Agricultural Activity concept for simulating strategic agricultural production decisions: Case study of weed resistance to herbicide treatments in South-West France

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Abstract:

In an uncertain socio-economic and climatic context, sustainable farming is a major challenge for farmers as well as for their agricultural advisors. It is therefore essential to develop a decision support tool (DST) that is likely to be useful to establish and evaluate new production strategies, in accordance with farm sustainability and environmental protection. This paper aims, by using the Agricultural Activity concept, to put forward and test a DST based on mathematical programming used to evaluate strategic production decisions, in conjunction with farmers and agricultural advisors. In the test case, the decisions concern the crop activities and their spatiotemporal combinations in order to reduce both the use of herbicides and the risk of weed resistance to herbicides in cereal-based production systems. Moreover, the DST considers the availability of the workforce during the crop cycle to determine the periods which are likely to require the most significant increase in comparison to the current situation. One scenario showing the current situation (Sc_baseline) and two alternative scenarios have been defined to address the weed-herbicide issue. The comparison of the scenario promoting soil tillage and the introduction of spring crops with Sc_Baseline has shown that the adoption of long-term rotations, the increase in winter crop frequency and the return to deep soil tillage have contributed to an increase in farmer income, total labor and water consumption by 7, 21 and 22% respectively. However, the intensity of pesticide use and nitrate fertilization have dropped by 15% and 17% respectively. By allowing the farmer to establish specific contracts for certain crops, the average income as well as the use of pesticide and nitrate fertilization were increased by at least 10%. This situation is the result of a simplification of rotations with a predominance of winter cereals and the elimination of deep soil tillage.

The analysis of these scenarios shows that the use of the DST has made it possible not only to put forward and evaluate alternatives that result in strategic decisions but also to understand, with the concept of Agricultural Activity, the biophysical and technical processes relating to farmer decisions and their impacts at field and farm level. Understanding and sharing this functional chain at farm level is expected to strengthen the farmer-advisor relationship in order to address the complex challenges of farming system sustainability.

Keywords: Strategic decisions, Weed resistance, DST, Mathematical programming, Activity concept

- Introduction

As well as an increase in production, the intensification of agricultural systems in Europe has often been followed by a degradation of the environment: excessive water consumption, nitrate leaching, emission of pesticides into the environment, etc. (Hanson and Hendrickson, 2009; Hoogesteger and Wester, 2015; Kirchmann and Thorvaldsson, 2000; Sumberg et al., 2013). Another significant effect of this intensification is the simplification of cereal systems (Zahm et al., 2015). This simplification results in shorter rotations (biennial, triennial) and the frequent use of pesticides (Tilman et al., 2002). One of the consequences of this intensification process is the appearance of weed resistance to herbicides which leads to substantial production losses every year and/or to an increase in the amount of herbicides used (Heap, 2014, 1997).

In this context, agricultural advisors together with farmers have to design innovative production strategies (Le Gal et al., 2011). These recommendations must be developed while taking into account the diversity of cereal farms (in their structure and practices) but also of the socio-economic and political contexts. Advisors often rely on two types of approach to meet this requirement. First, they use their practical experience (Doré et al., 2011; Giller et al., 2011; Kropff et al., 2001): this often involves advice concerning choices of little significance in the face of a partial change of an element of the context. Introducing sorghum for energy production instead of maize in order to benefit from the incitement towards bioenergy crops is a typical example of this kind of decision (Gabrielle et al., 2014). This involves substituting one crop for another similar but more profitable one, while avoiding a real disruption of the whole production system at farm level.

The second approach advocates the use of farm models by mobilizing mathematical programming (Beaumel and Breuil-Genier, 2011) or an Agent Based Model (ABM) without mathematical programming. It should be noted that both types of farm models were always embedded in model frameworks, including crop models, environmental models and more or less participatory approaches

ABMs are often used in order to evaluate the impact of a number of decisions previously made by stakeholders in response to partial changes in the context (Bachelier, 2012; Le Gal et al., 2010; Vayssières et al., 2009). These models can be biophysical at plot or farm level, as are the Olympe simulator (Le Grusse et al., 2006), OptiPhy (Benoit, 2017), and DairyNZ (Bachelier, 2012). These models do not generally simulate the decisions of farmers concerning their technical systems, but they are often used as an intermediary object with stakeholders for a participatory design of adaptive and/or innovative strategies (Berthe and Ferrari, 2015).

Moreover, the formulation of strategic decisions essentially based on expertise by combining several types of factors (socio-economic, biophysical and political) is relatively complex (Attonaty et al., 1999). This formulation must be designed both at plot and farm level. The second difficulty lies in the evaluation of the environmental and economic effect of these decisions in relation to a change in the biophysical (e.g. crop management), socio-economic (price of products and inputs) or institutional (e.g. subsidies and incitements) contexts (Reinmuth and Dabbert, 2017; Rose et al., 2016).

