Beillouin et al. 2017)

Culture	Comparison culture	Evolution of leaching (kg N/ha)	Country
Peas	Wheat	From 0 to 11	France
Peas	Wheat	0	England
Rapeseed without regrowth	Wheat	From +5 to +37	France Germany
Rapeseed with regrowth	Wheat	From - 30 to + 15	France
Peas	Barley	> 13	Denmark

Table 2 - Changes in autumn leaching following a cereal crop preceded by pea or oilseed rape compared to a cereal crop preceded by grain (Beillouin et al. 2017)

Culture	Previous culture	Previous comparison crop	Evolution of leaching (kg N/ha)	Country
Wheat	Peas	Wheat	-7	France
Wheat	rapeseed	Wheat	- 9	France
Barley	Peas	Barley	- 13	Denmark
Wheat	Peas	Barley	- 16	Denmark

Table 3 - Simulation of leaching loss at the scale of cropping successions in France over 20 years (Beillouin et al. 2017)

Succession	Average leaching	Changes in leaching (kg N/ha) compared to wheat monoculture
Single-crop wheat	35	
Rape wheat peas	27	- 8
Rapeseed at the head of the succession	< à 24	> à - 15
Head peas	< à 29	> à - 6

The inclusion of other crop species in the rotation improves the biodiversity harvested. They allow alternating the phytosanitary products used and thus reduce the risks of resistance. The succession of different root types improves soil structure and quality and reduces the risks of compaction (Verdier et al. 2019; Preissel et al. 2017). Finally, if pesticide amounts and fertilizers are adapted to the observed pest pressure, they reduce water and air toxicity (Hunt, Hill, and Liebman 2017).

2. Remarks

The choice of crops and their inclusion in the rotations depend on the bio-aggressors present in the plots as well as on the regional scale. The soil-climate and socio-economic conditions in which the farm is located also influence this choice. Diversifying rotations does not mean massively replacing one crop with another but rather introducing specific crops adapted to the regional context (Benoit MOUREAUX 2014). Support may be necessary.

Longer and more diversified rotations multiply income, providing security against natural hazards. Larger farms benefit from a larger portfolio of crops to insert into rotations (Weigel et al. 2018). However, the insertion of diversification crops, particularly legumes, in rotations can weaken the economic performance of farms, which explains the reluctance of some farmers (Verdier et al. 2019; Baddeley et al. 2017). They can have a more fluctuating yield, as well as a much lower productivity and cost price than those obtained for cereals. Downstream buyers are not always guaranteed. This explains the extent of cereal specialization seen in Europe and the need to import soybeans (Preissel et al. 2017).

3. Conclusion

The value of diversification crops in terms of productivity should be considered at the rotation scale, as their yields may be low, but they can increase those of the following crop. The effect of diversification on working time is discussed. Peak workloads are better distributed and sensitivity to price volatility is reduced. These crops can reduce the use of fertilizers and pesticides, but their effect on fuel consumption is mixed. The gross margin depends on the yields obtained.

Rotations can become less dependent on water resources. Periods of water deficit can be avoided for certain crops. The inclusion of diversification crops reduces direct energy consumption and therefore GHG emissions. The quantities of leached nitrogen can be compensated between crops. The risks of bio-aggressor resistance and air and water toxicity are reduced. Biodiversity, soil quality and soil structure are improved.

Rotation diversification is a combination of solutions specific to the plot context. The effects mentioned above depend on the choice of crops to be inserted, their place in the rotation and the way they are planted and harvested.

B. Land use

1. Crop associations

The association or overlap of two or more compatible species at the same time on the same plot improves the efficiency of water, nutrients, light, and agricultural land used (Jabran et al. 2015). Combined crops can be used to reduce bio-aggressive pressure, especially weeds.

They can be associations of cash crops only or of cash crops with companion crops. They can take different configurations (Laurent Bedoussac 2009):

- Cereals and legumes can be sown together in mixed cropping. Seeding rates are lower, between 50% and 75%, than when pure species are grown (L. Bedoussac et al. 2011).
- Crops can be planted in alternate rows or between the rows of the main crop, such as a corn crop (Trezzi et al. 2016).
- They can also be planted in more or less wide mono-specific strips (strip intercropping). This is the case for cotton and sorghum or sunflower or for some cereals and legumes (Kandhro et al. 2014).
- Two species overlap during a certain period of their development in relay crops. A fast crop can be planted at the same time as a slower crop, to be harvested before the second one to let it develop. Another alternative is to plant a second crop shortly before the first crop matures, which will be harvested quickly so as not to compete with the second (Tanveer et al. 2017).

Little developed in Europe compared to the rest of the world, the most frequent crop associations in field crops are with cereals and legumes.

a. Results obtained

Effects on input use

Pesticides

Numerous studies show that crop associations reduce the incidence of bio-aggressors compared to crops alone. Yet few quantify their potential to reduce pesticide use (Lopes et al. 2016).

A reduction in the Treatment Frequency Index (TFI) of between 21 and 26% is observed for a pea-wheat mixture compared to crops alone, with or without nitrogen fertilization (Pelzer et al. 2012). A similar reduction was observed with farmers who diversified their rotations and introduced crop association systems (Cadoux et al. 2019). One farm that carried out the same approach was able to reduce its TFI by 50% in eight years (Viguier and Hellou 2019).

Concerning weed management, when the sum of the densities of the associated crops is higher than 170% compared to the densities of the crops alone, some farmers feel that there is no need to weed the legume-cereal mixtures. If the varieties have low coverage, up to two treatments can be made. Figure 2 illustrates the results of a survey on weed management in crop associations with 37 farmers (Lamé et al. 2015).

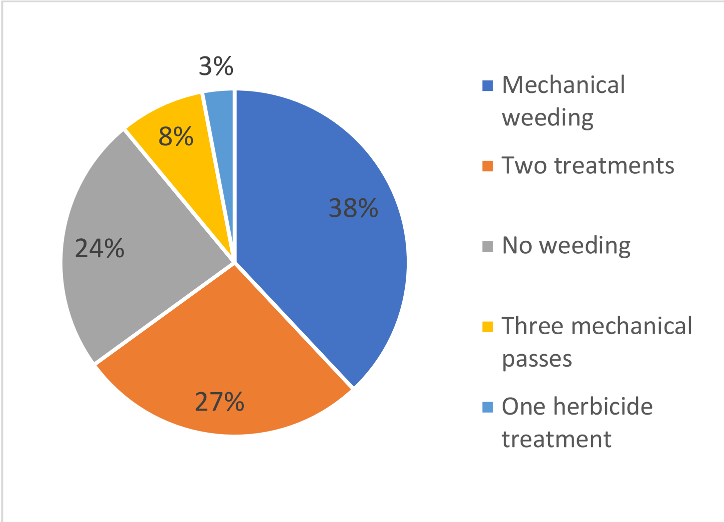

Figure 2 - Weed management in crop combinations (Lamé et al. 2015) (Lamé et al. 2015)

Fertilizers

The presence of legumes increases the rate of nitrogen available for associated crops. They can contribute up to 15% of nitrogen inputs in associations with cereals (Stagnari et al. 2017). A review of 132 studies on crop associations indicates that they save between 19 and 36% of fertilizer compared to monocultures with the same management (Li et al. 2020). According to an analysis of 9 different sites, a cereal-legume association requires on average half as much nitrogen input (60kg N/ha) as wheat crops alone (140kg N/ha). Under such fertilization conditions, the efficiency of fertilizer applied per ton of grain produced is 2.5 times higher for a wheat-legume combination than for wheat alone (Pelzer et al. 2012).

Nitrogen fertilization increases the competitiveness and development of cereals (Pelzer et al. 2012; Ghaley et al. 2005)). The development of legumes and their biological N-fixing capacity are inhibited, thus removing the interest of associations with them (Stagnari et al. 2017; Ghaley et al. 2005). The selection of legumes that are able to maintain their biological N-fixing capacity when soil mineral N is increased becomes crucial when adopting this type of association (Stagnari et al. 2017).

The presence of legumes in an association increases the nitrogen level in the soil after harvest (Tanveer et al. 2017; Pelzer et al. 2012). This rate is even higher in the absence of nitrogen fertilization, as shown in Table 4.

Table 4 - Amount of mineral nitrogen in the soil after harvest (Pelzer et al. 2012)

Culture	Nitrogen fertilization	Mineral nitrogen in the soil after harvest (kg N/ha)
Wheat alone	No	39,9
	Yes	47
Wheat and pea association	Yes	41
Wheat and pea association	No	52,1
Peas	No	67

Water

A review of 132 studies on crop combinations shows an increase in water use due to longer cropping periods compared to single crops. The effect of crop associations on water consumption is very poorly documented. Work to quantify this effect needs to be done at the global level (Li et al. 2020).

Effects on yields

58 field studies in Europe under contrasting soil and climate conditions show that intercropping increases yields by up to 19% (Laurent Bedoussac et al. 2015). The yield of maize following a relay crop of wheat and legumes increases by 30% (Tanveer et al. 2017). The yield gain is on average 2.1 T/ha if the association includes a maize crop. Without a maize crop, it averages 0.5 T/ha (Li et al. 2020).

The protein concentration of legume-cereal mixtures, fertilized or not, is on average 11%, which is higher than that of unfertilized wheat (9.4%). It remains on average lower than fertilized wheat (12%) (Pelzer et al. 2012) but can reach up to 14% (Laurent Bedoussac 2009). The nitrogen content of the above-ground parts of a maize following a relay crop of wheat and legumes is 55% higher than the control (Tanveer et al. 2017).

Crop combinations allow for more production on smaller areas. The "land equivalent ratio" (LER) measures the relative area required to produce a yield in pure crops that is equal to that obtained with associated crops. It is equal to 1.3 on average (Himanen et al. 2016; Laurent Bedoussac et al. 2015; Laurent Bedoussac 2009; Ghaley et al. 2005). Combined crops reduce the occupation of agricultural land by 16-29% compared to monocultures (Li et al. 2020).

Effects on working time

The impact of crop combinations on labor time varies according to the type of configuration used. It can lead to an increase in the number of machine passes for strip crops, row crops or relay crops. A 15% increase in workload can occur (Viguier and Hellou 2019). If the species are grown as a mixture, grain sorting can be time consuming. Conversely, if well controlled, intercropping can reduce the phytosanitary program and fertilizer application, thus reducing the workload (Guyomard et al. 2013; Himanen et al. 2016).

Effects on the cost of production

Despite the reduction in input consumption, the production cost of crop associations remains high because of the specific operations that may take place. An additional sowing costs 40€/ha/pass, a harvest 80€/ha and seed sorting 15 to 30€/T of seeds (Laurent Bedoussac et al. 2015; Mamine and Farès 2020).

The profitability of associated crops is increased and more stable compared to pure crops (Laurent Bedoussac et al. 2015; Mamine and Farès 2020; Pelzer et al. 2012). If we consider the sales revenue, the CAP subsidies, the operational and material costs, the associated crops are more interesting than pure crops, whether or not there is an organic fertilizer input or a sorting stage on the farm. It would even be more profitable to grow two hectares of associated crops than one hectare of wheat and one hectare of legumes (L. Bedoussac et al. 2011).

Effects on climate change mitigation

Cadoux et *al.* observe a 24% reduction in GHG emissions when rotations are diversified and crop associations are implemented (Cadoux et al. 2019).

A 31% reduction in N_2O fluxes is observed when combining beans with wheat, compared to wheat that received N applications. Different factors such as applied N rate, Soil Organic Carbon (SOC) rate, pH and soil texture influence the amounts of N_2O emitted (Stagnari et al. 2017).

Up to one third of indirect CO_2 emissions from fertilizer use are avoided with the reduction of synthetic fertilizer use. According to Stagnari et al.(2017), 2.6 to 3.7 kg of CO_2 are generated per kg of synthesized nitrogen fertilizer. If we consider that crop associations avoid 50 kg N/ha, a reduction of 130 to 185 kg eCO_2/ha takes place. An increase in direct CO_2 emissions due to fuel consumption can be observed if the crop combinations require several tractor passes during sowing and harvesting.

According to Laurent Bedoussac(2009), the yield of crop associations is reduced when nitrogen is applied because wheat smothers the legumes. An attenuation of NH_3 (ammonia) emissions also takes place, but it is not quantified.

Other effects on soil, water, air and biodiversity

Associated crops improve soil quality, biological activity, SOC content, fertility, structure and permeability. Runoff and erosion phenomena are thus limited (Chenu et al. 2014; Stagnari et al. 2017). These effects are studied if the number of farm machinery passages increases. The insertion of legumes as an associated crop reduces pollution related to the leaching of nutrients. Some consider this reduction to be more effective than that provided by catch crops and fallows (SoCo Project Team 2009). Finally, they promote biodiversity - harvested or not - and increase the protein and nutrient self-sufficiency of farms (SoCo Project Team 2009; Eglin and Trévisiol 2015; Himanen et al. 2016).

b. Remarks

Lack of knowledge about the characteristics of the varieties, the density to be sown and the harvesting period can hinder farmers from implementing them. The same applies to the control required to reduce weed pressure while maintaining yields. The low commercialization of species mixtures, the lack of exchange rules between farms and the fear of not being able to use farm varieties anymore are other elements raised (Himanen et al. 2016).

The market value associated with these crops is problematic. They have so far proven to be uncompetitive compared to imported rapeseed meal for animal feed (Cholez and Magrini 2014). In general, the downstream industry generally demands pure and standardized products (Stagnari et al. 2017). This limits mixed crops to niche markets or adds a sorting step at farm level, when the chosen species allow it (Himanen et al. 2016). This sorting induces an increase in labor time and is not always efficient as it can leave a high dockage (15%). A second sorting would be necessary to use the production for human food, which represents a high cost (L. Bedoussac et al. 2011).

c. Conclusion

Crop associations show interesting results in terms of fertilizer and pesticide reduction. An increase in water consumption is noted but not quantified. The workload is greater than in monoculture, but the reduction in phytosanitary treatments sometimes counters this observation. Crop associations have a higher production cost than monoculture. This cost of production is counterbalanced by a high yield, making the gross margin higher than that of single crops. GHG emissions are reduced. Associated crops are beneficial for water quality and biodiversity. Their effects on soil quality depend on their management, especially the number of passes of agricultural machinery. Little recognized in Europe compared to the rest of the world, their development would require an adaptation of the sector both upstream and downstream.

2. Intercrop management

a. Cover crops

The term "cover crop" or "living mulch" is used here to refer to all crops planted during the intercropping period. They can be grown for the non-market ecosystem services they provide or to export and value their biomass. Harvested or not, part of their biomass is buried or left on the soil before the next crop is planted. Cover crops can be planted for specific purposes such as nitrate-fixing intermediate crops or IEC (Intermediate Energy Crops) or not (Ceschia et al. 2017). The term cover crop does not refer to relay crops, overflowing onto previous or following crops.

The average duration of intercropping periods is 6 months in Europe, varying from 5 months in the Northeast, around the Baltic Sea, to 9 months in the Southwest, in Spain. Intercrops are usually planted in September after a winter crop harvested in August, for durations longer than 3 months (Carrer et al. 2018).

Some species planted during intercropping can impact the growth of the main crop. This is particularly the case for ryegrass, which inhibits the root growth of the following crop by 34% if a period of at least two weeks is not observed between the intercrop and the crop that follows it (Trezzi et al. 2016). The choice of the covering crop, the timing of its establishment and its destruction should be considered at the scale of the rotation, depending on the previous and following crops (Eric Justes and Richard 2017).

A cover crop can be destroyed naturally if it freezes sufficiently in winter, avoiding the need for herbicides. Another alternative to herbicides is to destroy them by mechanical action (Guyomard et al. 2013; Eric Justes and Richard 2017). It is sometimes difficult to do without herbicides. This is particularly the case in Simplified Cultural Techniques (SCT) if the frost is not sufficient.

i. Results obtained

Effects on input use

Pesticides

The establishment of cover crops regulates the bio-aggressors that are present during the intercropping period, and in the following crop. Some species of cereals, *polygonaceae* and brassicas secrete allelopathic substances. Among these species can be mentioned rye, winter wheat, barley, oats, rice, sorghum, alfalfa, buckwheat, mustard, radish, rape and sunflowers (Jabran et al. 2015; Koehler-Cole et al. 2020). These allelopathic molecules are, once in the soil, active principles regulating the germination and growth of certain weeds. They also impact the development of pests such as nematodes or diseases caused by fungi and bacteria (Eric Justes and Richard 2017; Guyomard et al. 2013; M. Farooq et al. 2013).

These cover crops compete with weeds for light, water or nutrients. They thus compete with their development and growth. They attract and trap or poison pests, or repel them, reducing their presence on subsequent crops (Eric Justes and Richard 2017; Couëdel et al. 2017; Cordeau and Moreau 2017). The effect of intercrops depends on the type of intercrops planted, their arrangement (type of mixture) and their density (Cordeau and Moreau 2017).

Many studies report a reduction in weed numbers during intercropping with cover crops. Disease incidence and severity are also reduced in the following crop, as shown in Table 5and Table 6. Several studies mention the effectiveness of brassicas against nematodes (Couëdel et al. 2017; E Justes et al. 2012; Eric Justes and Richard 2017), but few studies quantify this effect.

The period from the end of August to mid-November corresponds to a period of herbicide treatment and the establishment of cover crops (Lazartigues 2010). The months of May and June correspond to a period of fungicide treatment on the crops preceding the intercrop (Lazartigues 2010). No study has quantified the reduction in the use of these pesticides.

Table 5 - Weed control effectiveness of cover crops

Cover crop	Measurement of	Effect	Comparison to	Source
Vicia villosa and oats	The weed seed bank	- 30% à - 70%		(Jabran et al. 2015)
Brassicaceae (rapeseed)	Weed biomass	- 85% à -96%	Bare soil in interculture	(Couëdel et al. 2017)
Brassicas (rapeseed, brown mustard or white mustard)	Total weed biomass	- 49%	Six weeks after emergence of the canopy compared to before	(Couëdel et al. 2017)
Radish, oats or buckwheat	Weed biomass	-28%		(Koehler-Cole et al. 2020)

Table 6 - Effectiveness of cover crops against soil-borne diseases (Couëdel et al. 2017)

Cover crop	Next crop	Disease	Effect on disease	Effect on the yields	Comparison to
Brassicaceae	Sunflower	*Verticulum*	- 60%		Bare soil before planting the crop
Brassicas (rapeseed and brown mustard)	Wheat	*Scalding petrified*	- 70%	Increase	A pasture
Brassicaceae (brown mustard)	Beet	*Rhizoctonia solani*	- 45% of the incidence - 7% of severity	+ 13%	A mustard-free witness
Brassicaceae (rapeseed)	Potato	*Rhizoctonia solani*	- 65% of the incidence - 50% à -70% of the severity	+27%	
Brassicaceae (white mustard)	Potato	*Rhizoctonia solani*	- 45% of the incidence - 47% of severity		
Brassicaceae (brown mustard)	Potato	*Rhizoctonia solani*	+ 35% of the incidence 17% increase in severity		
Brassicaceae (brown mustard)	Wheat	*Fusarium wilt F. graminearum*	- 30% of severity		
Brassicaceae (rapeseed)	Wheat	*Fusarium wilt F. graminearum*	- 45% of the severity		
Brassicaceae (cabbage)	Potato	*Streptomyces scabies*	-90% of the incidence		

Some species planted in cover crops may be hosts to pathogens and favor their presence. Attention must be paid to the fungi present in the plot or to which the following crop would be susceptible, in order not to choose a cover crop that would favor their establishment. Brassicas are, for example, hosts of fungi causing fusarium. Turnips and arugula can be used as cover crops but are susceptible to root-knot nematodes (Couëdel et al. 2017).

Some studies recommend applying a half-dose of herbicide following a cover crop, before planting a cash crop such as maize, to effectively control weeds (Couëdel et al. 2017). Such management raises the issue of the risk of weed resistance to the herbicides used, if they are applied in low concentration.

Fertilizers

If they contain legumes, cover crops can store up to 100 Nitrogen Units (NU) per hectare (Eric Justes and Richard 2017). This amount varies according to the legume species planted, their proportion in relation to other species if they are mixed, the soil and climatic conditions and the date of destruction. The nitrogen assimilated by legumes comes from atmospheric nitrogen. A legume intercrop does not capture and convert as much mineral N into organic N as grasses or brassicas (Constantin et al. 2017).

Up to 50% of the nitrogen acquired by a cover crop is made available within 6 months for the following crop (Constantin et al. 2017). The green manure section, page 103, details the fertilizer savings that can be achieved for a crop following legumes.

The date of destruction of the cover must be reasoned so that the mineralization of the released nitrogen matches the period of nitrogen assimilation of the following crop. Otherwise, a risk of leaching exists (Stagnari et al. 2017).

Water

Cover crops alter the water balance by increasing evapotranspiration and infiltration of water and reducing runoff. There is generally no impact on the water reserve available for the following crop if the covers are destroyed and buried one and a half months before its establishment (Carrer et al. 2018). In case of low winter precipitation or very late destruction of the cover crop (mid-March to mid-April), a reduction of about 10% in drainage and thus in groundwater recharge for the following crop is observed. This reduction can reach 25% in extreme cases (Constantin et al. 2017).

Effects on yields

The effect of cover crops on the yield of the following crop is mixed. The results in Table 6show that the presence of cover crops maintains or even increases yields (Altieri et al. 2011). The synthesis of 106 studies shows that cover crops of all types reduce the yield of the following crop by an average of 4%. But those containing a legume plus non-legume mixture increase on average the yield of the following crop by 13% (Abdalla et al. 2019). The green manure section on page 103 shows an increase in crop yield following legumes.

The effect of cover crops on the protein content of the following crop is highly variable (Abdalla et al. 2019).

Effects on working time

An increase of 0.6h/ha to 2.2h/ha in work time is observed, depending on the practices implemented to establish and destroy the cover crop. This increase is generally higher than 1.5h/ha (Colnenne-David and Bamière 2013).

Effects on the cost of production

An increase in fuel consumption occurs during the installation and destruction of the cover crop. The duration of the intercropping period, the method chosen to establish and destroy the cover crop, and the equipment used all affect this consumption (Labreuche and Deschamps 2016; Chambre d'Agriculture d'Isère 2017). A study conducted by INRA estimates the cost related to the establishment and destruction of a cover crop between 30€/ha and 150€/ha depending on the techniques used. These estimates take into account fuel consumption, tractor and equipment maintenance. The cost of seeds varies between 14 and 60€/ha (Colnenne-David and Bamière 2013). Labor costs vary from 9€/ha to 33€/ha, if the work is done by an employee. This increase is generally above 22.5€/ha (Colnenne-David and Bamière 2013).

A regrowth intercrop saves labor time, fuel, seed and equipment maintenance (Guyomard et al. 2013). However, it is likely to be less effective than an implanted cover crop.

A legume crop reduces the production cost of the following crop, thanks to less fertilizer use. These gains are detailed in the section on green manures.

Effects on climate change mitigation

Cover crops reduce global warming through biogeochemical effects by modifying GHG emissions or sequestering carbon (Carrer et al. 2018; Ceschia et al. 2017). They also act through biophysical actions on energy balance and albedo, the way solar energy is reflected from the earth's surface. The sum of biogeochemical and biophysical effects associated with the presence of a cover crop influences radiative forcing relative to bare soil (Ceschia et al. 2017).

Biogeochemical effects

N_2O emissions related to nitrification/denitrification processes in cover crops are about 6 kg eCO_2/ha/year. GHGs emitted during the technical operations of semi and destruction of these crops represent less than 30 kg eCO_2/ha/year (Ceschia et al. 2017). The carbon sequestration presented in Table 7- Carbon storage capacity of cover crops therefore much higher than the GHG emissions attributable to cover crops. The GHG balance related to the biogeochemical properties of these crops is therefore positive compared to bare soil. Other less recent studies estimate these emissions higher: according to Chenu et al.(2014, GHG emissions are in the range of 522 to 1,305 kg CO e/ha/year.

Table 7- Carbon storage capacity of cover crops

Carbon storage (kg eCO $_2$/ha/yr)	Specificity	Regions studied	Source
1 160	Without legumes	Pennsylvania (USA) and Spain	(Kaye and Quemada 2017)
1 350	In the presence of legumes	Pennsylvania (USA) and Spain	(Kaye and Quemada 2017)
1 100		37 different locations	(Poeplau and Don 2015)
865 à 1 380			(Ceschia et al. 2017)
1 000	Without legumes	46 trials worldwide	(E Justes et al. 2012)
477 à 1 360			(Chenu et al. 2014)

Although sequestration capacity is more related to the biomass produced than to the nature of the cover crops, some studies show that carbon storage increases in the presence of legumes (Ceschia et al. 2017).

Biophysical effects

Cover crops increase most of the time the albedo of the plots compared to bare soil. An increase in albedo has a cooling effect on the climate, which can be equated to equivalent atmospheric CO_2 sequestration. Table 8compiles the results of equivalent atmospheric CO_2 sequestration resulting from the increase in albedo by the presence of cover crops during intercropping periods.

Table 8 - Equivalent atmospheric CO sequestration $_2$by the albedo of cover crops compared to bare soil (Carrer et al. 2018)

Equivalent atmospheric CO sequestration $_2$ (kg eCO $_2$/ha/yr) over a 100-year horizon.	Duration of cover crops	Specificity	Regions studied
159	3 months		Europe
201,93	More than 3 months		Europe
114,48	3 months	Without irrigation	Europe
120 à 460			Pennsylvania (USA) and Spain

Albedo varies with location, geography, soil color, cover crop establishment (duration, density, type of cover crop), species selection and stage of development. Light soils can sometimes have a higher albedo than cover crops. The presence of cover crops rather than leaving the soil bare during the intercropping period on such plots would cause warming, thus reducing the equivalent atmospheric CO_2 sequestration. However, this reduction is still less than the effect of intercropping on carbon storage and would only compensate for part of it (Ceschia et al. 2017). Water availability is another factor reducing the albedo of cover crops. A 28% reduction in the albedo of cover crops compared to bare soil can occur under water stress (Ceschia et al. 2017).

According to Carrer et al.(2018, by cumulating the albedo effect of cover crops and their carbon sequestration capacities, GHGs can be reduced at a rate of 1,500 kg eCO_2/ha/year.

Cover crops have other effects on the biophysical properties of the plots. They contribute to reducing surface temperature and heat fluxes in favor of evapotranspiration fluxes, which tends to cool the climate as well. These phenomena are assumed to be of the same order of magnitude as the cooling effects of albedo (Ceschia et al. 2017). The impact on climate of cover crops planted on a large scale, such as changes in cloudiness due to their evapotranspiration, is not well known.

Other effects on soil, water, air and biodiversity

Cover crops protect soils from water erosion, runoff and capping. They improve their structural condition and maintain their organic matter richness (Eric Justes and Richard 2017; Carrer et al. 2018; Guyomard et al. 2013). Their roots foster soil water properties and filtration capacities.

The uptake and release of the canopy when it is not harvested ensures that minerals are recycled and maintained at the surface. Crucifers and grasses are more efficient than legumes in immobilizing mineral nitrogen. This nitrogen will not leach out, thus improving water quality. The destruction of the canopy leads to the release of minerals and the mineralization of nitrogen. In the absence of nitrogen fertilization, the balance of immobilization and release of soil nitrogen elements is zero (Constantin et al. 2017; Carrer et al. 2018; Guyomard et al. 2013).

These crops serve as a refuge for birds, wildlife and soil biodiversity (Eric Justes and Richard 2017; Carrer et al. 2018). In a mixed farming operation, they could contribute to herd's forage autonomy, depending on the species chosen.

ii. Remarks

The consequences of allelopathic effects on the reduction of symbioses with beneficial fungi and on the growth of the following crop are debated (Couëdel et al. 2017; Trezzi et al. 2016). According to Trezzi et al.(2016), allelopathic effects depend on the exudates of the varieties planted in the cover crop and the susceptibility of the following crop (Koehler-Cole et al. 2020). (Altieri et al. 2011) states on the contrary that an increase in above-ground biomass and seed germination of the following crop is observed.

All the benefits mentioned above are only valid if the cover crop is different from the previous and following crops. A crop identical to the main crop but with a different outlet, such as a IEC, will have an inverse effect on :

- Incidence of pests and diseases ;
- Reducing the use of nitrogen fertilizers ;
- Recharging the water supply ;
- Improvement of the soil structure.

iii. Conclusion

Cover crops reduce the incidence of pests but the reduction in pesticides is not quantified. If they contain legumes, less nitrogen fertilizer may be used for subsequent crops. They reduce eCO_2 emissions. Cover crops ensure nutrient recycling. They improve soil structure, water quality and biodiversity. Labour time and production costs increase, especially if the biomass of cover crops is not harvested. The effects of cover crops on the yield of the following crop vary according to the species they contain.

Undesirable effects on the following crops may occur. In order to minimize the occurrence of these effects and to take advantage of the benefits of cover crops, the choice of species, of their mixture, and of the technical itinerary (sowing and destruction dates) must be carefully made. The previous and following crops, the geo-pedological and climatic context of the plot, the number of days when practices can be carried out are all key elements to be taken into consideration when inserting cover crops in the rotation (Guyomard et al. 2013).

b. False seedbeds

False seedbed has been practiced since the dawn of time. The aim is to reduce the weed seed stock by repeatedly working the soil at less than 5 cm. The aim is to increase weed emergence in order to destroy them before sowing the next crop, thus limiting their development during the crop (Moureaux 2020; Matthieu Hirschy 2020). This practice is part of the no-till techniques (NTT) that are detailed in the section on tillage, page 48. It can also be carried out after ploughing or in a rotation that regularly alternates false seedbed and ploughing. This section focuses on the effect of false seedbed on weed management.

Done once or three times, two or three weeks apart during intercropping, false seedbed is effective for annual weeds that are not very dormant, such as grasses or for regrowth from the previous crop. It is not recommended to carry out false seedbed in the presence of perennial weeds because they multiply by vegetative reproduction. The effectiveness of this practice remains nevertheless dependent on the climatic conditions (temperature and humidity of the soil). The conditions must be favorable to seed emergence during the intervention and then ensure that the plants dry out the following days to avoid the risk of transplanting (Moureaux 2020; Matthieu Hirschy 2020).

Fine tillage also foster weed germination through good seed/soil contact. Tools such as stubble harrows, rolling spades and vibratory stubble cultivators are preferred to disc tools that cut the rhizomes of perennial weeds and multiply them.

Figure 3 illustrates the efficiency of some tools for weed control during false-seedbed according to Arvalis and TIOA (Technical institute for Organic Agriculture) (Moureaux 2020; Matthieu Hirschy 2020).

Type of tool	Working depth (cm)	False seedbed	Annual weed control
Cover crop (with roller)	4-5	Fair	Good
Stubble cultivation with independent discs	3-4	Good	Fairly good
Neo-stubble cultivator	4-5	Fairly good	Very good
Tools with vibrating tines (shares or crow's feet)	4-5	Good	Very good
Stubble harrow	1-2	Fairly good	Poor

Figure 3 - Efficiency of false seedbed according to the type of tool used, (Arvalis, TIOA), figure taken from (Matthieu Hirschy 2020)

This practice can be generalized for all crops. It is better suited to silty soils than to clay soils where the surface preparation of the soil starts early. Nevertheless, in some silty soils, the refinement and the absence of clods can favor the formation of capping (Moureaux 2020; Matthieu Hirschy 2020).

The timing of the false seedbed depends on the type of weed targeted, as shown in

Figure 4 - Emergence period of some weeds after a summer harvest, table from (Matthieu Hirschy 2020) (Matthieu Hirschy 2020)

. This practice is fully justified before a summer crop because it strongly reduces weeds in the crop. It is also interesting for grass control in winter crops, especially if there is no ploughing (Matthieu Hirschy 2020).

	Early harvest	Early September	Late September Early October	Late October
Cereal regrowth				
Rape regrowth				
Sterile brome				
Other Bromes				
Ryegrass				
Geranium				
Vulpine				
Cottontail				
Bentgrass				
Matricaria				
Speedwell				
Pansies				

Figure 4 - Emergence period of some weeds after a summer harvest, table from (Matthieu Hirschy 2020) (Matthieu Hirschy 2020)

The time available for repeated passes can be a limiting factor in the implementation of this practice. It is influenced by the presence of a cover crop, the previous crop and the following crop (Matthieu Hirschy 2020).

i. Results obtained

Effects on pesticide use

Weed management

This practice targets annual weeds with low dormancy. It has a weak or even opposite effect on perennial weeds (Mischler and Pernel 2011b).

Reductions in dry weight and weed density ranging from 30% to 95% are observed (Matthieu Hirschy 2020; Kanatas et al. 2020; Mischler and Pernel 2011a). The efficiency of false seedbed increases with the number of passes after (Matthieu Hirschy 2020). It is lowest for broadleaf weeds as shown in Figure 5 (Kanatas et al. 2020; Mischler and Pernel 2011a).

False seedbed is more effective than direct seeding in reducing weeds. It can be paired with a post-emergence herbicide for more efficiency (Kanatas et al. 2020).

Weeds concerned	Average effectiveness of delayed sowing date on weed density (on average the late sowing was done 19 days after the normal sowing date)
All	-67%
Broadleaf weeds (bedstraw, veronicas...)	-38%
Vulpine	-56%
Ryegrass	-68%
Sterile brome grass	-72%
Depending on the species considered, the reduction in weed densities varies from -38 to -72% with late autumn sowing. The effect is more marked for weeds such as vulpine, ryegrass or sterile bromegrass thanks to their narrow emergence peak.	

Figure 5 - Efficiency of late semis compared to normal date semis, tables from Mischler and Pernel 2011a)

Pest management

False seedbed could favor the seed fly, which likes freshly worked soils to lay its eggs, but it also helps to destroy slug eggs (Moureaux 2020).

Effects on yields

False seedbed can lead to a drying out of the seedbed and make irrigation necessary for crop emergence, especially if the seed is smaller than 1 mm. Yield degradation can also occur if the destruction of weeds emerged during the false seedbed is not complete (Matthieu Hirschy 2020). According to (Verschwele 2021) this risk is also present, especially for spring crops, if the false seedbed leads to a reduction in the vegetative growth time of the crop.

Other studies show that this practice maintains or even improves yields when combined with ploughing or post-emergence treatment (Verschwele 2021; Kanatas et al. 2020). It can increase yields by 22-32% compared to a direct seeding. This increase can be as high as 63% when a post-emergence herbicide treatment is applied after the false seedbed, compared to a direct drill followed by the same type of treatment (Kanatas et al. 2020).

Effects on working time

Performing a false seedbed requires about 30 minutes per hectare per pass, but a time saving can be perceived during other weed control related operations (Van Dijk et al. 2018).

Effects on the cost of production

The increase in the number of passes leads to an increase in fuel consumption. This cost can be offset by the absence of a herbicide treatment (Matthieu Hirschy 2020). The use of false seedbed can lead to an increase in the number of equipment on a farm, which also has a cost (Matthieu Hirschy 2020).

Figure 6 shows that two or three stubble ploughings are cheaper than one stubble ploughing followed by a herbicide treatment before sowing. Although more economical, strategy 1 is not recommended because without ploughing there is an increased risk of weed re-sprouting which could reduce yields and therefore gross margin (Mischler and Pernel 2011b).

	Intercrop				Wheat				
Strategy	Stubble ploughing mid-August (€/ha)	Stubble ploughing beginning of Sept (€/ha)	Stubble ploughing end of Sept (€/ha)	Glyphosate beginning of Oct (€/ha)[1]	Early sowing (€/ha)[2]	Late sowing (€/ha)[3]	Weeding end of Oct[4] + autumn insecticide (€/ha)[5]	Rotary hoe end of Oct (€/ha)	Total cost of the strategy (€/ha)
1	8,9				38,2		19,6		66,7
2	8,9			16,4	38,2		19,6		83,1
3	8,9	8,9			38,2			12,1	68,8
4	8,9	8,9				42,8			60,5
5	8,9	8,9	8,9			42,8			69,4

The economic simulation above shows that, contrary to what is expected, a strategy with 3 shallow stubble ploughings (and a late sowing) costs less than a strategy with one stubble ploughing and a glyphosate weeding (early sowing). Strategy n°1, with only one stubble ploughing and an early sowing, seems hardly tenable without a ploughing (more expensive), because of the risks of weed transplanting.

Cost of passage = cost of traction + cost of labour, according to the mutual aid scale, depreciated equipment except rotary hoe[1]
1,5 L de glyphosate/ha
[2] Sowing at 01/10 à 140 gr/m^2 with a T2
[3] Sowing at 01/10 à 140 gr/m^2 with a T2
[4] 2 L d'isporoturon + 0,2 L of First/ha
[5] 0,2 L of cyperméthrine/ha

Figure 6 - Costs of different false seedbed strategies, table from (Mischler and Pernel 2011b)

Effects on climate change mitigation

Although false seedbed requires less energy than deep tillage, an increase in fuel consumption is observed and varies with the number of passes. As with the cost of production, this increase can be offset by a reduction in herbicide consumption. An increase in N_2O emissions related to false seedbed is also induced, but it is very little studied. It should be of the same order of magnitude as the emissions observed under CSM, described in the section on tillage, page 48.

Other effects on soil, water, air and biodiversity

A reduction in the amount of weed seed stock will reduce the amount of herbicides used. If herbicide quantities are adapted to weed pressure, the risks of transfer to surface and ground water and to the air are reduced. Little information is available on the impact of false seedbed on functional biodiversity. However, the pass of tools may disturb the macro- and micro-fauna present on the surface. The soil remains bare when this practice is implemented. There is a risk of compaction and the formation of crusts when false seedbed is carried out in excessively wet conditions or on very silty soils (Matthieu Hirschy 2020).

ii. Remarks

False seedbed does not always eliminate the need for herbicides. In wet conditions, the use of glyphosate may be necessary, especially if the time between the destruction of the false seed and the sowing of the following crop is short. Although the delay of the sowing date facilitates the efficiency of a false seedbed, this delay is not systematic and depends on the farmers' choice (Moureaux 2020).

This practice cannot be combined with the other practices carried out and the demands made on farmers. The obligation to plant cover crops, for example, reduces the possibility of false seedbed (Matthieu Hirschy 2020). Conversely, it appears to be a practice that ensures efficient weed management when combined with the wheat-sorghum association (Shahzad et al. 2021). As it can favor the proliferation of perennial weeds, it is more suitable for farms with low weed pressure (Verschwele 2021).

A good adjustment of the equipment makes it possible to reduce fuel consumption and working time, which are two negative points of this practice (Mischler and Pernel 2011b). It is also possible to pool the purchase of equipment in order to reduce the related investments (three to seven tools are recommended) and to have the possibility to choose the tool most adapted to the conditions (Moureaux 2020).

iii. Conclusion

False seedbed reduces the pressure of annual weeds but can favor the multiplication of perennial weeds. It is a generalizable practice on all crops. Although it depends on climatic conditions, the choice of its implementation is made when defining the rotation. Intercrop management, soil type and other practices implemented are important factors to take into consideration. The tools available to carry out a false seedbed also condition its implementation.

If it allows to reduce the number of herbicide treatments, it does not always allow to do without it completely. It can even be more effective when combined with a post-emergence herbicide treatment. Work time and production costs increase with the number of replications carried out in the plots and with the purchase of specific equipment. This increase can potentially be counterbalanced by a reduction in the number of phytosanitary treatments. Energy consumption follows the same trend. The effect of crop residues on yields is mixed and seems to be very climate dependent. Increased tillage can lead to increased GHG emissions. This practice can increase the formation of capping and have negative externalities on wildlife. Conversely, it can reduce air, soil and water pollution if phytosanitary treatments are reduced.

c. Crop residues

After harvesting, the residues can be returned to the soil during the intercropping period. The main objectives are to reduce the development of weeds and to control the development of pests and diseases. This practice is also implemented to improve the yield of the following crop, especially for a wheat or maize crop (Nichols et al. 2015).

Straw and stubble from cereals, maize and soya beans are crushed, mixed and spread evenly over the field to be more easily broken down by soil micro-organisms during stubble ploughing. They can also be left on the surface. This succession of shredding and incorporation by shallow tillage is commonly called mulching (Nichols et al. 2015; Labreuche and Deschamps 2016). This section deals with crushed and buried crop residues, also known as mulch. It does not deal with living mulch, which corresponds to a soil cover by plants, which are treated in the cover crop section.

This reuse of residues is not suitable for certain crops such as silage maize, fiber crops such as flax or potatoes. Nevertheless, it is possible to apply residues from other crops after planting, after the first mechanical weeding or after ridging potatoes (Blaszczyk 2020). However, these alternatives remain uncommon on this type of crop. The application of a sufficient amount of residues, about 10 tons per hectare, is necessary for it to be effective (Blaszczyk 2020).

This practice requires technicality to break up the residues and spread them to a thickness of less than 5 cm, promoting close contact with the soil and micro-organisms. The depth varies depending on the type of tool used (Nichols et al. 2015). Multiple shreds can promote this contact, but they are not always feasible depending on the duration of the intercrop. The following crop can be directly sown on it, semi-direct or tillage can be done in between.

Residues will induce physical and chemical changes on the soil surface by influencing temperature, moisture, light and soil composition. Their effects depend on environmental conditions, soil type, C/N ratio of the residue and the chemical compounds they release (Nichols et al. 2015).

i. Results obtained

Effects on input use

Pesticides

Weed management

Crop residues regulate the presence of weeds by reducing temperature and humidity and increasing soil moisture. Residues of some crops secrete allelopathic substances that inhibit the growth of weeds, especially small seeds (Jabran et al. 2015; Nichols et al. 2015). The presence of crop residues creates habitats for granivorous fauna. Nevertheless, the effectiveness of this practice on weed management is not unanimous (Nichols et al. 2015).

All these effects are highly dependent on the weeds present, the type of residues and the environment of the plot, both in terms of the climatic context and the native predators. As an example, in humid areas crop residues limit the germination of small seeds (Machet et al. 2018). While in dry areas, increased moisture favors weed development (Nichols et al. 2015).

As shown in Table 9effect of crop residues on weed reduction is very variable, ranging from 0 to 95%. This maximum percentage corresponds to the result obtained with mechanical weeding. Weed management is considered to be effective if weed reduction is above 80%.

The decomposition over time of crop residues allows new weeds to emerge. This may also explain the average and variable impact of crop residues on weeds (Van Dijk et al. 2018).