Mathematical farm models based on non-linear programming aim to overcome these limitations (Delmotte et al., 2016; Flichman et al., 2011). These models have been widely used to evaluate *ex ante* the impacts of new agricultural policies (Flichman and Jacquet, 2003; Janssen et al., 2011), of the biophysical environment or context of access to resources (water, labor market) (Gibbons et al., 2005) or of the introduction of new crops or techniques (Plaza-Bonilla et al., 2015), on the socio-economic and environmental performances of farms. With this type of approach, local actors are more or less involved in the acquisition of data or in the formulation of several scenarios of context change. This often makes these evaluations difficult for agricultural advisors to verify and use (Vayssières et al., 2009).

The use of this type of model for advising farmers began in the 1980s (Attonaty et al., 1991; Rossing et al., 1997). Despite the potential of this type of model for designing innovative systems and above all justify their performance regarding several durability criteria, their use in helping agricultural advisors remains very marginal today. Five main reasons are often cited to explain the low use of such a model: (i) at field level, decisions are often designed without considering socioeconomic constraints (Ko et al., 2012). The estimation of pest populations to inform when the density of the pest population reaches the economic threshold and when an integrated pest management strategy should be applied is a good illustration of such a use (ROUX, 2013), (ii) at farm level, in many cases alternative strategies (e.g. reducing pesticide use) are elaborated in order to help with the design of environmental and socio-economic policies, without contextualization or a target for the implementation of these strategies on real farms (Insee, 2012; Robert et al., 2016). Such models are not usually directly accessible to farmers, and in many cases these key farm decision-makers are excluded from the model development and application process (Donnelly et al., 2002; Papy, 2000), (iii) for the lack of detailed quantitative farmer data. This data concerns both the technical and socio-economic determinants that explain farmers' choices in terms of crops, but also their spatial and temporal allocations and their associated crop management (Rahman, 2008; Taechatanasat and Armstrong, 2014), (iv) the difficulty of structuring the model-database in a homogeneous way to take into account both the production process (crop selection and management), and the impact of this process on socio-economic and environmental farm behaviors (Attonaty et al., 1999), and (v) often the very high cost in terms of money and time of collecting all the data needed to perfect the model simulations, while much of this data is available, at least partially. In fact, several regional databases based on farm surveys could be explored, such as FADN or those in the possession of cooperatives for premium calculation or for advising farmers.

In light of these recurrent issues, this paper aims to put forward and test a decision support tool (DST) based on a mathematical farm model in order to formulate and evaluate strategic decisions, in close interaction with farmers and agricultural advisors. The simulated model decisions should be considered here as the first step in a whole approach in designing innovative farms as proposed by Giller et al. (2011) and Dogliotti et al. (2014).

Here, as a case study, the developed support tool is applied to strategic thinking on how cropping system structure and management can make it possible to solve the increasing problem of weed resistance to herbicide treatments in cereal-based farming systems of SouthWestern France.

2. Materials and methods

2.1. Conceptual and methodological framework

The decision support tool put forward by this study seeks to help agricultural advisors who offer advice regarding the strategic decisions that farmers have to make in a specific region when faced with possible context changes. These changes are of a biophysical (climatic), technical (agricultural practices such as the introduction of irrigation) or socio-economic nature such as the development of agro-environmental measures. Based on this assumption, the development of the decision support tool was built around three principles:

(i) The tool must be applicable for a wide range of cereal-based farming systems. This diversity encompasses farm structure as well as cropping system structure (crops and successions) and crop management systems.
(ii) The database developed for farm modelling must therefore be areabased in order to describe agricultural practices for all cereal-based farming systems in the area. This will make it possible to avoid building a database for each farmer by reducing the time spent in the pre-modelling phase and allowing for data sharing among farmers concerning crops and crop management.
(iii) The tool must be generic and be able to answer a wide range ofconcurrent challenges raised by farmers, advisors or stakeholders, such as nitrate leaching, weed resistance to herbicide treatments, the impact of the introduction of irrigation, etc.

The application of these three principles led to a decision support tool (DST) in which the farm model must include a database for “farmer’s activities” and a list of socio-economic constraints (labor availability, crop contracts, etc.) and agronomic as well as technical constraints (rotation, irrigation, soil, etc.). The “farmer’s activities” database is directly selected from the regional database of Agricultural Activities, while the constraints are collected directly from the farmer.