Table 9 - Effects of crop residue on weeds

Residues of	Produced in a culture of	Elements evaluated	Reduction obtained	Source
Rye	Corn	Monocotyledonous weed density	61%	(Gavazzi et al. 2010)
Rye	Corn	Broadleaf weed density	96%	(Gavazzi et al. 2010)
Crucifers		Density of Digitaria sanguinalis	79%	(Couëdel et al. 2017) 3 weeks after incorporation
Crucifers		Density of Palmer's Amaranth	48%	(Couëdel et al. 2017) 3 weeks after incorporation
Five crucifers		Germination of *Sesbania Herbacea*	95%	(Couëdel et al. 2017)
Sunflower, rapeseed, sorghum combination	Corn	Density and biomass of purslane and round nutsedge	90% approx.	(Jabran et al. 2015)
Sorghum	Wheat	Biomass of Phalaris minor and White Needlewort	48% – 56%	(M. Farooq et al. 2013)
Combination of barley, triticale and rye	Corn	Emergence of *S. verticillata*	0-67%	(Jabran et al. 2015)
Combination of barley, triticale and rye	Corn	Emergence of switchgrass	27-80%	(Jabran et al. 2015)
Combination of sunflower, rice and crucifers	Corn	Purslane biomass	60%	(M. Farooq et al. 2013)
Rice straw	Potatoes		90%	(Blaszczyk 2020)
Wheat straw	Potatoes		84%	(Blaszczyk 2020)
Rape straw	Potatoes		79%	(Blaszczyk 2020)

Pest management

This practice controls the larvae of boring insects such as the sesamia or the corn borer by crushing them and then exposing them to birds and soil bacteria. It has limited effectiveness at the plot level and would be much more effective if done at the watershed level, according to Labreuche and Deschamps (2016). Table 10shows the effectiveness of mulches in combination with other practices on the reduction of moth and sesamia numbers (Labreuche and Deschamps 2016).

Table 10 - Effectiveness of mulches combined with other practices on borers (Labreuche and Deschamps 2016) (Labreuche and Deschamps 2016)

Practices	Effectiveness against borers
Grinding	50 à 75%
Grinding and shallow tillage	75 à 85%
Crushing and stump removal of the collar	95%

However, this effectiveness remains migrated or even disputed as an increase in molluscicides consumption may take place. This practice may also foster small mammal damage (Machet et al. 2018; Van Dijk et al. 2018).

Disease management

Crop residues alter the viability of fungal disease spores by burying them. Their effect on reducing the incidence of foliar diseases such as helminthosporiosis of wheat or maize, kabatiellosis have been noted in different studies. The same is true for fungal diseases such as Fusarium wilt, which cause the production of mycotoxins in grains or for the *Streptomyces scabies* bacterium, responsible for potato gall (Labreuche and Deschamps 2016; Couëdel et al. 2017). Table 11shows some quantified effects of mulches on the incidence of Fusarium head blight and the presence of mycotoxins in wheat grains in Switzerland (Drakopoulos et al. 2020).

Table 11 - Effects of mulch on the incidence of Fusarium head blight and mycotoxins in wheat grains in Switzerland (Drakopoulos et al. 2020)

Mulch	Effect on disease incidence	Effect on the presence of mycotoxins in grains
White mustard	- 32%	- 41%
Indian mustard	- 28%	- 45%
Alexandria Clover	- 41%	- 50%

However, this effectiveness remains mixed or even disputed as an increase in disease risk is increased in wetlands, which may induce an increase in fungicide consumption (Jabran et al. 2015; Tanveer et al. 2017; Machet et al. 2018; Van Dijk et al. 2018).

Fertilizers

The composition of crop residues influences the nutrients returned to the soil. Carbon-rich residues can increase nitrogen fertilizer consumption by up to 20 NU. Magnesium amounts can also increase, while phosphorus fertilizer amounts can decrease (Machet et al. 2018).

If the crop residues are rich in nitrogen, they can sequester the same amount of nitrogen as an intercropping cover crop, i.e. about 20-30 kg N/ha. A good C/N ratio of shredded stems favors nitrogen mineralization (Labreuche and Deschamps 2016).

A reduction of nitrogen fertilizers is possible, if the phases of residue mineralization and crop uptake coincide (Machet et al. 2018).

Water

Residue reduces soil temperature and increases moisture. Mulching is recommended under dry conditions to reduce evapotranspiration and maintain water availability (Blaszczyk 2020).

Effects on yields

As a result of the effects mentioned in the Water section above, crop residues may reduce yields and slow crop germination or tuber emergence in wet climates. This may explain the limited data available from northern Europe. No significant effect of residue incorporation on yields was perceived in an 8-year study in Belgium (Hiel et al. 2017).

This practice is recommended under dry conditions where yields will increase due to reduced evapotranspiration and water availability (Blaszczyk 2020; Machet et al. 2018; Van Dijk et al. 2018; Nichols et al. 2015).

Table 12shows data from outside Europe, as very little European data on mulch is available. This practice is very often associated with SCT and NTT, whose effects on yields are presented in the tillage section on page 51.

Table 12- Effects of mulches on yields of the following crop

Mulch of	Culture	Effect on yields	Source
Sorghum	Wheat	+ 16 à 17%	(Muhammad Farooq et al. 2013)
Combination of sorghum, rice and crucifers	Corn	+ 41%	(Muhammad Farooq et al. 2013)
Barley	Corn	+45%	(Jabran et al. 2015)
Combination of sunflower, rapeseed and sorghum	Corn	+54%	(Jabran et al. 2015)

Effects on working time

Depending on the type of equipment used and the usual practices of the farm, the restitution of crop residues can lead to up to 1 hour of additional mechanical work. Stubble ploughing takes about ½ h/ha and is generally carried out systematically. Shredding takes an average of ½ h/ha. A combine equipped with a shredder can perform this step during harvest. An increase in observation time to check for the presence of bio-pests can add to these workloads (Machet et al. 2018; Van Dijk et al. 2018).

Effects on the cost of production

The cost of mechanization varies between 10€/ha per pass if the equipment is available on the farm and 35€/ha per pass for a rental or service, depending on the equipment rented. In addition, the cost of labor is about 18€/ha. Fuel consumption varies according to the type of tillage performed and its depth (Machet et al. 2018). A potential increase in nitrogen fertilization can raise operational costs to about 30€/ha. A necessary use of pesticides may also add up (Machet et al. 2018; Van Dijk et al. 2018).

An application of 1.25 tons (T) of straw per hectare from bales costs about 270€/ha for crops that cannot reuse their residues. If the straw is purchased and transported, an additional 45 to 200€/T can occur (Cerdà et al. 2016).

Not using the straw may reduce the gross margin despite a potential increase in yield. The latter will be further reduced if the residue return is paired with an increase in inputs (pesticides and fertilizers) (Van Dijk et al. 2018).

Effects on climate change mitigation

Mulches reduce direct CO_2 emissions due to less mechanical work (Van Dijk et al. 2018). Nevertheless, the GHG balance is variable and can increase due to the mineralization process of OM (Organic Matter) and the related N_2O emissions. This process of humus degradation in the soil plays in favor of SOC sequestration. Unfortunately few data are available today (Labreuche and Deschamps 2016).

It appears that practices following residue burial will have a greater impact on direct fuel-related CO_2 emissions, GHG balance, and carbon sequestration. These are described in the tillage section on page 54.

Other effects on soil, water, air and biodiversity

The restitution of crop residues limits the risks of formation of slaking crust, soil compaction and erosion (Cerdà et al. 2016; Labreuche and Deschamps 2016). They reduce the rate of soil acidification (Machet et al. 2018). Their degradation increases the organic matter content. For example, crushing 8 to 10 tons of corn stalks produced 1600 to 2000 kg of OM (Labreuche and Deschamps 2016). The improvement of the soil structure is linked to the increase of the biodiversity that resides in the soil. Residues buried in the soil are in close proximity to microorganisms that rapidly degrade them, ensuring recycling of nutrients and thus a reduction in leaching (Labreuche and Deschamps 2016; Machet et al. 2018). Infiltration and storage of water in the soil are promoted, reducing the risk of transfer and runoff (Jabran et al. 2015; Tanveer et al. 2017).

ii. Remarks

Crop residue release is a practice that is very much associated with SCTs and NTTs, especially when direct seeding is performed there (Machet et al. 2018; Van Dijk et al. 2018). It can have very contrasting impacts on the incidence of bio-aggressors and on yields. The value of this practice needs to be analyzed according to the climatic context. If demonstrated, the implementation of this practice on a block of plots would be much more effective than on a plot scale only (Labreuche and Deschamps 2016; Blaszczyk 2020; Machet et al. 2018).

This practice should be considered in relation to other uses of straw. A risk of competition with livestock feed and bedding or the manufacture of insulation or bioenergy may occur (Machet et al. 2018).

iii. Conclusion

Burying crop residues provides soil protection comparable to that of covering crop (Labreuche and Deschamps 2016). Residues reduce soil temperature and increase moisture. They are used to control weeds, diseases, pests or to influence fertilization. Their effectiveness is variable and depends on the type of weeds, the C/N ratio of the weeds, the native predators and the climatic context. Yields will tend to decrease in wet climates and increase in dry conditions. Labor time will increase with the implementation of this practice. The cost of production varies according to the equipment available, the nature of the residues and their origin and the other possible ways of valorization.

The GHG emissions balance is mixed and depends mainly on the type of tillage carried out between the burial of the residues and the sowing of the next crop. However, this practice seems to be beneficial to the sequestration of SOC. It improves soil quality and limits soil erosion. Water quality and infiltration are also improved. This practice favors soil micro-biodiversity. Closely related to the SCT and NTT, described on page 48, its effectiveness seems to be greater at the scale of a block than at the scale of isolated plots. The choice of this practice depends on the other possibilities for reusing crop residues.

3. Introduction of agroecological infrastructure

Agroecological infrastructures (AEI) correspond to fixed and semi-natural elements of the landscape that do not receive chemical fertilizers or pesticides. Located near cultivated plots, they are maintained for their services to crops and the environment. They are a source of habitat for wildlife and promote the presence of crop protection agents to control pests (Sarthou 2016). Some AEIs such as grass strips, hedges and coppices are also Buffer Zones (BZs) and ensure interception and mitigation of molecule transfers to the environment ("Functions and Effectiveness Of Buffer Zones" n.d.). This section focuses on the latter.

a. Results obtained

Effects on input use

The main inputs affected by Buffer Zones are insecticides. They do not have a direct effect on fertilizer consumption, but may have an effect on water availability for crops.

Insecticides

The level of biological regulation of pests varies greatly between studies (Jeanneret et al. 2017; Lacas et al. 2005). According to an analysis of 18 studies conducted in Europe, the USA, and New Zealand, the implementation of grass and flower strips reduces pest pressure on adjacent cultivated plots by about 16% (Albrecht, Tschumi, and Blaauw 2020). This reduction does not mean that insecticides can abandoned. However, feedback from French and Dutch farmers shows that once the balance between pests and crop protection agents is restored thanks to flower strips, it is possible to do without certain insecticides on potato, rape, cereal and beet crops (Viel 2014).

The presence of grass or flower strips can increase weed abundance in the first meter of adjacent crop. From two meters away, weed cover within the crop plot is not influenced by the weed strip (Caroline Gibert 2020).

Water

In field crops, the presence of hedges or trees can compete with crops for water resources. This water stress can in some cases reduce crop nitrogen uptake, which in turn affects crop growth and dry weight (Swieter, Langhof, and Lamerre 2021).

Effects on yields

Grass strips do not have a significant and consistent effect on yields (Albrecht, Tschumi, and Blaauw 2020; Viel 2014). When AEIs are wooded areas, hedgerows, or agroforestry areas, yield losses can be observed in the first few meters due to root competition for water resources and shading (Caroline Gibert 2020).

It is possible to recover biomass from certain infrastructures. The cuttings from grass strips, when they are not declared as set-aside, can be used as fodder, litter or to produce methane. It is possible to harvest 7 to 16 tons of biomass or energy wood 7 to 10 years after the establishment of short rotation coppice (Bailleux 2017).

Effects on working time

The establishment of Buffer Zones requires between two and ten hours of work per hectare per year for soil preparation, sowing and maintenance (Kürsten 2020). In addition, there is the time required to observe the interactions between crop protection agents and pests (Viel 2014). Nevertheless, their presence can potentially avoid the time spent on an insecticide application.

Effects on the cost of production

The preparation of the soil, the semi and the maintenance of a grassed strip costs between 400 and 630€/ha/year (Chenu et al. 2014; Colnenne-David and Bamière 2013). These practices may require specific tools. An economic gain of 4 to 40€/ha on the adjacent plot can be achieved if phytosanitary treatments are dispensed with. These costs are ⅔ to ¾ lower than those of a cereal crop.

There are several types of funding for the establishment of these Buffer Zones. Most of them are linked to the CAP. Subsidies of up to 975€/ha exist in Germany. They allow a margin of up to 600 or 800€/ha (Kürsten 2020).

Effects on climate change mitigation

The tillage of AEIs is equal to or less than that of the adjacent crop. The associated $_2$are therefore lower or equal. Since they are neither treated nor fertilized, they emit less direct and indirect CO_2 and N_2O than adjacent crops. However, these emissions remain poorly quantified (Colnenne-David and Bamière 2013).

Coppice can store up to 3.4 T C/ha/yr in their vegetation and up to 0.62 T C/ha/yr in the soil (Kürsten 2020). Some soil analyses in England and Hungary find that grass strips contain more carbon (4.3%) than the soil in wooded AEIs (3.4%) or adjacent cultivated plots (2.6%) (Caroline Gibert 2020). Other research has shown that the presence of coppice at the edge of crops increases the carbon content in the first few cm of the crop soil for up to 30 meters. According to them, 1 to 5 tons of carbon can be stored in the first cm of the soil of crops located up to 30 meters from a wooded AEI, thanks to restitutions (leaves...) (Kürsten 2020). INRAE estimates the carbon sequestration capacity of grass strips at about 0.49 Mg C/ha/year (Colnenne-David and Bamière 2013).

Other effects on soil, water, air and biodiversity

Runoff is reduced by 50% between a plot and a stream for a Buffer Zone of 15 m (Lacas et al. 2005). Pesticides and nutrients are infiltrated, retained, dissolved or degraded (Liger et al. 2015). This allows a reduction of 25 to 96% of their concentration between the initial runoff and the concentration observed at the level of a water table, depending on the type of soil and the type of Buffer Zone implanted (Lacas et al. 2005; Liger et al. 2015). In addition to the protection of water resources, these areas provide shelter for birds, mammals and auxiliary fauna. They favor the presence of pollinators. An improvement of soil quality and a reduction of erosion risks are also observed (Gril, Carluer, and Le Hénaff 2011). All these effects depend strongly on the type of Buffer Zone planted.

b. Remarks

The impact of Buffer Zones on pests and their effectiveness in biological control depends on their type, proximity to crops and proportion (Jeanneret et al. 2017). Their ability to filter 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; Lacas et al. 2005).

c. Conclusion

AEIs such as grass strips and coppice have very variable effects on the control of pests in adjacent crops and thus on the reduction of insecticide use. No significant effect on adjacent crop yield was found and it is possible to make use of the biomass produced by some AEIs.

Their management requires about 10 hours of labor per year and their cost of production is ⅔ to ¾ of that of a cereal crop. These AEIs emit as much or less GHG as adjacent crops and sequester greater volumes of carbon. Better water infiltration is observed, reducing runoff and pesticide concentrations, thus protecting water resources. Soil quality is improved, erosion risks are reduced and biodiversity is preserved.

C. Varietal choices

1. 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 ATEV (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 evaluation are not harmonized between the Member States (GNIS n.d.).

No variety systematically combines all the criteria of interest (resistance to water stress, yield capacity, resistance to bio-aggressors, adequate bread-making, nutritional and taste 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 (AUDIGEOS et al. 2018).

a. 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).

A reduction ranging from 25 to 50% in fungicide use for field crops has been found in France, England and Denmark, if plant protection programs are adapted (Jorgensen et al. 2017). The use of septoria-resistant wheat varieties allows a reduction in fungicide expenditure of 20€/ha to 30€/ha on average (Hourcade et al. 2015; AUDIGEOS et al. 2018).

No variety cumulates a sufficient level and diversity of resistance to allow to completely dispense with chemical protection without risking a significant yield loss compared to conventional pesticide use (AUDIGEOS et al. 2018). Follow-ups in field crop farms have shown that the adjustment of the treatment program according to plots containing resistant, tolerant or susceptible varieties is not systematically carried out (Guyomard et al. 2013). The benefit of using such varieties is therefore not fully valued by farmers.

Fertilizers

The capacity of a variety to reduce nitrogen consumption is not expressed. Instead, the Nitrate Use Efficiency (NUE) of a variety is studied. Varieties with improved NUE are selected indirectly. They correspond to varieties improved to increase yields and their qualities (Guyomard et al. 2013; Cormier et al. 2016). Several studies have shown a posteriori that varietal selection has led to savings of 6 to 8 kg.N/ha in wheat crops after 10 years of genetic improvement (Cormier et al. 2016). A reduction of 40 units of nitrogen compared to the recommendations was obtained for oilseed rape, while maintaining yields and protein contents acceptable according to the specifications (Charbonnier and Fugeray-scarbel 2019).

The lack of quantification of the potential to reduce nitrogen fertilizers and the failure to disseminate this potential to farmers stem from this indirect selection. There is no specific valuation for the more N-efficient varieties for their inclusion in the catalogue (Charbonnier and Fugeray-scarbel 2019). NUE needs to be taken more into account in varietal selection (Cormier et al. 2016). The development of varieties selected for their NUE could reduce the use of nitrogen fertilizer by an average of 25% ("Whealbi" 2021).

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 ATEV mention assessing the adaptation of the variety to technical itineraries with limited access to water, some feel that this is not sufficiently taken into account (Quenin 2020).

Some wheat varieties have yield losses of less than 10% when subjected to water stress, which is low compared to other less adapted varieties. Farmers' seeds, which are selected and replanted from one year to the next by farmers, are more heterogeneous and better adapted to climatic variations. However, they have a lower yield than "conventional" varieties (Aspar 2019).

The choice of early or late flowering varieties avoids coinciding the sensitive periods of the vegetative cycle with periods of water stress. One study estimates that maize yields could increase by 4-7% by 2050 if this dodging strategy is implemented. This possibility is not feasible for all field crop species. It mainly concerns maize, sunflower and sorghum (Parent, Welcker, and Tardieu 2019).

Effects on yields

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

The field loss potential is lower (1 T/ha) for pest resistant varieties than for more susceptible varieties (2.5 T/ha) (Jorgensen et al. 2017). Gains of 7 to 10 q/ha have been observed for septoria and rust resistant wheat varieties compared to susceptible varieties (Hourcade et al. 2015; AUDIGEOS et al. 2018).

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

Effects on working time

A wheat variety resistant to foot rot, fusarium or lodging may allow the suppression of a treatment provided that production targets are satisfactory, which translates into a reduction in workload (AUDIGEOS et al. 2018). Nevertheless, fine observation of crop health status to reason the treatment program according to pest pressure can be time-consuming, as can the acquisition of skills needed to do so (Guyomard et al. 2013).

Effects on the cost of production

The cost of resistant or tolerant seed may be higher than that of non-resistant seed. This difference is negligible compared to the cost of investing in equipment. It is therefore a low-cost alternative (Guyomard et al. 2013). If a phytosanitary treatment can be avoided, a saving in fuel and labor can be observed in addition to a saving in pesticides, which represents a potential gain of 30 to 60 €/ha in field crops (AUDIGEOS et al. 2018).

The effects of a potential reduction in nitrogen fertilizer due to the use of varieties with high NUE are not accounted for here.

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).

Other effects on soil, water, air and biodiversity

Following the same framework, a reduction in the passage of agricultural machinery linked to treatments reduces the risk of settling. If the quantities of nitrogen spread are reduced, the risk of leaching is reduced ("Whealbi" 2021). A reduction in the number of treatments also reduces the risk of groundwater pollution and increases the presence of biodiversity. Such varieties are less sensitive to natural hazards and the effects of climate change (Guyomard et al. 2013).

b. Conclusion

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 with efficient nitrogen use could potentially reduce the use of nitrogen fertilizers. Drought-tolerant varieties or those with the ability to adapt their production cycle to water constraints are of great interest for coping with climate change. However, these criteria may not be sufficiently taken into account at the time of listing.

2. Mixtures of varieties on the same plot

Varietal mixtures are gaining interest. The main objectives of farmers are to ensure yield stability, reduce the incidence of pests and consequently the use of pesticides. The research work done so far is mainly focused on disease management and yield gains (Borg et al. 2018).

a. Results obtained

Effects on input use

Pesticides

The use of varietal mixtures on the same plot, for field crops, increases the allelic richness of resistance genes. A slowdown in the progression of epidemics is observed. The bypassing of varietal resistance by pathogen populations is delayed, thus lengthening their duration. The association of varieties carrying different genes and alleles can extend crop protection to various pests and improve the results obtained (Guyomard et al. 2013). Mixtures of 3 to 5 varieties have been shown to be more effective than binary associations. Still, the effectiveness of varietal mixtures compared to the average effectiveness of the single-variety crops that compose them remains variable depending on the crop, variety and bio-agressor (Vallavieille-Pope et al. 2016).

A lower use of pesticides, especially fungicides, is observed, reducing the costs related to their use (Vallavieille-Pope et al. 2016). Table 13summarizes the results obtained regarding the reduction of phytosanitary protection related to the use of varietal mixtures compared to the average of single varieties.

Table 13: Comparison of results obtained with and without varietal mixtures

Culture	Disease	Incidence of disease in monovarietal	Incidence of disease in varietal mix	Effects of mixing on pesticide use	Country	Source
Barley	Powdery mildew	50%	10%	Reduction	Germany	(Vallavieille-Pope et al. 2016)
Wheat	Septoria			7% reduction	France	(Vallavieille-Pope et al. 2016; Lorgeou and Philippe Du Cheyron 2019)
Rice	Leafhopper	20%	1%	Change from 3 to 7 treatments in monovarietal crops to 1 treatment in multivarietal crops	China	(Vallavieille-Pope et al. 2016)

Several European countries are already working with varietal mixtures. In Denmark, 9 to 12% of the spring barley is sown with a combination of 3 to 4 varieties. Combined barley varieties are produced for livestock feed in Scotland. In Poland, 22% of the cereals are produced with a combination of generally 3 varieties. Studies have shown that varietal mixtures reduce the severity of late blight on potato in France (Vallavieille-Pope et al. 2016).

Analysis of 60 studies shows that intra-specific crop diversity and thus the presence of several varieties within the same plot reduces the presence of insect herbivores and the damage they cause (Koricheva and Hayes 2018).

Nitrogen

Varietal mixtures would be more beneficial than single varieties when low amounts of fertilizer are used (Borg et al. 2018). The adoption of varietal mixtures complicates fertilization management, as nitrogen requirements do not coincide due to asynchronous development of varieties (Labarthe et al. 2018).

Water

Varietal mixtures do not influence the amount of water consumed but would help stabilize yields under water stress (irrigation deficit, drought or frost) (Borg et al. 2018).

Effects on yields

Yields obtained with varietal mixtures are greater than or equal to the yields obtained with monovarietal crops in 70% of cases.

The analysis of about thirty studies in North America and Europe shows an average yield increase of 3.5% for wheat varietal mixtures compared to the average yield of single varieties. Under high disease pressure, the yield increase can be as high as 6.2%. Yield increases on average by 5.3% for mixtures with high heterogeneity of resistance genes compared to more homogeneous variety mixtures (Borg et al. 2018). Yield increases ranging from 0.5 to 3.2 q/ha were obtained in wheat crops in France under light (one fungal treatment on average) or no plant protection (Vallavieille-Pope et al. 2016; Lorgeou and Philippe Du Cheyron 2019).

These differences in yields between single-variety crops or mixed-variety crops are not always significant. While varietal mixtures generally achieve higher yields than the average yield of single varieties, they often yield less than the most resistant varieties when grown alone (Lorgeou and Philippe Du Cheyron 2019). Some argue that varietal associations provide yield's stability compared to single-variety crops (Vallavieille-Pope et al. 2016; Snyder, Gómez, and Power 2020). However, for others, yield stability is mainly defined by the genetic lines involved (Lorgeou and Philippe Du Cheyron 2019).

An increase in production quality (wheat protein content, amount of nitrogen in seeds) and bread making equal to single variety crops is obtained in France (Vallavieille-Pope et al. 2016; Lorgeou and Philippe Du Cheyron 2019).

Effects on working time

As with the use of resistant varieties in single-variety crops, the use of varietal mixtures can lighten plant protection programs, thus reducing workloads. Adapting the protection program requires, on the other hand, time and knowledge to observe the sanitary status of the crops (Guyomard et al. 2013).

Effects on the cost of production

A reduction in treatments is expected to result in labor and fuel savings (Guyomard et al. 2013). Snyder, Gómez, and Power(2020) highlight the lack of data related to the cost of production and emphasize the need to take it into consideration to analyze the profitability of this alternative.

Effects on climate change mitigation

Direct CO_2 emissions can be reduced by reducing the amount of fuel used. They are reduced indirectly by reducing the energy cost associated with the manufacture of pesticides (Guyomard et al. 2013).

Other effects on soil, water, air and biodiversity

Varietal mixtures participate in production diversification if the varietal scale is accounted for (Guyomard et al. 2013). They are more beneficial than monovarietal crops when soils are compact or degraded (Borg et al. 2018).

b. Remarks

The effectiveness of varietal mixtures in controlling pests depends on the type of potential aggression, the soil and climate conditions of the plot, and the number of resistance genes available against the targeted pests. These mixtures are effective if the diversity of genes and resistance alleles they contain is sufficient. Fine characterization of the varieties ensures such diversity. However, this requires the publication of gene mapping, which is a matter of industrial secrecy (Guyomard et al. 2013). In addition to the upstream characterization and commercialization of variety mixtures, their collection once harvested is not always guaranteed (Guyomard et al. 2013; Vallavieille-Pope et al. 2016)).

The spatial and temporal distribution of disease proliferation is difficult to estimate, and gaps in knowledge of resistance genes make it difficult to formulate rules for the application of varietal mixtures. But, adapted to local conditions and pressures, varietal mixtures can be applied as a preventive measure avoiding pesticide resistance on the one hand and one or two fungal treatments on the other. Their implementation can be simpler than the association of different species. Indeed, varieties of the same species may have similar harvesting times and require the same type of equipment and agronomic knowledge (Snyder, Gómez, and Power 2020).

c. Conclusion

Varietal mixtures are preventive measures against pesticide resistance. They generally reduce fungal treatments by one or two while maintaining or improving yields compared to single-variety crops. It is inexpensive and also reduces pesticide, sprayer and labor costs. The effects on labor time are still debated, as the reduction in treatment time is offset by an increase in observation time. Indirectly, GHG emissions can be reduced. Varietal mixtures increase resistance and resilience to hazards such as soil degradation and water and nitrogen stress (Vallavieille-Pope et al. 2016; Borg et al. 2018; Guyomard et al. 2013; Snyder, Gómez, and Power 2020).

Varietal mixtures can be an alternative to crop diversification, simplifying management compared to combining different species. But their implementation requires an adaptation of the upstream and downstream channels.

D. Tillage

Tillage affects the physical, chemical and biological condition of a cultivated plot. It has a direct role on the location of organic matter, minerals and carbon, as well as on the transfer of water and molecules that are dissolved in it. It can also influence the presence of certain diseases and weeds. These effects vary according to the dates of intervention, the tools and the depth worked. The latter allows soil operations to be classified into three different categories.

The most common form of tillage in Europe is ploughing. It breaks up, turns over and moves the soil to a depth of 20 to 35 cm. Its purpose is to destroy weeds and regrowth and to bury soil improvers and crop residues or phytosanitary products that may be toxic to the following crop. It is the technique with the greatest impact on the physical, chemical and biological components of the soil, due to the volume of soil and the inversion of horizons that it creates. Poor ploughing is a fairly frequent risk. It can lead to ploughing soles and compaction under the ploughed horizon.

Shallow tillage, also known as simplified cultivation technics (SCT), at a depth of less than 15 cm, makes it possible to destroy weeds and regrowth by stubble ploughing and hoeing. It favors the humification of organic matter, levels the soil and creates a seedbed favorable to germination. No-tillage techniques (NTT) reduce tillage to less than 5 cm deep or even plant crops in direct seeding, without prior tillage (GUILLEMAN et al. 2003; Guyomard et al. 2013). Although it is tending to develop in Europe, it is much less popular than in America. False seedbed, detailed on page 26 is one of the practices implemented in NTT.

Subsoiling regenerates the structure of horizons that are located below the plough bottom and are not annually fragmented by soil preparation tools. This operation improves deep root growth and promotes water drainage to a depth of 50 to 85 cm (GUILLEMAN et al. 2003). As it is carried out less systematically than other types of tillage, it is not covered in this section.

1. Results obtained

Effects on input use

Pesticides

Herbicides

Ploughing buries weeds and their seeds deep into the soil, allowing them to be controlled without the use of herbicides. Conversely, SCT and NTT may increase the use of herbicides as shallow soil disturbance favors the emergence of some weeds (Guyomard et al. 2013). Table 14confirms this for cereal-legume rotations, although there were herbicide treatments.

Table 14 - Effects of SLC and SLT on weed occurrence compared to conventional tillage

Type of tillage	Effect on the presence of weeds compared to conventional tillage	Type of herbicide use	Source
SCT	+ 15%	3 L/ha of post-harvest glyphosate and selective herbicide	(Panasiewicz et al. 2020)
SCT	+ 16%	20% of the production cost	(Chetan et al. 2016)
SCT	2 times more	3 L/ha of glyphosate in post-harvest and pre-emergence	(Woźniak et al. 2019)
NTT	+ 30%	3 L/ha of glyphosate pre-emergence and post-harvest and selective herbicide	(Panasiewicz et al. 2020)
NTT	1 ½ times more	4 L/ha of glyphosate and selective herbicide	(Woźniak and Soroka 2018)

Fungicides

Ploughing buries crop residues and the pathogens that can contaminate them. This allows an initial control of diseases independently of fungicides. This disease control is achieved in SCT and NTT by microbial activity on the soil surface (Gawęda et al. 2020). Despite this, not burying contaminated crop residues can promote disease transmission to the following crop, especially in monoculture (Guyomard et al. 2013). SCT and NTT increase the incidence of fungal diseases as shown by the study results given in Table 15.

Table 15 - Effects of SCT and NTT on fungal disease incidence compared to conventional tillage

Culture	Type of tillage	Disease	Effect on incidence compared to conventional tillage (%)	Source
Barley	SCT	Fusarium	+ 49	(Schöneberg et al. 2016)
Soybeans	NTT	*Ascochyta*	+ 51,9	(Gawęda et al. 2020)
		Septoria wisteria	+ 32,4	(Gawęda et al. 2020)
		Cerospora sojina	+ 43,4	(Gawęda et al. 2020)

Ploughing also reduces the development of pests on crops (voles, slugs...). The SCT and NTT do not allow to control these bio-aggressors as effectively (Guyomard et al. 2013).

Fertilizers

Tillage helps to make nitrogen available to crops. It increases macropores in the soil, allowing for better air, temperature and water movement. Moist conditions and higher temperatures increase microbial activity. Organic matter is distributed and made available to microorganisms, promoting nitrogen mineralization (Lipenite, Karklins, and Ruza 2018; Broué 2016). Under certain conditions, such as poorly drained soil, tillage can cause structural accidents. The consequences are reduced porosity and reverse effects on microorganisms and nitrogen mineralization (Lipenite, Karklins, and Ruza 2018; Broué 2016).

The amounts of N mineralized are annually comparable regardless of tillage (Lipenite, Karklins, and Ruza 2018; Broué 2016). The type of tillage performed influences when N is mineralized and available to crops.

At the end of winter, excess water prevents the soil from warming up. Ploughing increases the temperature and promotes the mineralization of nitrogen that is available during the early stages of crop growth (BOURGEOIS et al. 2013; Lipenite, Karklins, and Ruza 2018). It allows a release of nitrogen of up to 50 or 100 kg N/ha (Thomas 2007). These amounts of N released during fall tillage are not fully captured, even when a cover crop is present during intercropping. Ploughing at this time may therefore favor leaching (BOURGEOIS et al. 2013).

In SCT and NTT, the increase in organic matter in the shallow soil horizons maintains high moisture throughout the season in dry regions (Lognoul 2020; Broué 2016). Combined with low temperatures at the end of winter, this creates conditions that are not favorable for mineralization processes. The slowing down of mineralization at this period induces an increase in fertilization of 10 to 20% in the first years (Lognoul 2020; Broué 2016). A later mineralization ensures a more spread out availability of nitrogen to the plants during the season.

Other factors such as soil type and site location also influence the availability of nitrogen to crops. This explains the very contrasting results obtained in trials on the impact of tillage on fertilization (Lipenite, Karklins, and Ruza 2018).

Burying fertilizer at a depth of 10 or 15 cm increases the efficiency of inputs. This allows a saving of 7 kg of organic nitrogen or 12 kg of mineral nitrogen per hectare on average (Normandy 2016).

Water

Tillage influences the capacity of the soil to infiltrate and retain water. Its effects, and more broadly those of different cropping systems on soil water use efficiency, vary with soil type, organic matter content and climate. They are little studied (Habbib et al. 2020). The results of a modelling on the water retention capacities of sandy or silty soils containing different organic matter rates confirm these claims (Lutz et al. 2019). They are presented in Table 16.

Table 16 - Effect of tillage type on water holding capacity as a function of soil type and organic matter content (Lutz et al. 2019) (Lutz et al. 2019)

Type of soil	Organic matter rate	Type of tillage	Effect on water retention capacity
Sandy	0%	Ploughing	+ 83%
	8%	NTT	+ 105%
		Ploughing	+ 84%
Silty	0%	Ploughing	+ 16%
	8%	NTT	+ 31%
		Ploughing	+ 26%

An increase in water storage capacity is observed after tillage with ploughing, NTT or SCT, but it is higher for SCT and NTT. However, some claim that this trend is reversed in the long term under tillage (Aspar 2019).

Effects on yields

No significant difference was found for yields obtained under NTT or conventional tillage according to a meta-analysis of 251 long-term studies in Europe (Sandén et al. 2018). However, under NTT an average yield reduction of 8.5% was found based on a review of 171 observations in Europe. A 9.8% reduction was also found in Sweden from 226 observations (Townsend, Ramsden, and Wilson 2016) .

According to the European meta-analysis, SCT induces an average yield loss of 4% compared to conventional tillage (Sandén et al. 2018). This is consistent with yield losses found in 563 other European studies (Townsend, Ramsden, and Wilson 2016).

Effects on working time

A reduction in working time is generally observed when shallow tillage or no-till is used. This time saving varies according to the crop and the soil, climate and geographical context. It can be as high as 60% for SCT and 80% for NTT as shown in Table 17Table 18. According to the ECAF (European Conservation Agriculture Federation), no-till saves 3 to 5 hours of work per hectare (ECAF 2021).

In addition to reducing pulling time, these techniques allow for a better distribution of work peaks during a year (Guyomard et al. 2013).

Table 17 - Comparison of the effect of CHT on working time compared to conventional tillage

Culture	Working time in SCT (h/ha)	Working time with conventional ploughing (h/ha)	Effect on working time compared to conventional tillage (%)	Source
Rice	3	4,5	32	(Calcante and Oberti 2019)
Wheat	1	2,5	60	(Calcante and Oberti 2019)
Corn	4,18	5,75	27	(Vach, Hlisnikovský, and Javůrek 2018)
Wheat			50	(Lithourgidis et al. 2006)

Table 18 - Comparison of the effect of SLI on working time compared to conventional tillage

Culture	Working time in NTT (h/ha)	Working time with conventional ploughing (h/ha)	Effect on working time compared to conventional tillage (%)	Source
Rice	2,8	4,5	38	(Calcante and Oberti 2019)
Wheat	0,5	2,5	80	Calcante and Oberti 2019)
Corn	5,04	5,75	12	(Vach, Hlisnikovský, and Javůrek 2018)
Wheat			50	(Lithourgidis et al. 2006)Lithourgidis 2006

Effects on the cost of production

In addition to the labor required, the consumption of fuel, pesticides and fertilizers is influenced by the type of tillage.

Reducing the depth of cultivation operations reduces fuel consumption in SCT up to about 50% as shown in Table 19. The reduction in fuel consumption is even greater in NTT, according to the data compiled in Table 20. According to ECAF (2021), a reduction of 60 to 80 liters of fuel can be achieved in NTT.

Table 19 – Fuel Consumption SCT versus Conventional Tillage

Culture	Effect on fuel consumption compared to conventional tillage (%)	Source
Rice	- 48	(Calcante and Oberti 2019)
Wheat	- 42	(Calcante and Oberti 2019)
Corn	- 57	(Calcante and Oberti 2019)
Wheat	- 32	(Calcante and Oberti 2019)
Cereals	- 23	(Townsend, Ramsden, and Wilson 2016)
Soya - wheat - corn	- 17	(Chetan et al. 2016)
Corn	- 33	(Vach, Hlisnikovský, and Javůrek 2018)

Table 20 - Fuel Consumption for NTT versus Conventional Tillage

Culture	Effect on fuel consumption compared to conventional tillage (%)	Source
Rice	- 63	(Calcante and Oberti 2019)
Wheat	- 75	(Calcante and Oberti 2019)
Corn	- 61	(Calcante and Oberti 2019)
Wheat	- 77 [1]	(Calcante and Oberti 2019)
Cereals	- 58	(Townsend, Ramsden, and Wilson 2016)
Corn	- 26	(Vach, Hlisnikovský, and Javůrek 2018)

Total production costs can thus be reduced if no pesticides are used to compensate for the effects of tillage. For example, they can be reduced by 16% under SCT and 19% under NTT for rice production in Italy (Calcante and Oberti 2019). A reduction of 1.5% is achieved under NTT in Poland for a cereal-legume rotation and 6.6% in Romania for a soybean-wheat-corn rotation compared to their respective conventional tillage control (Chetan et al. 2016; Panasiewicz et al. 2020). This load saving can sometimes counterbalance the yield loss and allow a higher gross margin than that obtained under conventional tillage. This is the case in England for a wheat crop where the gross margin is 6% higher than that obtained with tillage (Calcante and Oberti 2019).

Conversely, an increase in production cost of 20% under SCT and 22% to 28% under NTT, can occur if ploughing is replaced by an increase in pesticide use (Chetan et al. 2016; Panasiewicz et al. 2020).

Additional costs may also be incurred if fertilizer use increases by 10-20% in SCT and NTT (Lognoul 2020; Broué 2016).

This can lead to a decrease in gross margin. Gross margin decreases of 16% in SCT and 34% in NTT associated with high pesticide use compared to a ploughed control illustrate this case (Panasiewicz et al. 2020).

Effects on climate change mitigation

Tilling with NTT increases N_2O emissions on average by 68% compared to conventional tillage, according to a meta-analysis of 251 long-term studies in Europe (Sandén et al. 2018). These emissions would be higher in the first ten years and then decrease. A reduction in N_2O emissions is observed on average for a SCT tillage compared to a conventional ploughing. But the difference is not significant (Sandén et al. 2018).

As for N_2O, a non-significant reduction in CO_2 fluxes from the soil is observed on average for a SCT tillage compared to a conventional ploughing (Sandén et al. 2018).

Fuel consumption is the main factor influencing direct energy consumption and thus eCO_2 emissions during tillage. TEBRÜGGE and BÖHRNSEN(2001) estimate from an analysis on different soil types that a saving of 40L/ha of fuel would allow a reduction of 41 kg of eCO_2 per hectare each year (Guyomard et al. 2013). Considering the data described in the cost of production section, TNL would reduce CO_2 emissions by up to 82 kg eCO_2 compared to conventional tillage.

The SOC stock is equal regardless of tillage for the entire soil profile (0-150 cm). But as shown in

Table 21effect of tillage operations on SOC varies with the depth studied. On a horizon of 0-15 cm depth, NTT and SCT increase the concentration and storage of SOC compared to ploughing and turning. This trend is reversed for SCT and ploughing with turning for a horizon of 15 to 30 cm depth. In NTT, over a period longer than 10 years, the SOC stock of the 0-30 cm horizon increases by an average of 4.6 mg/ha compared to ploughing with turning, or by 5% according to Sandén et al.(2018) and by 3.85 mg/ha compared to tillage in SCT (Haddaway et al. 2017). No other comparisons were significant according to this meta-analysis of 351 studies in temperate climates.

Table 21 - Comparison of the effect of no depth limit and turning ploughing, SCT and NTT on soil SOC concentration (Haddaway et al. 2017).

Item assessed	Comparative operations	Result obtained	Depth assessed
SOC concentration	NTT versus SCT	+1.18 g/kg	0-15 cm
SOC concentration	NTT compared to plowing	2.09 g/kg	0-15 cm
SOC concentration	SCT compared to plowing	1,30 g/kg	0-15 cm
SOC concentration	IT compared to HT	- 0,89 g/kg	15-30 cm

Other effects on soil, water, air and biodiversity

The more tillage operations are minimized, the more the macro- and micro-fauna making up the soil's biodiversity are preserved. Biological activity in the first few centimeters of the soil is favored by no-till.

Both tillage and no-till are described as improving soil structure and reducing the risk of erosion and runoff. Tillage decompacts soils compacted by previous crops in the short term, allowing them to breathe. This results in improved rooting and water infiltration and a reduced risk of pesticide transfer to groundwater. No-till systems improve erosion risk in the short term and bearing capacity and infiltration in the medium to long term (GUILLEMAN et al. 2003; Guyomard et al. 2013).

The residue kept on the surface by no-till minimizes the impact of drips, limits evaporation and maintains soil moisture. Retained moisture is an asset in dry areas because it reduces irrigation. In wet regions, it can lead to increased disease proliferation (Guyomard et al. 2013).

2. Remarks

The choice of a type of tillage and its effects depend strongly on the nature and physical condition of the soil (texture, moisture, permeability and degree of compaction). For example, the risks of soil fragmentation, exposure to rain, erosion, and compaction may increase on sensitive, stony or steeply sloping soils. Conversely, SCTs and NTTs may reduce porosity and increase compaction, compaction, and rutting in soil that is sensitive to compaction. The nature and quantity of materials to be buried (soil amendments, residues from the previous crop, weeds), the risks associated with the climate (drought, driving rain, probability of frost), the requirements of the crop to be planted (seed size, root sensitivity to soil structure), as well as the phytosanitary risks related to the presence of slash or pathogens linked to the soil or residues of the previous crop must be taken into account in the choice of operations adapted to the context of the plot (GUILLEMAN et al. 2003; Guyomard et al. 2013).