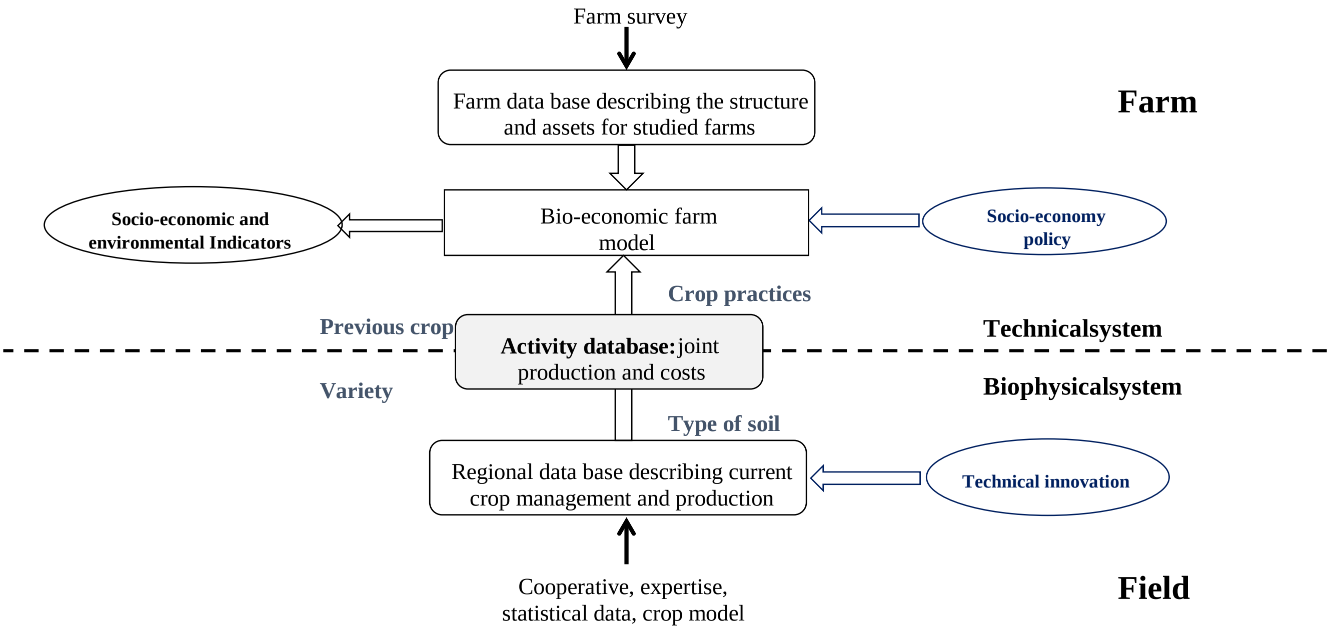

Fig. 1. The backbone activity-bioeconomic model to simulate farm behaviour.

2.1.1. Regional database based on the concept of Agricultural Activity

To achieve its purposes, the DST must be based on a regional database that describes exhaustively local production practices in accordance to the concept of the Agricultural Activities.

- The Agricultural Activity concept

The concept of Agricultural Activity is based on an approach known as “primal” (Flichman et al., 2011) which makes it possible to establish a direct relationship between the choice of inputs (in terms of quantity or timing) and their effects on production and externalities/services (Fig. 1), for every cropping system used. This approach differs from the conventional economic approach within which the Agricultural Activity is represented by a production or a cost without taking into account the way in which this activity is carried out and without specifying the biophysical context (soil, climate) in which it takes place (Vermersch, 1990). This conventional approach therefore implies that all the Agricultural Activities which have the same production level and/or production costs not only have the same crop management practices but also potentially the same externalities (Harper and Zilberman, 1989). Similarly, this implies that the production and the externalities produced are directly correlated to the cost of production and not to their production process (Flichman and Jacquet, 2003).

In order to overcome these limits, every Agricultural Activity is defined within our approach as a unique production process at the level of a given area. This Agricultural Activity is defined as the result of the combination of a biophysical and a technical system as presented in Fig. 1. This primal representation of the Agricultural Activity makes it possible (i) to quantify production but also the externalities linked to each Agricultural Activity according to its management practices in each biophysical environment, (ii) to quantify the impact of each possible change of input level on production and externalities, following a change in the climate or the market, (iii) to associate each Agricultural Activity with a production cost but also a gross margin that also includes the existing incentives or penalties, and (iv) to identify, for each Agricultural Activity, the resource needs (labor, Water, etc.) which will contribute to the selection of activities to be practiced according to resource availabilities at farm level.

Overall, the Agricultural Activity within our approach is defined as a vector that associates a biophysical system with a technical system for a joint production characterized by one or several types of production (grain, straw, etc.) and externalities (soil salinity, nitrate leaching, etc.). • Characterization of an Agricultural Activity

The definition and characterization of both biophysical and technical systems for the Agricultural Activity vector must be closely linked to the aim of the study and to the existing knowledge of crop management by farmers. In practical terms, this characterization is carried out through a three step process:

Step 1- Define current crops, associated previous crops and homogeneous soil-climate units at a regional level

In close interaction with farmers and agricultural advisors and by mobilizing existing regional databases, a list of current crops associated to their current previous crop observed in the area is to be defined. The current crops/previous crops refer to the main common crops cultivated in the study area. At a regional level, the current crops/previous crops means those dominant in terms of area and/or production, and/or environmental impacts (Therond et al., 2009). For this task a 3 h hour meeting involving 2 farmers cultivating mainly cereals with weeds resistant weed-resistance issues, and 3 advisories advisors from d’Invivo Agrosolutions Val de Gascogne cooperative was organized. The target of this meeting was to validate the list of current crops as extracted from the existing regional database.

For each current crop in association with its previous crops, an Homogeneous soil-climate units which will determine the production and externality potential for each crop must be associated with each current crop in association with previous crops. Here, the soil could be defined differently from one study to another depending on the spatial variability and the impact on yield and externality considered in the study. The water storage capacity of a soil or its fertility level are often considered to be key elements for the differentiation of soil types within an activity (Belhouchette et al., 2011). Climate is also similarly taken into account by specifying its effect on joint production.

The variability of rainfall or temperature in a given area is often taken into account for the definition of homogeneous climate-response units (Belhouchette et al., 2008).

Step 2- Associate each current crop-previous crop in a soil-climate unit with a specific crop management system
The management practices on a given crop are likely to be adjusted by farmers according to the biophysical context (soil, climate) and to the previous crop in order to optimize the use of biophysical inputs (water, fertilizers). However, this process is constrained by the use of the labor resources at farm level, leading farmers to simplify their crop management. Depending on the aim of the study, it is necessary to identify the most significant factors of crop management practices, which for each crop, its previous crop and soil-climate unit, account for the variability of joint production. For example, if the objective is to analyse the effect of fertilization on production and nitrate leaching, water as well as fertilization are important factors which significantly impact these two variables. Consequently, factors such as the level of phytosanitary treatments or the level of mechanization will not be considered to be dimensions of the activity vector, for we assume that these variables similarly affect the joint production of all activities even if their amounts (and therefore associated costs) can vary from one activity to another.

Step 3- Quantifying the input and output of eachAgricultural Activity
In order to characterize the Agricultural Activity vector, it is necessary to have quantifiable information on the inputs used for each activity, as well as, on its outputs (production and externalities). This data is generally extracted from several types of sources such as experimentation (Roetter et al., 2007; Stilma et al., 2007), statistical data (de Koning et al., 1995), expert statements (Alcamo, 2008; Dogliotti et al., 2003; Kerselaers et al., 2007), or by means of surveys among farmers (Delmotte et al., 2011; Jaeck and Lifran, 2009). Farmers and advisors further engaged in the simulation exercise (steps 2 and 3) are key providers of such types of data.

However, considering the different types of data (biophysical, technical, economic) but also the spatial scales on which they must be expressed (for example yield must be expressed per activity at field level whereas the price per product is often expressed at the level of a regional or national market), it is essential to obtain information concerning these activities from both farmers and agricultural advisors, but also to ensure coherence for this data according to the context of each studied area.

In practical terms, the quantification of the variables of the Agricultural Activity vector is a three-stage process:
(i)- Indicate the potential production and associated externalities (PPE) of each Agricultural Activity: in accordance with the yield gap concept (van Ittersum et al., 2013), the PPE for each Agricultural Activity is location specific (depending on the potential of each soil-climate unit) and defined as the production/externalities of a crop cultivar when grown with non-limiting water and nutrients and effectively controlled biotic stress (Gent, 1998; van Ittersum and Rabbinge, 1997).
(ii)- Indicate the achievable joint production (AP) for each Agricultural Activity: such as for the yield gap concept, the AP is defined here as the average production and externalities (in space and time) actually achieved in a farmer's field under the most widely used management practices such as sowing date, plant density, nutrient management and crop protection, etc. (van Ittersum et al., 2013).

At least five methods can often be observed in order to estimate potential and achievable joint productions such as stated by van Ittersum et al. (2013): (1) field experiments (Roetter et al., 2007; Stilma et al., 2007), (2) production contests (Cassman et al., 2003), (3) farm surveys (Lobell et al., 2009), (4) crop model simulations (Belhouchette et al., 2011; Grassini et al., 2011; Laborte et al., 2012), or (5) a combination of all the above methods (Belhouchette et al., 2011).
(ii) - Identify a unit cost that makes it possible to evaluate the grossmargin per activity, for each Agricultural Activity and production factor.

2.1.2. Development of a farm database
The Farm-database must contribute to the farm-bioeconomic modelling so as to simulate the structure and management of farm cropping systems and to calculate the socio-economic and environmental indicators that express the effects of the strategic decisions on the performance of the analysed farms.

The Farm-database is composed of four essential elements:
- Agricultural Activity- farm database: the regional database will serve as the basis for feeding the activity-database of farms. For each analysed farm, only the observed current Agricultural Activities on this farm will be extracted from the regional- database to feed the farmAgricultural Activity database.

Moreover, in the Agricultural Activity- farm database, Alternative Agricultural Activities could be defined in order to test new production strategies (see Sections 2.1.3 and 3.3). These Alternative Agricultural Activities, in contrast with current activities, are defined for each analysed farm in close collaboration with the farmer and his/her agricultural advisor according to the expected scenarios (see Sections 2.1.3 and 3.3).
- Resources-farm database: this database is defined by the farm's biophysical (water, soil), financial (capital, market access, etc.) and social (family labor, mutual aid, etc.) available resources.
- Policy-farm database: this database presents the opportunities (premiums, direct aid, etc.) but also the constraints (cross-compliance, penalties, etc.) which are available to the farmer in the context of agricultural policies or local incentives for agricultural production.
- Technical Constraints-farm database: this database defines the technical constraints such as crop rotation (i.e. no single rotation of legume), or biophysical (i.e. no rain-fed summer crops, etc.).