It is possible to reduce the frequency of ploughing by ploughing before a crop that is demanding in terms of soil structure, or after a crop that presents a high risk of creating ruts or settling rather than systematically ploughing. This would allow to benefit from its advantages in terms of soil aeration and weed seed burial. Production costs related to fuel consumption and mechanization would be reduced, as would CO_2 emissions and workload. The use of pesticides and fertilizers would be reduced compared to systematic NTT and SCT, as would the risks of compaction and the formation of capping (Guyomard et al. 2013).

A link can be made between the advent of NTT and SCT and the development of total herbicides replacing the action of tillage on weed management. The development of these practices on a large scale on the American continent has been reinforced by the development of GMO (Genetically Modified Organisms) plants resistant to herbicides. Problems of pesticide resistance related to the use of these plants are raised (Guyomard et al. 2013).

3. Conclusion

The management of pests, particularly weeds and fertilization is an issue when tillage is reduced. A potential increase in the use of pesticides and fertilizers may occur to cope with these pressures. SCT and NTT improve the water retention capacity of soils compared to tillage.

Although labor, mechanization and fuel costs are reduced in NTT and SCT compared to conventional tillage, increased fertilizer and pesticide use can reverse the trend and increase the cost of production. This combined with a potential yield reduction, reduced tillage does not always result in a higher gross margin than tillage systems.

NTT reduces CO_2 and increases N_2O emissions, as well as SOC in the top 30 cm of soil. However, the concentration of SOC in the total soil profile remains the same regardless of tillage.

SCTs and NTTs are beneficial for biodiversity. Negative and positive impacts can occur on soil structure, regardless of the type of work carried out. The choice of operations should be based on the soil and climate conditions of the plot, the rotation and the pressure of bio-aggressors.

II. Efficiency of input use

A. Agricultural equipment

1. Phytosanitary treatments

a. Results obtained

Effects of agricultural equipment on drift, pesticide consumption and production costs

Choice of sprayers

The purchase of a sprayer costs between €20,000 and €300,000 depending on the type of sprayer (trailed, self-propelled or mounted), the volume of the tank, the width of the boom, the material, the weight, the number of sections and the various options (GPS section cut-off, automatic boom height, *etc.*) (Cultivar 2021). Some of them are equipped with equipment to reduce the risk of drift and limit pesticide consumption.

Sub-foliar sprayers can reduce the amount of pesticides used by up to 80%. Anti-drift sprayers can reduce drift by up to 50% compared to conventional sprayers. These solutions are described as simple to use, easy to maintain and economical. However, it is difficult to find quantified data attesting to this (OFAG 2019).

If the renewal of a new sprayer is not financially feasible, it is possible to modernize the equipment by changing certain components, known as retrofits, if they are compatible with the rest of the equipment. As an example, investing in a retrofit section cutter costs between 5 000 and 10 000 € depending on the options chosen and the need to replace the electronics. The addition of a flow meter at the filling stage or an electronic gauge to control the quantities of spray liquid prepared costs between 650 and 750€. Changing from a FPM (Flow Proportional to Motor) regulation to a FPAEC (Flow Proportional to Advance with Electronic Control) regulation costs between 1 500 and 2 500 €. According to the feedback from farmers, such a replacement improves their working comfort and allows to reduce by up to half the quantities of spray applied (quantities of fungicides and pesticides reduced from 150 to 60-70L/ha) (David Laisney 2020).

Sprayers with air-assisted booms place the product droplets on their target. According to the manufacturers, these sprayers can reduce the risk of drift by more than 66%. Paired with anti-drift nozzles, these booms can reduce drift by 75 to 100%. A reduction of 17 to 30% of active ingredient occurs in bare soil or low plant conditions. They estimate greater reductions on dense plants due to better spray penetration and coverage. These booms increase the price of sprayers by 30% compared to conventional sprayers. Depending on the models and manufacturers, they have an additional cost that varies between 9,000 and 30,000€ (Perriot and Gaudillat 2013; Lecocq 2016; 2019).

Choice of nozzles

Nozzles are particularly important parts of the spraying process. Depending on the type of nozzle, they influence the droplet size and the application rate of the product on the target crop in different ways. The larger the droplet size, the lower the risk of drift, but the less homogeneous and therefore less effective the spraying ("How to reduce drift with your nozzles?" n.d.). The type of product, its density, the desired speed and yield, the desired droplet size, the target crop and the weather conditions are all factors that come into play when choosing the type of nozzle ("How to reduce drift with your nozzles?" n.d.). The challenge is to adjust the droplet size as much as possible, taking these parameters into account, without affecting the quality of the spraying (Lecocq 2016).

Table 22shows the effectiveness of the main nozzle types on drift reduction and crop protection product consumption. Air injection nozzles are considered the most accessible and versatile means to reduce drift. However, they can lead to an increase in the volume of product sprayed. Conventional low-pressure nozzles, mirror nozzles and calibration pellets provide, on average, a reduction in pesticide consumption (Jaunard 2020; Perriot and Gaudillat 2013). Nozzles cost less than one percent of the cost of a sprayer ("How to Reduce Drift with Your Nozzles?" n.d.).

Table 22 - Effectiveness of the main types of nozzles in reducing drift and consumption of plant protection products (Jaunard 2020; Perriot and Gaudillat 2013) (Jaunard 2020; Perriot and Gaudillat 2013)

Nozzle model	Percentage of drift reduction (Jaunard 2020)	Average volume consumed (l/ha)	Comparison of the average volume consumed compared to a conventional slot nozzle
Classic slot	0% 50% for calibres 05 and 06	114	
Classic low pressure slot		89	-22%
Calibration disc	50%	111	-3%
Conventional air injection	50 à 90%	132	+16%
Low pressure injection	50 à 90%	121	+6%
Classic mirror	50 à 75%	104	-9%
Air injection mirror	50 à 100%		

Settings

Droplet size can also vary depending on the liquid pressure and the volume applied per hectare. It is also possible to play on the pressure of the projected air when the sprayer is equipped with air-assisted booms (Lecocq 2016).

Adjusting the height and speed of travel is another factor in limiting the risk of drift.

Effects on working time

This equipment is primarily intended to reduce the risk of drift and, for some, to reduce the quantities of pesticides applied. They do not influence working time but improve working conditions and reduce the difficulty of these tasks.

Effects on climate change mitigation

This equipment has no effect on direct CO_2 emissions or on carbon sequestration. A reduction in indirect CO_2 emissions can occur when the volumes of product consumed are reduced. This can be achieved through the use of sub-foliar sprayers, switching from FPM to FPAEC control, air assist pumps or low pressure nozzles.

Effects on soil, air, water and biodiversity

Less drift and a reduction in the volume of product sprayed are to the advantage of water and air.

b. Conclusion

Among the variety of sprayers available, sub-foliar sprayers and drift control sprayers reduce the risk of drift and in some cases reduce the amount of pesticide applied. It is possible to upgrade some components of the equipment, when investment in a new sprayer is not an option. Nozzles also influence the quality of the spray and the risk of drift. Low pressure nozzles reduce the amount of sprayed material. Anti-drift nozzles are the most versatile and accessible way to reduce the risk of drift. Their choice depends on many factors. Other ways to reduce the risk of drift and the volume of sprayed product are to adjust the height and pressure of the equipment and the speed of operation. This equipment and adjustments limit the impact of spraying on air and water quality. If the quantities of pesticides are reduced, they limit indirect CO_2 emissions. They also ensure a gain in comfort for farmers.

2. Irrigation

a. Modernization of irrigation systems

Today, 80% of irrigation is done by surface irrigation with pressurized systems, which consume a lot of water. The main irrigation systems in Europe are: full coverage irrigation, hose-reel irrigation, pivotal or central booms ("Which Irrigation System to Choose?" 2017).

The use of micro-irrigation systems, which are used in vineyards, orchards and horticulture, have been studied over the last decade in field crops. These systems are suitable for wide-spaced crops such as corn, sugar beets or potatoes. Drip systems distribute water at the base of the crop in above-ground systems or at the root level in systems where the tubes are buried 30 cm deep. The buried systems are suitable for plots cultivated in SCT or direct seeding. Fertigation or fertirrigation ensures better uptake of fertilizers by crops by diluting soluble liquid fertilizers in these systems ("Which Irrigation System to Choose?" 2017; Soto et al. 2019).

i. Results obtained

Effects on water use

Table 23summarizes the estimated water savings from a change in equipment according to (Serra-Wittling and Molle 2017). These savings are mainly achieved through a reduction in the risk of drift. It is much lower for low-pressure pivots (about 2%) than for hose-reel or full coverage (10% on average).

Drip systems provide the greatest water savings. Water savings of 10 to 40% on average are obtained compared to other irrigation systems. Irrigation efficiency, the ratio between the amount of water made available to the crop roots and the amount applied by the irrigation equipment can reach 98% ("Irrigation systems" n.d.; Carpentier 2014; Le Gonidec 2020; Serra-Wittling and Molle 2017).

Renewing the same equipment also saves money because wear and tear results in the equivalent of one to four percent loss in irrigation water use efficiency each year (Serra-Wittling and Molle 2017). The water savings from renewing a reel or full coverage system is estimated at 10%. 15-20% of water can be saved when renewing a precision irrigation system (micro-jet or drip) (Serra-Wittling and Molle 2017).

Table 23 - Potential water savings from a change in irrigation equipment, table from (Serra-Wittling and Molle 2017) Serra-Wittling and Molle 2017)

Water saving (%)	New				
Old	Hose-reel	Full coverage	Low pressure pivot	Surface drip	Underground drip
Hose-reel	10	10	5-20	10-20	15-35
Full cover	--	10	5-20	15-25	20-25
Pivot / Boom	--	--	5-10	5-15	10-25
Surface drip	--	--	--	10-20	15-20
Underground drip	--	--	--	--	10-20

Another alternative to improve irrigation water use efficiency is to reduce the height of the nozzles to limit the waste of the sprayed water, as shown in Table 24. Mid elevation spray application (MESA) systems deliver water at a height of about 150 cm. Low Elevation-Energy Precision Application (LEPA), and Low Elevation-Energy Spay Application (LESA) deliver water within 60 cm of the ground, i.e., below the canopy (Soto et al. 2019). Such a system allows a 20% water saving according to a study on 46 ha in Hungary (SERRA-WITTLING et al. 2020).

Table 24 - Efficiency of irrigation systems by nozzle height (Soto et al. 2019)

Systems	**Standard**	**MESA**	**LEPA - LESA**
Irrigation efficiency	60 %	85%	97%

These water savings depend on many factors such as the water available in the soil for the plants (useful reserve), the type of year (dry, wet...), the crop, the soil-climatic conditions *etc (*Serra-Wittling and Molle 2017).

Effects on yields

Yields obtained from the use of pivots or booms are generally not significantly different from yields obtained from full-cover or hose-reel irrigation (Serra-Wittling and Molle 2017). The effect of irrigation type on yield is difficult to isolate, except through notions of water use efficiency.

Theoretically, drip irrigation could maintain or increase yields. While yields have been maintained or increased by up to 3.5% for some maize growers, yield losses have also been observed in potato, wheat and maize crops. Losses of up to 15% have been observed in maize crops, caused by underestimating irrigation during the flowering period or by too wide a spacing of drippers (Le Gonidec 2020; Chambre d'agriculture des Landes 2017).

Effects on working time

Pivot systems save up to 95% labor time compared to other systems, as shown in Table 25. Hose-reel systems require 3 h/ha/year less than full cover systems (Serra-Wittling and Molle 2017). Additional time savings can occur if irrigation systems can be activated remotely or automatically ("Which Irrigation System to Choose?" 2017).

Disposable and recoverable surface drip irrigation systems (SDIS) are among the most time consuming irrigation systems. The underground drip system (UDG) is the most time-saving system after the pivot systems. It reduces irrigation management time by 55-75% compared to reels, full coverage and SDIS (Serra-Wittling and Molle 2017).

Table 25 - Total labor time for a campaign with different irrigation systems in field crops (UDG: underground drip system, SDIS: surface drip irrigation systems). Based on Pagliarino (2012) and Arvalis (2017), table from (Serra-Wittling and Molle 2017)

Time requirement	UGD	Recoverable SDIS	Disposable SDIS	Hose-reel	Pivot	Full coverage
(h/ha/year)	3	12	9,5	6,6	0,2	9,5
Comparison with hose-reel (%)	-55%	+82%	+44%	---	- 97% ??	+44%
Comparison with full coverage (%)	-68%	-26%	0%	-31%	-98%	---
Comparison with recoverable SDIS (%)	-75%	---	-21%	-45%	-98%	-21%
Comparison with disposable SDIS (%)	-68%	-26%	---	-31%	-98%	0%

Effects on the cost of production

Pivots or irrigation booms require a higher investment than a full cover or hose-reel irrigation system. As an example, the installation of irrigation ramps cost 72 141€ during an experiment on 46 ha in Hungary. Some suppliers indicate costs around 35 000€ ("Top Sale Center Pivot Irrigation System In Europe" n.d.). These investments are to be put into perspective as the life span of these systems can reach 20 years (Serra-Wittling and Molle 2017).

Due to their low pressure, pivots or irrigation booms allow water and energy savings, thus reducing the cost of production (Serra-Wittling and Molle 2017).

The investment related to the installation of a surface micro-irrigation costs between 1 200 and 1 500 €/ha for a surface system. In addition, there are between 205 and 400 €/ha/year for the renewal of the pipes. Underground irrigation costs between 2,500 and 4,500 €/ha (Deumier et al. 2014). According to Arvalis estimates (Deumier et al. 2014) presented in

Table 26, UGD irrigation would be more profitable than SDIS. However, these solutions are still

Type of equipment	Underground drip with flat drip lines	Surface recoverable cylindrical drip lines	Surface recoverable flat drip lines	Surface irrigation	Hose-reel	Pivot
Investment new value (in €)	118 900	115 590	54 870	45 900	40 590	46 650
Investment new value (in €/ha)	3 963	3 853	1 829	1 829	1 353	1 555
Fixed costs[1] (€/ha/year)	659	692	571	767	167	220
Operating costs (€/ha/year)	37	37	37	37	61	74
Labour costs[2] (€/ha/year)	14	147	189	133	92	5
Total costs, material under depreciation (€/ha/year)	710	866	830	937	320	299

two to three times higher than hose-reels or pivots.

The return on investment for a surface system is between 700 and 3,000 €/ha depending on the distance between the irrigated land and the water source. It takes two to three years. Underground irrigation systems have an average return on investment of 7 years. Both types of system have an estimated lifespan of 20 years (Le Gonidec 2020; "Systèmes d'irrigation" n.d.; Carpentier 2014).

Type of equipment	Underground drip with flat drip lines	Surface recoverable cylindrical drip lines	Surface recoverable flat drip lines	Surface irrigation	Hose-reel	Pivot
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Total costs, material under depreciation (€/ha/year)	710	866	830	937	320	299

Table 26 - Investments and expenses of different irrigation systems. Drip irrigation systems, table from (Deumier et al. 2014) (Deumier et al. 2014)

Effects on climate change mitigation

As shown in Table 27, boom and pivot irrigation systems are more energy efficient than hose-reels. Low-pressure sprinkler systems on a swivel provide energy savings of 15 to 90% (Serra-Wittling and Molle 2020). LESA system sprinkler drop canes also increase energy efficiency up to about 80% (Soto et al. 2019).

Energy savings ranging from 43-80%, 40-60% and 10-50% were respectively observed when using drip irrigation compared to the use of reel cannons, full coverage systems and pivot and boom systems (Serra-Wittling and Molle 2020).

There is little difference in energy efficiency when the same equipment is renewed. But it is possible to gain percentages of energy efficiency by adjusting certain parts. For example, it is possible to gain 18 to 36% in energy efficiency by adjusting the size of the nozzle on the reel. Similarly, a 22 to 37% gain in energy efficiency can be achieved by adjusting the tube diameter (Serra-Wittling and Molle 2020).

Table 27 - Order of magnitude of achievable energy savings in field crops (Serra-Wittling and Molle 2020)

Energy saving	Full coverage	Pivot and ramp	Drip irrigation
Compared to a reel	32%	40% (from 29 to 50%)	70% (from 43 to 80%)
Compared to full coverage			50% (from 40 to 60%)
Compared to pivots or ramps			30% (from 10 to 50%)

ii. Remarks

Investing in more modern water-saving equipment does not always lead to a reduction in water consumption. It is the choice of irrigation management that primarily influences water consumption. There are many examples of this in Europe and around the world. There is a so-called "rebound effect" when switching from gravity to drip irrigation or when upgrading from a traditional pivot system to a more efficient one (Serra-Wittling and Molle 2020). This is why the report (Serra-Wittling and Molle 2020) emphasizes the importance of irrigation management, especially with the support of DSTs (Decision support tools), to improve water use efficiency.

Drip irrigation reduces weed growth between the rows. Pipe damage by pests, such as voles for underground systems or sesamia or moths for above ground systems, can occur. Even if filter systems are installed in subsurface irrigation, there is always a risk of clogging the pipes.

iii. Conclusion

In Europe, most irrigation is carried out by sprinkler systems that operate under pressure and are therefore very water intensive. Among sprinkler irrigation systems, pivots and booms provide the best water use efficiency. They reduce water and energy consumption while maintaining yield. They are the least time consuming systems. They are more expensive than hose-reel or full coverage irrigation systems.

Drip systems have been used for a decade in wide-spaced crops such as corn and sugar beets. It is the most efficient irrigation in terms of both water use and energy consumption. Dripper spacing and water volumes to be applied must be precisely defined otherwise yields may be impacted. UGD is much less time consuming to manage than SDIS, but is much more expensive to implement. These systems are two to three times more expensive than front booms and pivots or hose-reels.

False rebound effects on water use can occur following the installation of a new system or retrofit of the existing irrigation system if the irrigation line is not adequate. Drip irrigation systems are susceptible to degradation and clogging.

b. Other

i. Pumping and transporting water

Upgrading the infrastructure related to the transport of water from the source to the plot linked with an irrigation system could save 10 to 35% of water in the Mediterranean rim according to (Fader et al. 2016). Up to 45% energy savings can be achieved by increasing the flow rate and reducing the pressure at the pump (Serra-Wittling and Molle 2017).

Installing dimmers can reduce its energy consumption by up to 30% and its water consumption by up to 7% (Serra-Wittling and Molle 2017).

ii. Choice of nozzles

The choice of nozzle type also influences efficiency. For example, the larger a drop of irrigation water is, the less risk of loss to wind. Changing nozzles to more appropriate models would save 5% water for a boom or pivot (Serra-Wittling and Molle 2017).

Nozzle speed controllers could save 15% of water according to (Serra-Wittling, Molle, and Cheviron 2019).

iii. Other equipment

According to IRSTEA, a water saving achievable with jet breakers and adjustable angles on the guns can be expected to be 5-10% (Serra-Wittling and Molle 2017).

3. Machine guidance and controlled traffic system

Machine guidance of tractors in field crops reduces the risk of overlapping or interrupted spraying due to path deviation during application. Combined with data from previous years' trips and treatments, Controlled Traffic Farming (CTF) systems tend to reduce soil compaction and degradation (Balafoutis et al. 2017). These tools work on the basis of information given by DSTs (Decision Support Tools).

a. Results obtained

Effects on input use

According to a survey of 971 European farmers, nitrogen fertilizer use can be reduced by an average of 3% when using machine guidance. However, as shown in Figure 7, more than half of the farmers surveyed did not note any effect on nitrogen fertilizer consumption when using this technology (Soto et al. 2019).

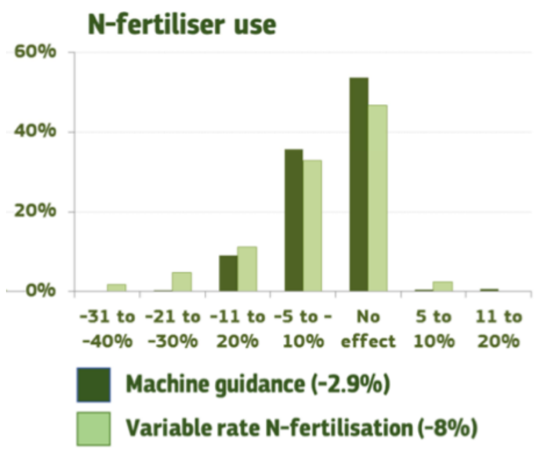

Figure 7 - Impacts perceived by farmers when using machine guidance (Machine guidance) and precision spraying (Variable rate N-fertilization) on nitrogen fertilizer use. Average impacts are shown in brackets, figure taken from (Soto et al. 2019) (Soto et al. 2019)

Additional reductions of 3-5% of pesticides and up to 15% of fertilizers are possible with the use of CTF systems (Soto et al. 2019).

Effects on yields

Machine guidance has, on average, no effect on yield, as shown in the results of a farmer survey in Figure 8.

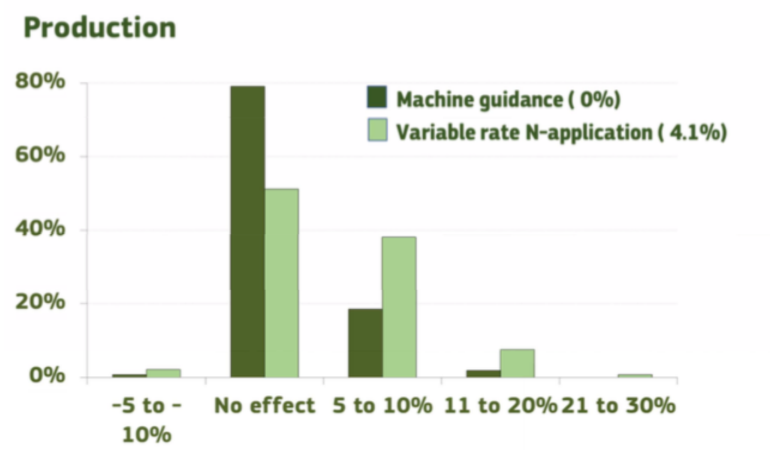

Figure 8 - Impacts perceived by farmers when using machine guidance (Machine guidance) and precision spraying (Variable rate N-fertilization) on yield. Average impacts are shown in brackets, figure taken from (Soto et al. 2019) (Soto et al. 2019)

CTF systems allow yield increases of 4% and 7.5% for wheat and oilseed rape crops. These increases can be as high as 15% (Soto et al. 2019).

Effects on working time

The use of machine guidance leads to a much greater reduction in working time (6.2%) than for the adjustment of input quantities by precision farming (1.6%). Combined with low training time (additional 1.3%) and low system management (additional 0.27%), machine guidance results in a time saving of 4.5% (Soto et al. 2019). In addition to this time saving, machine guidance improves the working conditions of farmers.

Effects on the cost of production

A saving of 2.1% in labor can be achieved through the time saved by machine guidance. Fuel consumption is reduced by an average of 5.4% and can be reduced by up to 10.4%. Together with a slight reduction in the amount of fertilizer, machine guidance reduces input costs. Few additional contractual costs (0.3%) are associated with machine guidance, as the majority of farm machinery on the market today has this option. All the advantages on the production cost do not always compensate for the investment linked to this technology. The use of machine guidance has an effect on the gross margin of between -18€/ha and +34€/ha. Between 40 and 47% of farmers perceive a return on investment in less than 5 years. Among the rest, 25% estimate that the return on investment takes place over periods longer than 11 years (Soto et al. 2019).

CTF systems allow a reduction of 25 to 35% of fuel in cereal crops. A saving of about 70% in time and energy takes place. These systems are increasingly being integrated into new agricultural machinery. They allow up to 14% return on investment and 8% profit in Europe. An increase in gross margin between 57 and 115€/ha can be seen (Soto et al. 2019).

Effects on climate change mitigation

Fuel consumption reductions enabled by machine guidance and CTF systems generate a reduction in direct CO_2. Similarly, reductions in fertilizer use decrease indirect CO_2 and N_2O emissions (Soto et al. 2019). According to a study modelling the effect of machine guidance on GHG emissions at the European scale, these technologies can reduce between 1,513 and 2,760 kT eCO_2/year, which corresponds to 0.3% of the total GHG emissions of the agricultural sector in 2015 (Soto et al. 2019).

Other effects on soil, water, air and biodiversity

These technologies allow for less compaction of the soil, which results in an increase in its porosity and therefore its permeability. The soil's potential to retain, stabilize and degrade pesticides is enhanced, thus improving the quality of water that seeps to groundwater. This ensures the maintenance of natural habitat areas for wildlife (Balafoutis et al. 2017).

b. Conclusion

Machine guidance and CTF systems reduce fertilizer and fuel consumption and lighten the workload. This results in lower N_2O emissions as well as direct and indirect CO_2. Machine guidance has a mixed effect on gross margin. The return on investment mentioned by farmers is over a very long period. CTF systems allow for a potential increase in yield, which ensures an increase in gross margin and a faster return on investment. Both technologies improve soil condition, water quality and promote natural habitats.

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 variable rate tools (or modulation) or automatic robots. Variable rate tools correspond to the methods of applying variable doses of inputs and machine guidance of tractors. They adjust the doses and their location according to the needs of the crops (Farm Europe 2019).

As shown in Figure 9, digital tools related to crop production can be classified into 5 levels according to their degree of accuracy, the equipment required and their cost. DSTs processing information from sensors, weather stations, satellite images and cameras are present at each level. They are detailed on page 69. From the third level, in field crops, these tools are associated with variable rate tools. They are discussed on page 74. Levels 4 and 5 add to the tools of the previous levels robotization as an alternative to pesticides for the management of bio-aggressors (Farm Europe 2019). Chemical weed control robots are discussed starting on page 83 and mechanical weed control robots are discussed starting on page 91.

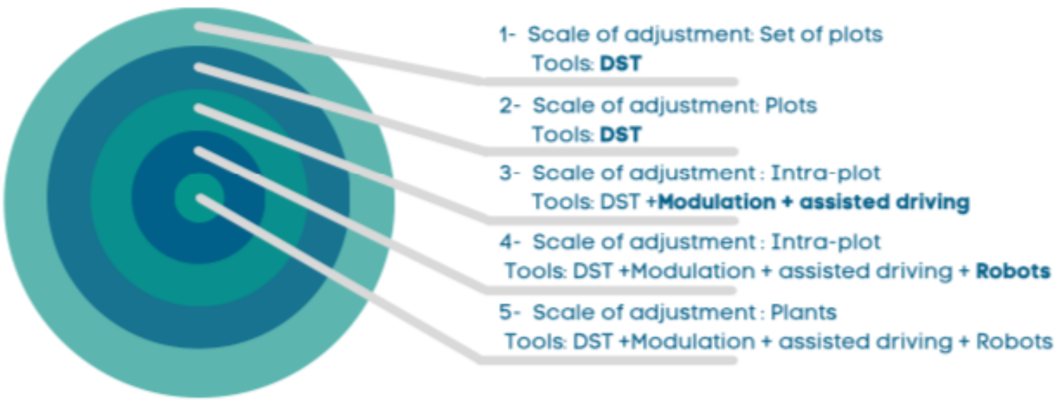

Figure 9 - The five levels of digital agriculture

1. Decision support tools

DSTs 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 material and setting);
- Complementary practices (choice of variety, rotation, preventive methods, etc.).

This section focuses on the DSTs that help reason out the use of inputs (pesticides, fertilizers and water). The results presented in this section correspond to the input prescriptions made by the DSTs and the yields obtained following the recommendations.

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

a. Results obtained

Effects on input use

Pesticides

As shown in Table 28, pesticide use expenses are reduced by an average of 8.5-32.5% using DST suggestions. This results in savings of up to €10/ha on average in Europe (Farm Europe 2019).

Table 28 - Average savings in pesticide-related costs due to ADO prescriptions (Farm Europe 2019)

Culture	Average savings in costs related to pest management due to DST suggestions	
	(%)	€/ha
Beet	8,49	4,44
Soft wheat	16,67	7,01
Durum wheat	26	10,92
Cotton	32	97,27
Barley	32,5	1,44
Potatoes	6,47	35,52

Fertilizers

In field crops, depending on the crop, DSTs can save between 7.65 and 65% of inputs on average compared to not using them, as shown in Table 29. Fertilization costs can be reduced by between 5.88 and 19.58% on average, which translates into savings of up to 152.63€/ha. It can happen that the cost of the DST is higher than the cost of the saved inputs, which leads to an increase in labor costs, as shown in the case of wheat.

Table 29 - Average savings in fertilization costs due to DST prescriptions in Europe (Farm Europe 2019)

Culture	Average amount of nutrients saved		Average savings in fertilization management costs	
	(%)	€/ha	(%)	€/ha
Wheat	7,65	9	5,88	- 2,13
Rapeseed	16	34,08	8,38	18,26
Cotton	41,32	92,42	7,19	152,97
Barley	No significant differences			
Potatoes	65 (78 kg N/ha, 162.71 kg P and 188.65 kg K/ha)		19,58	152,63

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 80. The irrigation suggestions of the DST are compared to irrigated systems without DST.

While some studies comparing precision irrigation to irrigation without DSTs show water savings, the implementation of precision irrigation can lead to an increase in water consumption to meet crop water requirements, depending on climate and weather conditions. The effect of precision irrigation on water consumption is the most widely disseminated information. The efficiency of irrigation use is a more relevant indicator than the water consumption.

Precision irrigation has the greatest potential around the Mediterranean. Water and energy consumption is reduced by 10 to 14% on average (FIGARO Irrigation Platform 2016). DST prescriptions save up to 32.5% of irrigated water in potato cultivation, or 1220 m^3 /ha on average. This leads to a 27.5% reduction in irrigation costs, i.e. 107.50€/ha. A saving of 43% of water is also observed for cotton crops, which represents an average of 930 m/ha and nearly 700€/ha less expenses. A saving of 40€/ha can take place in maize crops[3] (Farm Europe 2019). According to (Serra-Wittling and Molle 2017), the use of sensors and tensiometric probes allows savings of an average of 20 to 25% ranging from 8 to 41%. Tensiometric control resulted in water savings of 16-41% for potato crops. The use of a dendrometer ensures up to 30% additional water savings compared to a tensiometer alone. A map of the useful reserve of a soil allows to appreciate the heterogeneity of the useful reserve of the plot. It ensures reductions in water consumption of up to 66%, or 200 m/ha, without any loss of yield [3](Serra-Wittling and Molle 2017). These authors also claim that the overall efficiency of a pivot could increase by 10 to 25% by optimizing the steering.

An average water saving of 18% is found for cotton crops under micro-irrigation (Stamatiadis 2013). In Greece, irrigation can be reduced by 5 to 34%, but impacts yield in a highly variable way, as described in the section on variable rate irrigation on page 80. As a result, irrigation efficiency varies from -12% to 97% (Soto et al. 2019).

Effects on yields

DST suggestions can induce an increase in yield ranging on average from 0.2 to 4.7 q/ha, which can induce an increase in gross product ranging from 3 to 68€/ha, as shown in Table 30. Nevertheless, (Soto et al. 2019) highlights the variable effect of precision irrigation on yield, ranging from - 18 to + 31%. According to the different field returns described by Serra-Wittling and Molle(2017) irrigation control has no significant effect on yields.

Table 30 - Effects of DMOs on yields and gross products on average (Farm Europe 2019)

Culture		Average yields obtained from DST prescriptions.	
	Input concerned by the requirements	Average additional yield obtained following the DST prescriptions (q/ha).	Average additional gross product obtained as a result of DST prescriptions €/ha.
Beet	Pesticides	2	15
Soft wheat	Pesticides	4,7	65,8
Durum wheat	Pesticides	0,2	3
Barley	Pesticides	1,3	19,5
Wheat	Fertilizers	3,93	41,23
Barley	Fertilizers	3,5	52,50
Rapeseed	Fertilizers	1,43	58,90

A 10% increase in yield is seen in cotton crops under fertigation (Skakelja and McGlynn 2018).

Effects on working time

Producers of DSTs claim the simplicity of the interfaces and the time savings they bring through reduced fertilizer and pesticide applications (Sawyer, Oligschlaeger, and Nikolay Khabarov 2021). However, the time required to learn how to use them and to get used to them may deter farmers from using them (Zhai et al. 2020).

Effects on the cost of production

Some DSTs are free. Those that prescribe quantities of inputs to be applied from sensors and satellite images of crops have a maximum cost of €20/ha/year (Farm Europe 2019). As shown in Table 29Table 30, they are generally paid back by reducing the amount of inputs consumed or by increasing yield. The gross margin is generally higher than without the use of DSTs when gross revenues are added to the cost savings from input management, including the cost of DSTs. Average gross revenues are shown in Table 30examples. An increase in gross margin of between 12 and 45€/ha was observed for barley and wheat crops when using DSTs adjusting fertilizer and pesticide doses (Farm Europe 2019). Up to 310€/ha/year of benefits were obtained when fertigation was applied at prescribed fertilizer rates per area based on a nitrogen requirement map for cotton crops (Skakelja and McGlynn 2018).

DSTs are dependent on climate and weather data. Depending on the type of DST used, farmers may have to set up weather stations. Weather stations require an investment of between €400 and €2000 (Weenat, 2020, personal communication). These stations can be managed and benefited by organizations following the farmers, by an isolated farmer or by a group of farmers geographically close enough.

Effects on climate change mitigation

It is recognized that the use of input requirement maps allows for more efficient management of inputs, resulting in lower GHG emissions from 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 could reduce these emissions if it induces a reduction in water use (Soto et al. 2019).

Other effects on soil, water, air and biodiversity

Few studies analyze the effect of DSTs on environmental dimensions. It can be hypothesized that a reduction in the amount of pesticides applied is beneficial to biodiversity. A reduction in the amount of pesticides and/or fertilizers should also improve air, soil and water quality through less leaching and less presence of toxic molecules.

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 15% of field crop farms in France (Sawyer, Oligschlaeger, and Nikolay Khabarov 2021). The multiplication of similar services and competition will bring prices down in the coming years, leading to their democratization.

c. Conclusion

Many DSTs recommend pesticide and fertilizer application rates 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, as well as sanitary pressure.

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 yield. 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

Precision sprayers adapt the opening and closing of their nozzles based on a mapping of needs or on data from on-board cameras. The most precise ones can adjust the quantities of inputs sprayed according to the needs of the crop. They have a higher cost than standard sprayers (Zarco-Tejada, Hubbard, and Loudjani 2014). These techniques are becoming more widespread. Today, 70 to 80% of agricultural equipment on the market has components related to precision agriculture.

a. Results obtained

i. Variable rate pesticide application

Herbicides are the pesticides for which the effectiveness of precision agriculture has been mostly tested. This information is for liquid products only, not for powdered products.

Effect on pesticide use

Precision sprayers can reduce herbicide quantities by 54% on average. A reduction of 88% of herbicides has been observed thanks to the control of a localized treatment (Arvalis, ITB, and Terres inovia 2021). Reductions between 11% and 90%, compared to a conventional application, were observed on different crops such as winter cereals, maize, beet and cotton. Nevertheless, large variations between crops and years were found (Balafoutis et al. 2017). A 148% increase in herbicide use efficiency occurred in cotton crops due to reduced pesticide use and increased yield (Stamatiadis 2013).

These sprayers reduce the amount of insecticides on wheat crops by up to 13.4% (Soto et al. 2019).

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).

A 10% increase in yields was achieved for the cotton crop where pesticide management was complemented by precision fertigation (Stamatiadis 2013).

Effects on working time

Adjusting the amount of pesticide to be applied can save time in preparing the spray dose and 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).

This increase in labor time is of the same order of magnitude as that perceived during Variable Rate Fertilization detailed on page 77, i.e. 2.8%. Indeed, precision spraying technologies are identical for pesticides and for liquid fertilizers (Balafoutis et al. 2017).

Effect on the cost of production

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

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

In field crops, the herbicide savings detailed in the pesticide reduction section, page 75, reduce production costs. Savings ranging from €7 to €79/ha were obtained, as shown in Table 31. In addition to these savings, there are labor and fuel costs associated with these technologies. These are of the same order of magnitude as those associated with Variable Rate Fertilization which are detailed in Table 32, page 78.

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 more expensive 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 (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).

Table 31 - Summary of pesticide savings from precision spraying observed in the review by Balafoutis et al. (2017).

Culture	Pesticide savings (€/ha)
Corn	7 à 42
Beets	20 à 79
Winter cereals	27 à 36

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 (Balafoutis et al. 2017).

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

According to a survey of 971 European farmers, N fertilizer use can be reduced by an average of 8% when using intra-plot rate adjusting sprayers. Yet, as shown in Figure 10, almost half of the farmers surveyed did not note any effect on N fertilizer consumption when using this technology (Soto et al. 2019).

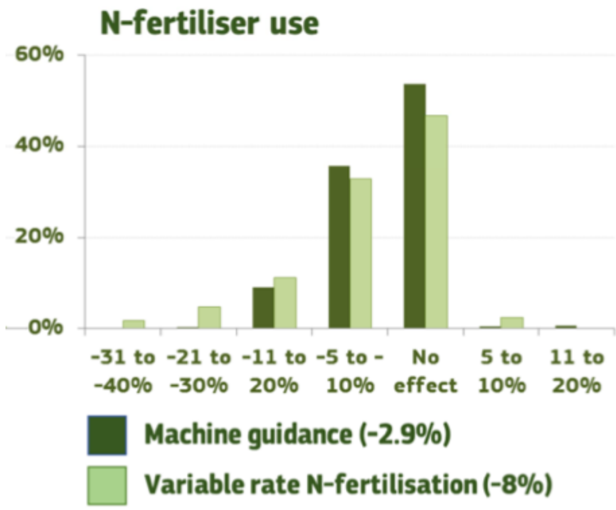

Figure 10 - Impacts perceived by farmers when using Machine guidance and Variable rate N-fertilization on N fertilizer use. Average impacts are shown in brackets, figure taken from Soto et al. (2019)

A 35% saving in fertilizer quantities and a 106% increase in nitrogen use efficiency were obtained in fertigation for cotton crops (Stamatiadis 2013). Other effects of this technique on yield and production costs are detailed on page 78.

Effects on yields

Adjusting the nitrogen amounts allows an increase in yield by 4% on average, according to the farmer survey, as shown in Figure 11, (Soto et al. 2019).

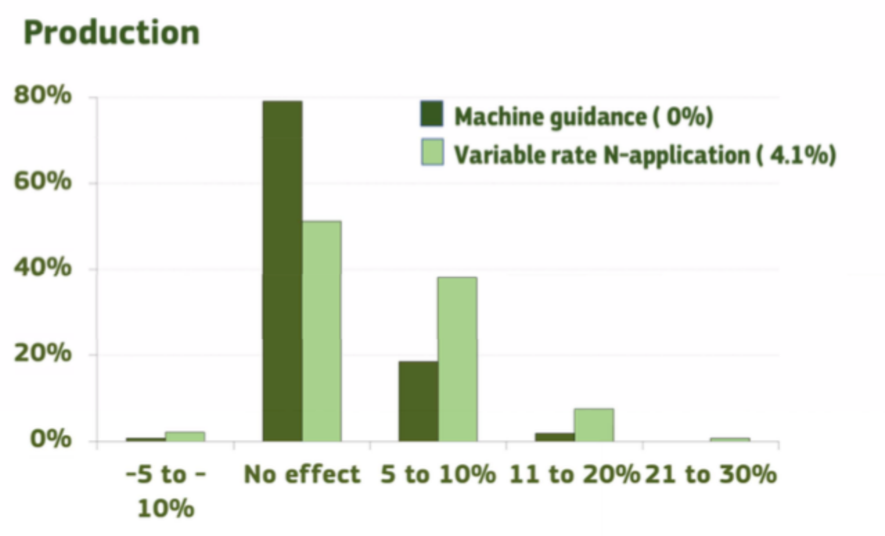

Figure 11 - Impacts perceived by farmers when using machine guidance and Variable rate N-fertilization on yield. Average impacts are shown in brackets, figure taken from (Soto et al. 2019) Soto et al. 2019)

Effects on working time

The time required to spread fertilizer is reduced by an average of 1.6% when using precision spreaders. However, the training required to master this technique and the setting of the system are time-consuming. They increase working time by an average of 2.2% and 2.3% respectively. Farmers report an increase in total working time of 2.8% on average (Soto et al. 2019).

Effect on the cost of production

The cost of production increases by 0.33% on average when adjusting the quantities of fertilizer applied. This increase is due in particular to the increase in contractual charges related to mechanization, which is of the order of 4.4% on average according to the survey conducted among farmers. Other studies quantify the increase in fixed and variable costs related to equipment at about 4€/ha. The decrease in fuel and labor costs during spreading, detailed in Table 32, counterbalances this increase. Fertilizer savings also occur. These can be up to 42€/ha for maize crops, 32€/ha for winter wheat, 27€/ha for barley and 20€/ha for oilseed rape (Soto et al. 2019).

Table 32 - Average impact perceived by farmers when using machine guidance and precision spraying on working time (Soto et al. 2019)

	Effect on contract costs (%)	Effect on the cost of labor required (%)	Effect on fuel costs	Total effect on production cost
Precision spraying	4,38	- 1,25	- 2,8	0,33

The reduction in inputs does not always compensate for the investment linked to this technology. Variable rate fertilization induces an effect on the gross margin ranging from -16€/ha to +440€/ha. Between 40 and 47% of farmers perceive a return on investment in less than 5 years. Of the remainder, 25% estimate that the return on investment takes place over periods longer than 11 years (Soto et al. 2019).

Effects on climate change mitigation

Reducing the amount of fertilizer leads to a decrease in direct and indirect N_2O emissions. Paired 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 3,805 and 6,567 kT eCO_2/year, which corresponds to 1.5% of the total GHG emissions of the agricultural sector in 2015 (Soto et al. 2019).

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

Adjustment of the amounts 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 boom from a recommendation map. Water pressure adjustment is another alternative (Soto et al. 2019). These techniques have been implemented on pivot systems in the USA. They can be applied to spray booms and hose-reels. They are starting to emerge in Europe.

Few data quantifying the effects of these techniques on water consumption, productivity and production costs exist today at European level. This is even more the case for precision micro-irrigation taken alone (Soto et al. 2019).

Reduction in irrigation water consumption

Pivot systems, spray booms and reels

Less water consumption leads to a decrease in the energy consumption needed for pumping and transporting water. A water and energy saving of about 30€/ha can take place for over-irrigated crops in humid climates (Soto et al. 2019). Reductions in water consumption ranging from 9 to 19% have been found in the USA, New Zealand and Germany (Neupane and Guo 2019).

Micro-irrigation

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 made possible by the DSTs linked to irrigation management, described on page 71.