2.1.3. Development of a farm model based on mathematical programming
The farm model based on mathematical modelling aims to simulate the farmer's decisions on the structure and management of his cropping systems in order to compare various strategies and their impact on farm sustainability (Flichman and Jacquet, 2003; Janssen and van Ittersum, 2007). These strategic decisions result in the choice of more profitable activities while taking into account a number of technical, socio-economic and environmental constraints and objectives (Janssen and van Ittersum, 2007; Sterk et al., 2007).

The proposed bio-economic farm model should follow a primalbased approach, in which technology is explicitly represented, using the activity concept as described in Section 2.1.1. Furthermore, this farm bio-economic model should be generic and modular in order to assess a large list of economic and environmental indicators (Belhouchette et al., 2012). It should be designed for simulating a wide range of farmers' systems and addressing a great variety of strategic questions.

2.1.4. Definition of scenarios resulting in strategic decisions

The concept of "scenario" used in this work can be defined as a set of alternatives expressed as options for agricultural practices previously developed by the farmer and his agricultural advisor in order to meet a change of context (Therond et al., 2009). This will allow the agricultural advisor and the farmer to jointly explore "*ex ante*" the options of Alternative Agricultural Activity practices worth putting forward for selection by the bio-economic farm model in order to analyse their impacts. The Alternative Agricultural Activities are defined here as marginal activities in the region (in terms of area and environmental impact) or new activities for which the impact on farm behaviour is to be explored.

To that end, the scenario definition is conducted as a five stage process by following a classic participatory approach involving:

(i)- Defining the challenge which the farmer must face while taking into account his production goals. This stage will allow the agricultural advisor to define the core issue (example: weed resistance, recurring water stress. etc.) during an interview with the farmer according to the structure of the farm, and the current production system and strategic choices of the farmer (such as exclusively working under contracts with companies for crop products and/or solely using family labor).

(ii)- Identifying technical and socio-economic levers: the discussions between the agricultural advisor and the farmer must lead to a number of possible levers in order to deal with the previously defined core issue. One possible lever in our test case example is the use of agronomic practices that make it possible to reduce the risk of diseases (e.g. diversified crop rotation) or the appearance of the weed resistance to herbicide treatments phenomenon.

(iii)- Expressing technical and socio-economic levers of the scenarios as parameters and variables within the bio-economic model: this work must be carried out by the modeller in concertation with the agricultural advisor. It mainly involves defining: (a) the spatial scale on which the scenarios will be tested, (b) the time scale which will determine the simulation horizon of these scenarios, (c) the options to be tested (e.g.: a new rotation, including its yield, its production costs and margin per activity), and (d) the indicators needed to measure the socio-economic and environmental impacts of each proposed scenario.

(iv)- Simulating and reporting scenarios with the bio-economic model: this stage is led by the modeller. It must result in a detailed report of the scenarios tested and of the main results expressed as indicators (i.e. farm income, total irrigation water use, etc.) for each scenario. Moreover, by adopting the activity approach, several intermediate variables can be calculated and displayed at the Agricultural Activity level (i.e. area allocated to each Agricultural Activity) or at each component of the Agricultural Activity vector (i.e. area allocated to rain-fed crops, working time allocated to spring crops, etc.). These intermediate variables are important for a better understanding of the values of the indicators, as well as to improve communication with farmers and agricultural advisors regarding the determinants of their strategic choices.

(v)- Discussing the main model indicators and intermediate variable results with each selected farmer and agricultural advisor in order to see to what extent the scenarios have managed to deal with the problems previously exposed by the farmer.

These discussions should help to: (a) have a better understanding, by the farmer and his agricultural advisor, of the functioning of current production systems with their limitations and strengths, (b) select the best alternative production strategy in response to production challenges which the farmer must face, and (c) propose additional scenarios to be explored which emanate from discussing the results of the tested scenarios.

2.2. Application of the framework: Development of scenarios resulting in technical decisions in order to deal with the issue of weed resistance to phytosanitary treatments (herbicides)

2.2.1. Description of the study zone and studied farm

The Midi-Pyrénées region is the second most important in France in terms of its utilized agricultural area (UAA) (Agreste, 2014). Cereals and oilseed crops hold a dominant position with 700 000 and 280 000 ha respectively. The main cereals grown are soft wheat (40% of the arable area) followed by maize (26%), barley (13%) and durum wheat (12%) (FranceAgriMer, 2013). These crops are the major orientation for 12 600 farms in the region. During the process of agricultural intensification, rotations became simplified and shorter for maximum profitability. This simplification especially characterized by rotations of the winter cereal_winter cereal type, has been made possible by mechanization and by a significant use of herbicides to control weeds. Nevertheless, chemical control is now reaching its limits with the appearance of weed resistance to herbicide treatments in several weed species. For example, in the past decade, only 31 species of resistant weeds in France have been noted, whereas at the global level this number amounts to 183 (Heap, 1997). In cereal rotations (winter_cereal/winter_cereal or winter cereal/rapeseed), the main species affected by resistance to herbicides in France are Foxtail, Rye-Grass and wild oats. There are two major resistances that have been expanding, depending on the mode of action of the herbicide used (Heap, 2014):