Effects on yields

Pivot systems, spray booms and reels

Very little information is available. Irrigation modulation seeks to maintain yields or to tend towards yield objectives while reducing water consumption. Projects are currently underway in Europe to quantify these technical and economic impacts on irrigation booms (Forschungsinstitut für Bergbaufolgelandschaften et al. n.d.). A study in the US showed a 27% increase in water productivity on corn crops compared to a uniformly irrigated plot with a pivot irrigation system (Neupane and Guo 2019).

Micro-irrigation and fertigation

Research conducted in fertigation showed 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 suggestions.

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 implanted, as well as the calibration of the system, are time-consuming (Soto et al. 2019). It can be estimated that these items induce an increase in work time of the same order of magnitude as for Variable Rate Fertilization, i.e. 2.8%, as detailed on page 78.

Effect on the cost of production

Pivot systems, spray booms and reels

While some studies have demonstrated the economic viability of VRIs, others argue that it depends on the crops, the cultivation practices carried out and the environment in which they are implemented. The economic viability of these technologies does not depend so much on the increase in production that is generated or the water and energy savings that are achieved, but rather on the investment cost associated with these tools. A benefit of more than $16/ha from the use of VRI was observed in an American study compared to the application of uniform irrigation. No studies quantifying the benefits have been conducted in Europe today. Most existing studies quantify input savings (energy and water) through modelling.

Micro-irrigation and fertigation

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, which is detailed on page 73. The automation of work time reduces the costs related to irrigation management. This counterbalances a potential increase in work time. The reduction of water and fertilizer consumption in fertigation leads to a decrease in production costs. Paired with an increase in yield, the gross margin increases.

The net profit can be up to 480 €/ha/year in VRI fertigation, even if the farmer has to make important investments in new equipment. These net profits have been obtained taking into account the important investments made. They are mainly influenced by the amounts of nitrogen fertilizers applied and the selling price of the crop (Stamatiadis 2013).

Effects on climate change mitigation

Irrigated crops emit more N_2O than non-irrigated crops. This increase is between 50 and 140%. VRI 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).

Effects on water, soil, air and biodiversity

VRI minimizes the risk of leaching and improves groundwater quality. Oxidation of OM is reduced, thus promoting soil quality. Micro irrigation reduces soil disturbance compared to mobile booms (Stamatiadis 2013).

b. Remarks

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; Kritikos 2017; Kernecker et al. 2019).

Field trials analyzing the contexts conducive to the profitability of new tools and their impacts on the socio-economic dimensions of users seem essential to complete the modelling and to have the interest of these tools recognized by farmers (Neupane and Guo 2019).

c. Conclusion

By reducing the quantities of pesticides and fertilizers and maintaining or increasing yields, these tools allow for efficient management of field crop inputs. The impact of these techniques on water efficiency is much more complicated to analyze.

Whatever the inputs, the gain in processing 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 size of the users (farm or group of farms) or by using third party organizations.

While variable rate fertilization has the potential to reduce GHG emissions, variable rate crop protection has no effect, and precision irrigation influences GHG emissions by increasing the volume of water irrigated, or vice versa.

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 (Aubertot et al. 2005).

3. Chemical weed control robots

Almost 90% of agricultural robots are milking robots for animals. In terms of crops, they were first developed for market gardening. Working in an open environment with topographical and meteorological variations, with different crops evolving as they grow, makes the design of robots for field crops complex. In field crops, robots are initially designed for wide-spaced weeding crops such as beets and corn. Tests are underway for straw cereals and rapeseed (Savary and Legrain 2020).

The different types of robots fall into three categories:

- Robots for monitoring, collecting data on plots (presence of pests, state of development...), or logistical assistance for transport, or for localized spreading and spraying. These are systems with embedded tools, without physical contact with the working environment (Cabeza-Orcel and Berducat 2016; Sorel 2019) ;
- Robot tools that are in contact with the environment but without gripping. These are mechanical maintenance robots (hoeing, weeding, thinning, mowing, etc.).
- Robots that perform physical and complex tasks such as pruning, harvesting, planting or transplanting. These robots that are not related to the studied inputs, so they are not considered in this section (Cabeza-Orcel and Berducat 2016).

The majority of robots marketed in field crops are self-guided, driverless platforms the size of small tractors. Many small robot prototypes are under development. These are mower- or vacuum cleaner-sized robots that operate in swarms and are very suitable for intercropping (Cabeza-Orcel and Berducat 2016).

The arrival of autonomous tractors was announced for 2020. These driverless tractors will develop from 2020-2025. The agricultural robotics market, which was worth 16.3 billion dollars in 2020, is expected to reach 74 billion dollars in 2024, half of which will be taken up by autonomous tractors. Their development is highly correlated with the expansion of farms (Savary and Legrain 2020).

Other types of robots, weeding with lazers, are emerging in Germany. Although not yet suitable for field crops, this type of weeding seems promising (Savary and Legrain 2020).

The objective of the robots is both to reduce work time and to have no fertilizer or pesticide residues. Little information is available on robots related to fertilization. There are about 15 field crop robots marketed in Europe, which are mainly chemical or mechanical weeding robots (Sorel 2019; Julien 2018). Mechanical maintenance robots are detailed on page 91. Thus, only chemical weeding robots, which carry out ultra-localized treatments on the row and the inter-row, thanks to weed detection at the cm, such as Ecorobotix®, are considered in this section (Julien 2018).

a. Results obtained

Effects on herbicide use

Depending on their technology, chemical weed control robots can reduce the amount of active ingredient by up to 20 times compared to a total herbicide pass (Julien 2018; Farm Europe 2020). Some manufacturers claim that they provide reductions of up to 90% in treatment volume (Sorel 2019).

Their efficiency on weeds varies between 30% and 80% (Julien 2018), depending on their ability to detect them. Some robots manage to detect about thirty of them (Sorel 2019). Others are learning machines, as the image bank that allows the algorithm to recognize weeds has the capacity to grow (Julien 2018).

Two passes of herbicide followed by four passes of a chemical weeding robot reduce herbicide consumption by 51% compared to a full herbicide treatment according to (Julien 2018). This amounts to maintaining the same level of weed control, i.e. a score of 8/10. In this experiment, one herbicide pass followed by four robot passes obtained a score of 7/10 (Julien 2018).

Effects on yields

Yields are not affected if more than 80% of the weeds are controlled.

Effects on working time

Small weeding robots have a work rate of 0.08 to 0.3 ha/h depending on how dirty the plot is and how the robot works (photovoltaic energy, etc.), which is much slower than a tractor with a weeder (13 ha/h on average). Yet they are intended to work collaboratively, by ten units and can work 10 to 12 hours/day. (Sorel 2019; Julien 2018; Cabeza-Orcel and Berducat 2016). They thus make it possible to reduce the drudgery of work (J.V. 2021).

Effects on the cost of production

These small robots currently cost between 23,000 and 27,000 euros. This cost is significant if it is necessary to invest in several robots to create a swarm and reach a productivity equivalent to that of conventional weed management. This cost is nevertheless to be put in front of the time saving, the possibility to continue weeding and the pesticide saving achieved thanks to these technologies (Julien 2018).

Effects on climate change mitigation

The reduced use of herbicides and lower fuel consumption observed compared to the use of trailed implements or sprayers reduces indirect CO_2 emissions (Farm Europe 2019; Balafoutis et al. 2017). However, it is very difficult to quantify these reductions (Lowenberg-DeBoer et al. 2020). They must be qualified with the emissions linked to the construction of robots, which is also difficult to quantify.

Other effects on soil, water, air and biodiversity

The light structures of the robots limit the risks of compaction and damage the soil structure less compared to current tractors (Julien 2018; Cabeza-Orcel and Berducat 2016). Adjusted and localized herbicide spraying also plays in favor of water and soil quality.

b. Remarks

Detection problems can occur when weeds are in their early stages or when crop leaves cover the weeds in the row. Light and shadow effects can also impact weed detection (Julien 2018).

Robots operate in a controlled environment for which farmers have trained them. Farmers must train them to adapt to field conditions. Training farmers to master these tools and adapt them to field conditions is the key to their democratization (Savary and Legrain 2020).

Many questions about the liability of a robot's actions remain unanswered, especially for agricultural robots that work in open and changing environments (Cabeza-Orcel and Berducat 2016).

c. Conclusion

Chemical weed control robots are making their appearance in field crops and are now targeting wide-spaced weeds and rapeseed. Their ability to detect weeds with great precision means that the quantities of herbicides sprayed can be reduced. Several passes of the robots paired with one or two passes of herbicide ensure satisfactory weed management that does not impact yields. However, this observation must be qualified according to multiple factors such as weed pressure, type, growth stage, weather and topographical conditions and the robot's operating mode. They reduce the laboriousness of the work, but the work rate of a robot is lower than that of a tractor or a sprayer because of its small size. This throughput increases if they work in swarms, which is their objective. However, their cost would become much higher. If their effect on reducing the risk of compaction is recognized, their potential effect in the fight against climate change is difficult to quantify. Their development is just beginning and seems promising, provided that farmers are trained to adapt them to their plots. Questions about the responsibility of a robot's actions still remain.

Nitrification stabilizers

Nitrification stabilizers are molecules that limit nitrate nitrogen peaks in the soil and the emission of N_2O and NH_3. These stabilizers can be divided into two groups:

- Urease inhibitors that prevent the conversion of urea to NH_4+ (ammonium) and slow down NH_3 emissions;
- Nitrification inhibitors that delay the nitrification process.

A fertilizer containing these molecules is called "stabilized".

Stabilized fertilizers are not to be confused with slow release or controlled release fertilizers. The latter delay or control their assimilation and use by the plant, which ensures assimilation over a much longer period. The duration of assimilation varies according to the mechanisms used (coating, slow hydrolysis of certain compounds...) (Trenkel 2010).

This section deals only with nitrification stabilizers in field crops.

4. Results obtained

Effects on fertilizer use

These molecules ensure the maintenance of plant-available nitrogen in the soil. Applied at the prescribed doses, nitrification inhibitors maintain the quantities of nitrogen assimilated by crops by reducing nitrogen fertilization by 10% (Gimat et al. 2019). According to a meta-analysis, the efficiency of nitrogen fertilizer use increases by 13% on average depending on climatic factors and crop management (Abalos et al. 2014).

Effect on yields

In most studies, inhibitors do not affect yields. However, other studies have found yield increases ranging from 0.8 to 10.2% depending on the species studied (Byrne et al. 2020).

Effect on working time

No extra work is associated with this practice (Gimat et al. 2019).

Effect on the cost of production

This practice leads to an additional cost of between 3.2 and 4.2% compared to the initial cost of fertilization (Carswell et al. 2019). It is estimated at 0.34€/ha/kg N applied, i.e. about 60€/ha/year (Gimat et al. 2019).

Effects on climate change mitigation

Reductions in N_2O emissions of an average of 60% were measured. This order of magnitude varies between soil types, as shown in Table 33. Combinations of several nitrification inhibitors increase N_2O reductions up to 90% (Byrne et al. 2020).

Table 33 - Reduction in N_2O emissions$_2$ following the use of nitrification inhibitors on different soil types (Byrne et al. 2020)

Type of soil	Maximum measured N_2O emission reduction
Silty	93%
Alkali clay	43%
Sandy	40%

Studies estimate that nitrification stabilizers can reduce GHG emissions by 317 kg CO_2 eq/ha/year (Gimat et al. 2019).

Other effects on soil, water, air and biodiversity

Reductions of 47-89% in NH_3-N (ammonia nitrogen) leaching losses have been observed when urease inhibitors are used, improving soil, water and air quality (Gimat et al. 2019). Nevertheless, doubts remain about their ecotoxicity and the persistence of some compounds (Gimat et al. 2019). Further studies on this topic seem necessary (Byrne et al. 2020).

5. Remarks

However, the accounting of emission reductions remains difficult to estimate due to uncertainties related to the reduction of N_2O emissions and the effectiveness of nitrification stabilizers (Gimat et al. 2019). Their effectiveness which is moreover very variable depending on their mode of operation: urease inhibitors have lifetimes of 3 to 7 days while nitrification inhibitors have lifetimes of between 4 and 8 weeks, depending on environmental conditions (Trenkel 2010).

6. Conclusion

Despite the interest that these molecules have on the efficiency of applied N, the better availability of N and the possible reduction of leaching, they are not economically profitable for farmers (Gimat et al. 2019).

C. Other alternatives

Other types of agricultural equipment without an on-board pilot are becoming more widespread. These include, for example, Unmanned Arial Vehicle. Flying Aerial material (UAVFA) or drones. They can take aerial photographs which are then fed into the control tools described on page 69. They can carry out the spraying of phytosanitary treatments while protecting the operator's health. Others are used to release biocontrol products in the fields (Soto et al. 2019; Sorel 2019).

III. Input substitution

A. Pesticides

1. Physical Control

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

The currycomb harrow and the rotary hoe make it possible to work the whole surface of the soil in a superficial way. Only the first few centimeters of soil are broken up, affecting only weak weeds. These tools are used in spring and winter barley and wheat, rapeseed, peas, faba beans, sunflower and maize (Arvalis 2014; Agro-transfert, n.d.). The weeder is used more on crops sown with a wide spacing such as maize, beetroot, sunflower, rapeseed or faba bean. It can be used on more developed weeds, several times per cycle (Arvalis 2014).

i. Results obtained

Effects on herbicide use

The use of the currycomb and rotary hoe shows mixed results on wheat, oilseed rape, barley and triticale crops. It is often necessary to multiply their use and combine them with herbicide treatments to obtain an efficiency on weeds higher than 80%, considered as satisfactory (Garnica et al. 2020; Vuillemin and Duroueix 2020). Mechanical control does not show any real efficiency on weeds in beet crops. The use of the weeder or hoeing alone has an efficiency below the limit of acceptability. The association with a herbicide treatment allows to reach 80% of efficiency (Vuillemin and Duroueix 2020). In maize crops, the effectiveness of hoeing combined with one or two localized herbicide treatments on the row is over 90%. It is about 70% on the inter-row, which is at the limit of the acceptability of soiling (Garnica et al. 2020). It is sometimes possible to do without a treatment, to choose less harmful molecules or to reduce the sprayed dose (Garnica et al. 2020; Arvalis 2014).

Weeding consists in simultaneously weeding the row chemically and the inter-row mechanically. This technique can be used in maize, rape, sunflower and soybean crops. This tool allows to reduce by 2/3 the treated areas and ensures a saving of 60 to 70% of herbicide (Vuillemin and Duroueix 2020; Hansen et al. 2019). This technique reduces drift by 75%. If anti-drift nozzles are used, drift can be reduced up to 90%.

Effects on yields

If the effectiveness of mechanical control (whether or not combined with herbicides) is satisfactory, there is no impact on the quantity and quality of yield, whatever the crop. The maximum decreases observed in experiments are of the order of one ton per hectare for wheat, 10% for beet, and 16% for maize (Garnica et al. 2020).

Effects on working time

The rotary hoe, the currycomb harrow and the hoe require a preparation of the soil beforehand to level it. The currycomb harrow and the rotary hoe have high work rates of 6 to 8 ha/h and 4 to 8 ha/h respectively. The weeder has a lower work rate ranging from 2 to 4 ha/h. This rate can increase if there is a self-guidance (Agro-transfer, n.d.). These operations must be repeated 2 to 3 times to increase their efficiency (Garnica et al. 2020).

One weed control reduces the time spent on weed control by half by making two passes in one (Hansen et al. 2019).

Effects on the cost of production

Mechanical weed control leads to increased fuel consumption and labor. It costs, with the cost of traction 10 €/ha for the curtain harrow and the rotary hoe and 18 €/ha for the weeder (Agro-transfert, n.d.). The cost of a weeder in beet varies between 23.88 €/ha and 105 €/ha depending on the equipment and the precision of the system (self-guidance by coulter or by camera) (Dubois and Pottiez 2013). It is advisable to increase the semi-density by 15-20% to prevent possible damage by tools, which increases the production cost (Vuillemin and Duroueix 2020). One avoided or reduced treatment represents a saving of 30 to 100 €/ha (Garnica et al. 2020).

A weed control costs about 18 €/ha and is not to be added to the cost of a spray. Pesticide-related expenses are reduced to 9-40 €/ha (Hansen et al. 2019).

Effects on climate change mitigation

Mechanical weeding does not induce an increase in N_2O emissions. A rotary hoe pass followed by bare soil in winter can induce leaching of 25kg N/ha on average (Hansen et al. 2019). Direct CO_2 emissions may also increase through fuel consumption, if additional chemical weed control is required.

Weed control reduces indirect CO_2 emissions by 60-70% compared to standard herbicide spraying. It also reduces fuel consumption by half, which is the amount of direct CO_2.

Other effects on soil, water, air and biodiversity

Mechanical control improves the structure of loamy soils that are susceptible to capping. The rotary hoe and the hoeing machine ensure that the soil is crushed and aerated. However, there may be an increased risk of erosion, loss of organic matter and phosphorus to water. These techniques prevent the selection of weeds resistant to the main herbicides (Guyomard et al. 2013; Agro-transfert, n.d.).

ii. Remarks

Mechanical weeding is highly dependent on rainfall. It must be carried out under favorable climatic conditions, over periods that can be very limited (Guyomard et al. 2013; Agro-transfert, n.d.). The weed cover, its development stage and the soil condition impact the type of tool needed and the intervention date. A packed, stony or cloddy soil is not suitable for either the rotary hoe or the curtain harrow (Arvalis 2014). Curves and unevenness are a source of damage to the crop during a weeder pass (Guyomard et al. 2013).

Weeding and weeding tools require an investment that can be made by a group of farmers, a cooperative or a CUMA. Such sharing can be complicated if the periods when climatic conditions for mechanical weeding are limited. Investing in such tools requires that favorable soil and climatic conditions are met (Guyomard et al. 2013). There are also some technical constraints such as the compatibility of the row spacing between the seeder and the weeder (Vuillemin and Duroueix 2020). These constraints require anticipating the use of mechanical weeding when defining the technical itinerary.

The use of these tools should be reasoned. The use of a harrow on a clean plot can increase weed germination. Mechanical weeding is not very effective against perennials, which are multiplied and disseminated by 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).

iii. Conclusion

Mechanical weeding requires specific tools depending on the stage of development in field crops. This solution is effective if it is repeated regularly or associated with herbicide treatments that can be applied in reduced doses or locally. It can avoid a treatment in field crops.

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 that of chemical weed control due to direct fuel-related CO_2 emissions.

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. The first hoeing robots were sold in 2016 in Europe. They are mainly developed for high value crops with a wide inter-row, such as in horticulture, market gardening or viticulture. Their market is slowly developing. As an example, about thirty Dino robots from Naïo Technologie® were marketed in 2019 to hoe crops in beds (Savary and Legrain 2020). A few projects exist in field crops, particularly in beet.

Mechanical weeding robots are different from robots that spray herbicides with high precision, which are described on page 7483. Some farmers combine mechanical and chemical weeding robots to perform weed control.

i. Results obtained

Effects on herbicide use

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

Mechanical weed control robots have a weed control efficiency measured at more than 80% on beets (Lowenberg-DeBoer et al. 2020; Fountas et al. 2020). On average, herbicide quantities are reduced by 20 times compared to chemical weed control (Farm Europe 2019). This amount can vary from 30 to 75% for beet and cereal crops (Lowenberg-DeBoer et al. 2020).

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, whatever the crop.

Effects on working time

Although the use of robots requires a human presence, they reduce working time by about 20% (Barbière 2020).

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).

In cereal crops, the hypothesis of a mechanical weeding carried out in 5 passes with a swarm of robots would cost 30 €/ha/year per robot. This type of robot costs about 600 € per unit (Lowenberg-DeBoer et al. 2020). The investment of a mechanical weeding robot in beets reduces the cost of weeding by 600 €, compared to manual weeding (100 h/ha) (Lowenberg-DeBoer et al. 2020). Robots combining mechanical and chemical weeding allow, for an 80-hectare beet farm, to reduce production costs by 12% to 24% over 10 years taking into account interest and depreciation (Balafoutis et al. 2017).

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 CO_2 A reduction in fuel is observed compared to the use of towed implements or sprayers, thus reducing direct CO_2 emissions (Lowenberg-DeBoer et al. 2020; Farm Europe 2019; 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

In view of the investment cost of a robot, solutions such as weed control services and contracts reduce the cost of use and make the robots profitable on larger surfaces (Lowenberg-DeBoer et al. 2020). A final alternative would be to support the investment in robots, as their use is a lever for reducing the use of herbicides and is environmentally friendly. However, the capacity of weed control robots to achieve environmental objectives compared to other alternative solutions is not unanimous (Lowenberg-DeBoer et al. 2020).

Weed control robots have more or less marked effects depending on the location. More economic benefits were found in the northern half of Europe (UK and Denmark) than in the southern part (Greece) (Lowenberg-DeBoer et al. 2020).

iii. Conclusion

Weed control robots are beginning to be developed in field crops. Little quantitative data on their performances is available today. They make it possible to reduce or even do without herbicides. Yields are generally not affected. The workload 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. Although less developed than in viticulture, alternatives that make them more accessible should help them to become more widely available.

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).

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 favor the pest's enemies is also part of the biological control process. This can be done, for example, by inserting agroecological elements (Aubertot et al. 2005). These are described in detail on page 38.