- ACCase inhibitor-resistant weeds;
- ALS inhibitor-resistant weeds;

The Service unit of the Agrofourniture department of the Invivo Agrosolutions company[1] is responsible for giving advice on crop management in several agricultural areas in France. To do so, it relies on existing cooperatives to obtain information on the issues at stake and to provide advice to farmers. In the Midi-Pyrénées region, Invivo Agrosolutions collaborates with the Val de Gascogne cooperative to advise farmers.

In order to provide advice, Invivo Agrosolutions has been using the « Epiclès » regional database since 2010. This database describes the structure of the farm and the existing cropping systems for each year and each farmer member ("Val de Gascogne" cooperative[2]). « Epiclès » is updated every year using farmer surveys.

[1] http://www.invivo-group.com/en/agriculture.

[2] http://www.valdegascogne.coop/web/epicles-cerelia-couple-gagnant/#.

The « Epiclès » database used for this paper is that of the 2014/2015 campaign. During this campaign, 3223 cropping systems were identified among the 650 farmers questioned covering more than 13400 ha of agricultural land.

For our study, a farmer member of the Val de Gascogne cooperative was chosen to test the decision support tool for strategic decisions. The selection of this farmer was motivated by his commitment to taking part in the current initiative for the implementation of the "Strategic Consulting" project in partnership with InVivo AgroSolutions, ARVALIS, CETIOM and the Val de Gascogne cooperative. This project aims to support farmers in adopting alternative practices to face weed resistance. Moreover, this farmer is representative of cereal farming systems in the study area in terms of cultivated cropping systems dominated by winter durum wheat, winter barley and winter soft wheat, by zero tillage, and by the proliferation of resistant weeds (wild oats, ryegrass) (Table 1).

The farmer is a cereal grower based in a nitrate vulnerable area, which imposes constraints on N fertilization, and he has 114 ha. His farm has limited access to irrigation water with only 29.5 ha of irrigated land, devoted to spring crops. The dominant soil on his farm is clay loam and is characterised by an available water capacity of 162 mm/m.

Until 2013, this farmer grew winter cereals (soft wheat. durum wheat. barley) across at least 60% of his land area. All crops were grown using shallow tillage (SCT). This farmer had contracts with private companies for 4 crops (seeds durum wheat, soft wheat "Galibier", seed grain maize and food soybean). These contracts ensure a higher gross margin than that of the market but for a maximum area per contracted crop (1).

In 2014, this farmer lost his contracts due to the dominance of the resistant weeds on the winter cereal and rapeseed cultivated fields. Since then, he has stopped cultivating rapeseeds and winter cereals have only accounted for 45% of his total agricultural land area (9 ha of durum wheat and 42 ha of soft wheat). The rest is represented by spring crops (24 ha of soybean, 35 ha of sunflower, 4 ha of sorghum) and grassland (4 ha). Overall this farmer has seen his income drop by at least 15%. **3. Results**

3.1. Building the regional database on agricultural activities • Characterization of the current Agricultural Activities in the study zone

Table 1
Representativeness of the selected cereal farm in comparison with the cereal farms in the study area. The regional average data are calculated based on 5413 real farms in the study area which represents of 55% of the total cereal farms (Belhouchette et al., 2011).

Variables	Case study selected cereal farm	Regional average data per farm
Farm size (ha)	114	113
Percentage of cereal crops (% of total farm area)	60	53
Irrigable area (ha)	29.5	28
Number of worker (day/ha)	92	88
Number of contracted crops	4	3.5

The « Epiclès » Invivo Agrosolutions regional database is essentially divided into 3 components: soil, crop and type and quantity of inputs. The climate (notably rain) is considered to be relatively homogeneous throughout the area (Viet, 2013). One crop yield and three inputs for each crop are specifically described in this database: the quantity of irrigation, fertilizer (nitrogen and others) and herbicide expressed as costs of HTFI (herbicide treatment frequency index) (Gravesen, 2003). For each crop, the cost of HIFT is calculated as the estimated cost of a unit of HITF multiplied by the number of treatments. The main assumption here is that, for each crop, the herbicides used are fairly homogeneous in terms of efficacy and environmental pressure. The average cost of a unit of HITF per crop is updated annually at Epiclès by Invivo Agrosolutions. Only the number of herbicides is collected during the farm annual survey. An average cost per herbicide per crop is then automatically calculated at database level as the average cost of a unit of HITF multiplied by the number of treatments.