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

Sclerotinia is, along with fusarium and powdery mildew, one of the main diseases for which biocontrol solutions are developed in field crops (Dumoulin et al. 2019). Different controls using bacteria (*Bacillus pumilus*), oomycetes (*Pythium oligandrum),* mycoparasites *(Coniothyrium minitans),* or minerals (sulfur) are alternatives to fungicides. The main pests against which biocontrol solutions are being developed are the European corn borer, Colorado potato beetles and Colorado potato beetles in potatoes and maize. The biocontrol agents used are insects such as Trichogramma larvae or Spinosad, a substance obtained from the fermentation of *Saccharopolyspora spinosa*, a bacterium present in the soil.

The results obtained are not always conclusive and can be controversial, either between trials conducted for the same biocontrol product/bio-pest pair, or between different products. Variability in results is influenced by the crop, pests, degree of contamination, type of biological agents that exist, and climate. Some will be less effective than conventional pesticides. Others will be close to or better than synthetic molecules. Spinosad, for example, is known to be as effective an alternative to neonicotinoids against Colorado potato beetles. Their effectiveness varies over time depending on the product. It can sometimes increase gradually or be effective for 18 months (Dumoulin et al. 2019).

Biocontrol agents against weeds are not well developed today. Solutions based on the principle of allelopathy, seed predation by crops auxiliaries 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; Le Bars et al. 2019).

Effect 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 uncontrolled control. However, as shown in Table 34not always greater than or equal to yields obtained with a crop protection treatment.

Table 34 - Effects of biocontrol products on yield (Dumoulin et al. 2019)

Culture	Bio-pest	Biocontrol organism	Compared to	Effect on yield
Rapeseed	Sclerotinia	Spore of *Coniothyrium minitans*	Untreated control	6-10 q/ha
Rapeseed	Sclerotinia	Spore of *Coniothyrium minitans*	Treatment with fungicides	Non-significant difference
Corn	Moth	Trichogramma	Untreated control	100€/ha
Rapeseed	Sclerotinia	*Pythium oligandrum*	Untreated control	+ 3 T
Rapeseed	Sclerotinia	*Pythium oligandrum*	Treatment with fungicides	- 1 T

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 from €15 to €60 per hectare in field crops (Dumoulin et al. 2019). Costs can vary from simple to double for a biological agent/bio-pest pair, depending on the formulation of the different products. A product is said to be as cost-effective as a conventional phytosanitary treatment up to about €40/ha and are 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, incurring an additional cost related to labor and equipment, if carried out using 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 N_2O emissions and carbon sequestration. These practices are generally inexpensive in direct and indirect energy, thus limiting CO_2 emissions (Guyomard et al. 2013).

Some biocontrol agents, such as bacteria or fungi can produce NH_3 (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 (plant defense stimulators). This is the case with the oomycete *Pythium oligandrum* on wheat and rapeseed. Other products, such as sulphur 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 (Guyomard et al. 2013; Dumoulin et al. 2019). In order to ensure effective pest control, 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 like the oomycete *Pythium oligandrum* 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 (Aubertot et al. 2005; Dumoulin et al. 2019).

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 implies cumbersome logistical and storage conditions, both at distribution and farm level (Aubertot et al. 2005; Bailey 2014).

iii. Conclusion

Biocontrol products are less developed in field crops than in other crops and mainly concern diseases and pests. Their effectiveness is not always equal to that of conventional pesticides and depends on many factors, particularly climatic. Production yield is 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 lead to 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 defense 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). Widely developed in viticulture and arboriculture, it is much less so in field crops. Recent studies on the use of mating disruption against wireworms in maize crops show mixed results (Larroudé and Thibord 2018).

ii. Natural defense 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

Reduction of inputs

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

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 PDSs are combined with half-dose fungal treatments, rather than alternating full-dose fungal and PDS treatments (Maumene et al. 2018).

Effects on yields

Whatever the crop, its yield and quality are, because of the variability of action of NDS, lower or equal to the yields obtained using pesticides (Faessel et al. 2014; Guyomard et al. 2013; RIVIÈRE-WEKSTIEN 2015).

Effects on working time

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

Effects on the cost of production

PDSs have a cost comparable to much higher than fungicides in field crops (Hirschy, Leveau, and Halska 2018). An increase in production cost may occur if they are combined with pesticides or if the occurrence of treatments is high (Guyomard et al. 2013).

Effects on climate change mitigation

NDS do not consume more energy than pesticides. GHG emissions are equal if they are applied alone (Hirschy, Leveau, and Halska 2018). They increase if they are combined with fungal treatments (Guyomard et al. 2013).

Other effects on soil, water, air and biodiversity

The effect of PDSs on water quality, air quality and biodiversity depends on the eco-toxicology of the molecule used (Hirschy, Leveau, and Halska 2018).

2) Remarks

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

3) Conclusion

PDSs have a set of economic constraints (potentially lower yields, additional labor 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 fertilizer

The amounts of synthetic fertilizers applied have decreased by 12% over the last 20 years but the emissions related to them have increased by 5% between 2005 and 2018 (Debarge and Tenaud 2015; "AMMONIAC (FORMAT SECTEN)" n.d.). This can be explained by the composition of the fertilizers used. Urea-based fertilizers have seen their use increase over this period. However, they are more emissive than other forms of fertilizers such as ammonium nitrate, thus increasing total fertilizer-related emissions. Their consumption slowed down in 2017, leading to a slight decrease in emissions in 2018 ("AMMONIAC (FORMAT SECTEN)" n.a.).

Emissions related to the use of organic fertilizers and soil improvers such as composting of green waste from communities, the use of manure and livestock effluents or digestates from methanation vary by country. They remained constant between 2005 and 2018 in France but increased in Belgium, Luxembourg, the Netherlands and Italy ("AMMONIAC (FORMAT SECTEN)" n.a.).

Fertilization is globally overestimated. This surplus is estimated in France at an average of 30 kg of nitrogen per hectare, which corresponds to 28% of the fertilization carried out. It has also been found that plots fertilized with mineral and organic fertilizers have on average a higher nitrogen surplus than plots fertilized with mineral fertilizers only (Debarge and Tenaud 2015).

a. Results obtained

Effects on fertilizer use

An improvement in the inclusion of organic N inputs in the calculation of the application rate would increase their use to replace synthetic mineral N. This would reduce the need for mineral N fertilizers by 15 kg N/ha on average. This would reduce the need for mineral nitrogen fertilizers by 15 kg N/ha on average. However, this figure masks a great heterogeneity that depends on the type of crop and the way organic products are used (Debarge and Tenaud 2015).

Effects on yields

A lack of characterization of organic fertilizers can have a negative impact on yield. Nevertheless, there are many tools such as DSTs to adjust and complete these inputs by taking into account the inputs, the fertilization dynamics, the organic fractions, the input modalities, *etc*. It is therefore considered that the choice of the type of fertilizer - organic or synthetic - does not impact the yield (Debarge and Tenaud 2015).

Effects on working time

The management of organic fertilizers requires more technicality than that of mineral fertilizers, because of the variability of the richness of these inputs that depends on their form and origin. A slight increase in labor time can be observed, due to a slower field rate and an increase in observation time, according to (Guyomard et al. 2013). But according to Debarge and Tenaud(2015), the impact on working time is small.

Effects on the cost of production

Fertilization corresponds to about 20-30% of the variable cost of production (Denhartigh, Dumas, and Lebahers 2018). Although the application of organic fertilizers results in equal or higher fuel consumption, their cost is considered lower than synthetic fertilizers (Guyomard et al. 2013). According to (Debarge and Tenaud 2015), a reasoned fertilization that is based on a higher consumption of organic fertilizer ensures a saving of 20 to 40€/ha/year on fertilizer purchase.

Effects on climate change mitigation

Nitrogen fertilization is one of the biggest energy consumption items on a farm. 25 to 30% of the price of synthetic fertilizers corresponds to their energy cost. The manufacture of mineral fertilizers accounts for 95% of the emissions linked to them. The manufacture of one ton of ammonia emits an average of 2 tons of CO_2 and one tons of nitric acid emits an average of 2 kg of N_2O, i.e. 0.6 tons of CO_2. This represented nearly 40% of the expenses of a field crop farm in 2009. The use of organic fertilizer would save about 20% of indirect energy consumption compared to synthetic fertilizers. Combined with a reasoned management of fertilization, this would reduce the emissions linked to the manufacture and transport of fertilizers to 280 kg CO eq/ha/year. A saving of 35 kg mineral N/ha is equivalent to about 525 kWh/ha, or 236 kg CO_2/ha (Denhartigh, Dumas, and Lebahers 2018; Debarge and Tenaud 2015).

N_2O emissions increase sharply after N inputs. They are mainly emitted by microbial activity and depend strongly on agronomic practices and soil and climatic characteristics. The effect and location of mineral fertilizer forms on soil N_2O emissions are still poorly referenced (Debarge and Tenaud 2015).

Other effects on soil, water, air and biodiversity

The main mineral fertilizers used in Europe (urea, calcium ammonate and nitrogen-phosphorus-potassium (NPK) fertilizers) have an acidifying effect on the soil. Livestock manure inputs do not have a direct acidifying effect. They are beneficial for the diversity and abundance of soil micro-organisms and fauna. They effectively maintain OM levels. However, they can be a source of soil and water pollution due to the TMs (Trace Metals), zinc, copper and drugs (antibiotics and antiparasitics) they contain. The extent and frequency of these phenomena fortunately remains relatively low (Guyomard et al. 2013; Debarge and Tenaud 2015).

The form of the fertilizer determines the emissions of NH_3 or its precursors. This influences air quality. These losses of nitrogen to the air contribute through atmospheric deposition to increase the risks of acidification of other more sensitive soils, including forest soils (Debarge and Tenaud 2015). Among the different forms of mineral fertilizer, urea is the most sensitive to volatilization. Organic fertilizers can also emit NH_3, depending on their composition, especially if they are liquid livestock manure (Guyomard et al. 2013).

The substitution of synthetic fertilizers by organic fertilizers associated with fertilization management allows a reduction of NH_3 emissions from 1 to 6 kg/ha depending on the forms of nitrogen involved (Debarge and Tenaud 2015).

Another alternative is the use of additives and denitrification stabilizers, which are detailed on page 86. Ammonia emissions are influenced by many other factors such as soil pH, product pH, cropping practices and timing of application (Tailleur et al. 2020).

b. Remarks

Beyond the type of fertilizer, the spreading technique influences GHG emissions related to fertilizers and their environmental impact. Even shallow burial of fertilizers can drastically reduce NH_3 emissions (Tailleur et al. 2020).

Variations in NH_3 emissions between two consecutive years can be explained in part by fluctuations in fertilizer deliveries. Annual fertilizer deliveries were found to increase when commodity prices are high as farmers seek to maximize their yields. Conversely, annual fertilizer deliveries are much lower when commodity prices are low as farmers seek to limit their expenditure ('AMMONIAC (FORMAT SECTEN)' n.a.).

Many tools exist to support the change in fertilization practices and to gain precision. This practice is complementary to steering tools, assisted steering and localized application systems, as well as to varietal choices (Debarge and Tenaud 2015).

Mixed crop-livestock systems have fertilizer consumption that is on average 74% lower than in conventional systems. Overall income per asset is higher in grassland systems (Denhartigh, Dumas, and Lebahers 2018).

c. Conclusion

The use of organic fertilizer reduces the consumption of mineral fertilizers. This leads to savings in production costs and reduces indirect CO_2 emissions linked to the manufacture of synthetic fertilizers. The choice of organic or synthetic fertilization does not impact N_2O emissions. The composition of fertilizers and soil improvers, whether organic or synthetic, influences NH_3 emissions and therefore the acidification of certain areas. It is possible to reduce these emissions by burying fertilizers after their application. The characterization of organic fertilizers is essential to benefit from their positive effects on soil OM content without polluting the soil. Combined with fertilization management tools, it ensures that yields are not impacted by the composition of organic fertilizers, which may be more variable. Their use can nevertheless lead to a slight increase in working time. This practice is complementary to control tools, assisted steering and localized application systems, as well as to varietal choices. Together, they guarantee a reasoned management of fertilization that reduces fertilizer consumption, GHG and NH_3 emissions and ensures savings for farmers (Debarge and Tenaud 2015).

2. Green manure

Green manures are crops containing legumes sown with the aim of providing nitrogen to the following crop (Thromas, Bompard, and Giuliano 2018). 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 usually planted in mixtures with other legumes, brassicas or cereals rather than alone. They are established for a few months to a few years (Baddeley et al. 2017). In field crops, they are most often planted during intercropping, after the harvest of the previous crop or in association with it. They are degraded or even buried by the same means as cover crops, detailed on page 18(Thromas, Bompard, and Giuliano 2018).

a. Results obtained

Effects on the use of mineral fertilizer

The uptake of this nitrogen allows a nitrogen fertilizer saving of up to 23 kg N/ha to 70 kg N/ha in the following crop without yield loss in Europe (Stagnari et al. 2017; Véricel et al. 2018). These reductions translate into a saving of 18 to 24€/ha.

The amount of nitrogen available to the following crop depends on the BNF capacity of the different legume species, climate and water availability. The uptake of N released by legumes is more important if the amount of N supplied matches the N requirements of the following crop and if low N fertilization is applied. These factors complicate the isolation and quantification of N made available by legumes to the following crop compared to other sources (Stagnari et al. 2017).

Effects on yields

The yield increase of a cereal crop following a legume crop is between 0.1 T/ha and 1.6 T/ha compared to a cereal monocrop. This increase is greater than that obtained by diversifying the rotation with non-nitrogen fixing species, as shown in Table 35. It allows a gain of 20 to 300€ per hectare compared to a cereal monoculture. This can restore a satisfactory average yield across the rotation and even increase the gross margin to more than 10€/ha/year (Preissel et al. 2017). In Poland, a 25% increase in yields was achieved on average following the introduction of legumes in conventional tillage, SCT or no-till rotations, compared to these cereal monoculture systems (Woźniak et al. 2019).

Table 35 - Effect of a diversified crop on the following cereal crop compared to two consecutive cereal crops, from (Preissel et al. 2017)

Previous culture	Culture studied	Effect of previous crop on grain yield	Specificity
Pulses	Cereals and sunflower	0.2 to 1.6 T/ha	With moderate or high fertilization
Brassicaceae (rapeseed)	Cereals	0.1 to 0.4 T/ha	With moderate fertilization but without high fertilization

Nevertheless, if the period of nitrogen release does not match the period of assimilation of the following crop or if climatic and water conditions are not favorable, the productivity of rotations can drop by 6 to 9% compared to control rotations with or without legumes (Lechenet et al. 2014; Véricel et al. 2018).

Effects on working time

In field crops, the effect of legume inclusion on labor time varies depending on the introduction of legumes into the rotation. According to the sources, there may be no impact on the workload. Others report an increase of up to 2.2h/ha/year. More precise estimates are given in the sections on rotation diversification, page 9, crop associations, page 13, and insertion of cover crops 21.

Effects on the cost of production

The economic interest of green manures is calculated by adding the savings in inputs made on the green manures and on the following crop as well as the gain linked to the increase in the yield of the following crop. Pesticide savings of up to 50€/ha, fertilizer savings of an average of 18 to 24€/ha and fuel savings of 20 to 60€/ha have been observed. However, for equal amounts of nitrogen, the cost of nitrogen made available to the following crop by green manures is higher than the cost of nitrogen provided by synthetic fertilizers (Baddeley et al. 2017). The increase in revenue from yield gains has a much greater impact on economic performance than these input reductions (Preissel et al. 2017).

Effects on climate change mitigation

Adjusting fertilizer quantities on the crop following green manures would avoid the emission of 1 kg N_2O/ha from fertilizer production and application (Véricel et al. 2018). Soil and climatic conditions play a role in the emission of N_2O when green manure is applied (Stagnari et al. 2017).

The role of legumes in improving the energy efficiency of cropping systems has been clearly demonstrated (Lechenet et al. 2014). The reduction in nitrogen inputs that legumes provide on the following crop translates into a reduction in indirect CO_2 emissions of 277 kg eCO_2/ha/year on average (Stagnari et al. 2017).

Growing legumes increases the SOC and humus content of cultivated soils. According to a study conducted in Poland during three years on sandy soil, SOC content increases by 7.21 g/kg OM for legume crops compared to oat crops (Stagnari et al. 2017).

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 (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.

c. Conclusion

Green manures make it possible to reduce part of the nitrogen applied to the following crop in field crops. This compensation takes place on condition that the nitrogen supplied by the green manure is available when the following crop needs it. If this is the case, an increase in the yield of the following crop is observed in the field. The creation of water stress by green manures can be a source of yield reduction for the following crop.

Input costs are reduced, but labor time is increased. Green manures reduce N_2O and CO_2 emissions and improve SOC levels. Biodiversity, soil structure and water quality are improved.

Discussion

This review shows that there are various levers to be used and no silver bullet solution to be promoted throughout the European Union. On a European scale, certain practices can have both beneficial and negative effects. The choice of practices depends on many factors that influence their effects on input use, climate, environment and socio-economic conditions. These include:

- Farm and plot situation;
- Pedoclimatic conditions;
- Topography;
- Practices already implemented;
- Former practices carried out;
- Quantities of inputs that have been applied (very variable form one crop to another);
- Material available;
- Settings;
- Mastery of practices;
- Farm size;
- Proximity of urban areas...

The study nevertheless identifies practices that have proven their worth, under given conditions, and that would make it possible to move towards the objectives of neutrality of GHG emissions and economical use of inputs, the basis of the F2F and biodiversity strategies.

Among practices linked to the re-designing agrosystems strategy, **diversification of rotations and maximum soil cover, particularly during the intercropping period**, stand out as one of the solutions that could be most beneficial.

The same is true for **alternating ploughing and shallow tillage**.

The selection of resistant, early or late varieties also has many advantages. There are many ways to implement these practices: choosing the crops, the varieties, their insertion in the rotations*, etc.,* depending on what is best suited for each specific farm.

At the same time, there are many ways to improve the efficiency of pesticide, fertilizer and irrigation use through **modernization of agri-equipment, DST recommendations and both localized and adjusted input application**. Most of the new equipment marketed today includes some precision farming technologies. Of course, the more agri-equipment adjusts inputs or limits losses, the more expensive it is. Nevertheless, there are **affordable alternatives such as DSTs or the replacement of certain parts**.

Practices that seek to limit input use do not generally make it possible to do without pesticides completely. Some solutions, such as biocontrol, are not well developed in field crops compared to other crops and can be costly and time consuming. These practices remain preventive and complementary alternatives. They can be interesting to implement on small farms or plots.

Replacing synthetic fertilizers with green or organic fertilizers reduces the GHG emissions associated with their manufacturing process. Green fertilizers require technical skills to provide part of the nitrogen needed by crops. Organic fertilizers can completely replace synthetic fertilizers, but their availability can be limited for field crop farms.

There is a lot of information available on different practices that can sometimes appear contradictory. Selecting data corresponding to the local context makes it possible to deduct which practices are beneficial. Some practices, such as diversification of rotations, cover crops, green manures, shredding of residues, biocontrol, use of DSTs, *etc.,* or even false seedbed and SCT are interdependent and complementary. Taking this complementarity into account by working on sets of practices facilitates the distribution of workloads during the year.

In the short term, **local or even regional support for farmers** seems useful to help them identify these sets of practices. **Training is needed** to enable them to quickly benefit and take maximum advantage of the potential of their agricultural equipment. **The suggestions of DSTs must also be adjusted to local conditions**.

In addition to supporting farmers**, it is essential to ensure the accessibility of agricultural equipment and DSTs and to support the modernization of equipment to improve the efficiency of input use**. This is a priority that public policies should give themselves.

Robotics, on the other hand, is too new and too expensive. In 15 or 20 years, it could be a promising additional solution.

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List of acronyms

NH_4+.	Ammonium
AEI	Agroecological Infrastructures
ATEV	Agronomic, Technological and Environmental Value
BZ	Buffer Zones
C	Carbon
CAP	Common Agricultural Policy
CO_2	Carbon dioxide
CTF	Controlled Traffic Farming
eCO_2	equivalent CO $_2$
FPAEC	Flow Proportional to Advance with Electronic Control
FPM	Flow Proportional to Motor
GHG	Greenhouse Gases
GMO	Genetically Modified Organism
GPS	Geolocation by Satellite
h	Hours
h/ha	Hour per hectare
ha	Hectare
IEC	Intermediate Energy Crops
LEPA	Low Elevation-Energy Precision Application
LER	Land Equivalent Ratio
LESA	Low Elevation-Energy Spay Application
MESA	Mid Elevation Spray Application
N	Nitrogen
N/ha	Nitrogen per Hectare
N_2O	Nitrous Oxide
NDS	Natural Defenses Stimulators
NH_3	Ammonia
NH_3-N	Nitrogen Ammoniacal
NPK	Nitrogen Potassium Magnesium
NTT	No-till techniques
NU	Nitrogen Unit
NUE	Nitrate Use Efficiency
OM	Organic Matter
PDS	Plant Defense Stimulators
q	Quintals
q/ha	Quintals per hectare
SCT	Simplified cultivation techniques
SD	Surface Drip
SOC	Soil Organic Carbon
T	Ton
TFI	Treatment Frequency Index
TIOA	Technical Institute for Organic Agriculture
TM	Trace Metal
UAVFA	Unmanned Arial Vehicle Flying Aerial Material
UD	Underground Drip
USA	United States

VRI	Variable Rate Irrigation