The choice of variables, which concerns both biophysical and technical systems, was established in consultation with the agricultural advisors in order to develop and provide information regarding agricultural activities. The main assumption for the choice of these variables is that the expected yield as well as the doses of inputs associated with each crop essentially depend on the previous crop type, the soil type, the presence of irrigation or not and the current existence of the resistance phenomenon or not. In practical terms, the "Agricultural Activity" database was built as such using the Epiclès database:

Step 1- Define current crops, associated previous crops and homogeneous soil-climate units at a regional level
Sixteen crops were identified as dominant in terms of area in the study zone. The area occupied by these crops in 2014/2015 was 11121 ha. i.e. 83% of the total surveyed area of the Epiclès database. This consists of 5 winter crops mainly represented by soft wheat, durum wheat and barley and 11 spring crops. i.e. grain maize, sunflower and soybean.

A possible previous crop was defined for each crop based on agronomic expertise in consultation with the agricultural advisors of the area. Only the previous crops commonly grown in the area were selected. The choice of the previous crop is very important and goes beyond the residues generated for the next crop as it may influence the potential yield and the pest, disease and weed pressure. Winter cereal_winter cereal or winter cereal_rapeseed successions contribute to the appearance of the weed resistance to herbicides phenomenon. In practical terms, 140 combinations (previous-following crops) were selected as possible two-year rotations.

For each crop and its previous crop, one or several soil types were considered. In the Epiclès database, 11 soil types were identified and described based on several criteria such as texture, soil depth, permeability, etc. The 11 soil types were grouped into 6 categories of soil water holding capacity (SWHC) based only on soil texture and depth. The main assumption for this simplification in soil

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characterization is that in the absence of nutritional and biotic stresses, the potential yield of cereals is determined by the water supply itself depending on the soil water holding capacity. The selected SWHC categories are respectively: < 40 mm/m, 40–80 mm/m, 80–120 mm/m, 120–160 mm/m, 160–200 mm/m and > 200 mm/m.

Step 2- Associate each current crop-previous crop in a soil-climate unit with a specific crop management system
For each crop, previous crop and soil type the "presence of irrigation" or not" dimension was added. The assumption here is that for spring crops, the applied amounts of irrigation depend on the previous crop type, on the soil type and achievable yield targets.

The achievable yield for every crop, previous crop, soil type and irrigation level also depends on the type of tillage. At a regional level, all spring crops are managed using no-till farming. For winter cereals and rapeseed, the prevalent practice is that of no-till farming but some farmers still use deep tillage. On average deep tillage increases potential yield by 10%, compared to no-till, for winter cereals and rapeseed but it also increases production costs by 8% (Terresinovia, 2005).

The last variable of the activity vector which could affect the achievable yield is the initial presence or not of a herbicide resistant weed population. This resistance phenomenon only concerns winter cereals and rapeseed. This phenomenon is not found in spring crops because spring sowing provides a greater time period between the harvest of one crop and planting the next, which allows weeds to be removed before the planting of the next crop (Wentworth, 2015).

Step 3- Quantifying the input and output of each agricultural activity
All the identical current Agricultural Activities (Activities with the same dimensions as described in Section 2.1.1) are compiled in the Epiclès database. The main assumption here is that, as those Agricultural Activities have the same biophysical conditions (soil and climate) and production processes (previous crop and quantity of inputs), they should have the same level of production and externalities. Based on this assumption, for each group of identical Agricultural Activities, an average yield and average quantities of inputs (water, nitrogen, HTFI, labor, etc.) are calculated based on the information available in the Epiclès database.

Once the list of Current Agricultural Activities is fixed, the Agricultural Activities with potential production (PP) are derived by considering the Agricultural Activities that have the upper percentiles of the yield distributions of farmers. The rest of the activities are considered to be Agricultural Activities with Achievable production.

The prices of each type of inputs (water, fertilizer, etc.) as well as the prices of agricultural products (wheat, barley, etc.) and their variability over the last 4 years were collected by the Val de Gascogne cooperative. The variability of the prices of agricultural products is needed for profitability risk analysis as presented in Section 3.3.

In order to calculate the costs due to mechanized operations (irrigation, sowing, no-till farming, tillage, etc.) a set of operations and machine types were defined in consultation with agricultural advisors. The number of working hours, rental costs for every machine as well as the energy cost for every machine were calculated according to regional standards and based on the average prices of rental machines and energy over a period of four years: from 2012 to 2016.
This work has led to the creation of a regional database describing 527 current Agricultural Activities as well as their production cost (Supplementary material 1).

3.2. Development of a farm database

As stated in Section 2.2.1, a farmer member of the Val de Gascogne cooperative was chosen to test the decision support tool for strategic decisions. The database corresponding to this farmer is composed of:

– Agricultural Activity-farm database: 51 activities extracted from the regional database composed this database. Moreover, 59 Alternative Agricultural Activities are defined and added to this database in concertation with the selected farmer and the agricultural advisor.

Table 2
Contract crops of the farmer with the gross margin for each crop and maximum contractual area for 2013.

Crops	Without contract	With contract	
	Gross margin (€/t)	Gross margin (€/ha)	Maximum area (ha)
Seeds durum wheat	714	1111	9.5
Soft wheat « Galibier »	511	750	29
Seeds grain maize	640	3740	1.5
Food soybean	804	909	28

– Main farm resources such as family labor and UAA (utilized agricultural area) and also the constraints faced by the farmer (biophysical, policy, technical and socio-economic constraints), summarized in Table 2.

3.3. Description of the bio-economic model for the cereal grower

The mathematical bio-economic farm model developed in this study is based on a non-linear optimization program. In this program, production and resource usage decisions are interdependent. It is a static annual model based on farm profits. Even though the model is static, the agricultural activities are specified according to crop successions in order to account for the effect of the previous crop on the yield of the current crop and inputs used (Belhouchette et al., 2012, 2011). The model takes temporal interactions into account, such as crop rotations, following the approach used by Janssen et al. (2010) and Komarek et al. (2017). Eq. (1) provides the objective function of the model:

$$U = \sum_{ij} p_{ij}\, q_{ij} + \sum_{ij} Area_{ij}\, f_{ij} + NPD - \sum_i c_i - \emptyset\delta \quad (1)$$

Where: i: index of agricultural activities, j: index of crop products (grain, straw, etc.), p: is a vector of average product prices, q: is a vector of sold production (the production is calculated here as a crop yield multiplied by the area of each crop), Area: is the surface for each contracted crop, f: is a vector of prices per area (and not per production such as for seed maize), NPD: represents EU farm subsidies, c: is a vector of variable cost per crop within an agricultural activity i.

The behaviour towards risk is modelled using the mean-standard deviation method in which the expected utility is defined as expected income and risk (Norton and Hazell, 1986). This approach has been used in recent similar studies (Chenoune et al., 2017; Komarek et al., 2017; Louhichi and Gomez y Paloma, 2014). The risk term in the model is then calculated as a product of the Arrow-Pratt relative risk aversion coefficient (∅) (considered as a constant in the model) and the standard deviation of farm income (δ) calculated by considering market price and yield variability in the past 4 years (Komarek et al., 2017).

Overall the model has three main subsections:

(i)- Utility maximization is considered by taking into account three resource constraints (as expressed by Eq. (2)):

$$\sum_i a_{i,n} X_i \leq b_n \quad (2)$$

Where:

$a_{i,n}$: are the required resources for each activity (i) and resource type (n) (land, labor, fertilizer, etc.). X_i: is the area kept for each activity and b_n: are the available resources at farm level.

(ii)- The required as well as the available labor are expressed per period of the year and per task. Three periods of critical labor requirement have been defined in consultation with agricultural advisors: from September to January corresponding with winter cereal sowing period (P1), from February to June corresponding with cereal herbicide spring spraying and spring crop sowing period (P2) and from July to August corresponding with cereal harvest period and spring crop irrigation (P3). For each crop, the main crop interventions as well as the machines used were specified and the required labor and costs were then estimated. The total labor requirement per period and the selected activities ought to be lower than the available family labor per period, as expressed in Eq. (3):

$$\sum_{i,pe} X_i RL_{i,pe} \leq AL_{pe} \quad (3)$$

Where:

X_i: is the simulated area for each activity (*i*), RL: the required labor for each activity (*i*) and period *pe* and *AL:* is the available labor for each period (*pe*).

(iii)-The area reserved for each contracted activity should not exceed the area specified in the contract, as expressed in Eq. (4):

$$\sum_{Ci} X_{Ci} \leq \sum_{crp} CA_{crp} \quad (4)$$

Where:

X_{Ci}: is the simulated area for each contracted activity (*i*) and CA_{crp}: is the maximum area for each contracted crop (*crp*) as specified in the contract.

3.4. Description of the scenarios

i- The main challenge

The core issue for the farmer selected for this study was the need to limit weed resistance to herbicides in order to retrieve the contracts he lost in 2014. In line with his previous experience, the farmer logically wishes to mostly keep growing winter cereals which are less demanding in terms of labor production and have a better economic perspective in comparison with other crops. However, the proposed solutions must allow him to retrieve his 2013 income without increasing the volume of labor which is mainly family-based.

ii- Identify technical levers which make it possible to deal with the “weed resistance to herbicides” issue

Weed control within the study zone has been obtained with increasing applications of herbicide doses to cope with the emergence of weed resistance accordingly (Heap, 2014). This strategy is obviously not sustainable as it increases the use of pesticides without any benefit and more often with a loss in crop yields. Several technical options leading to a change in the organization of production at farm level have been put forward to overcome this problem (Deike et al., 2008; Massa et al., 2013; Reganold et al., 2001). The discussion with the local agricultural advisors led to the identification of two technical levers to be tested with the model: extending current rotations with more spring crops in order to break the weed cycle and reintroducing deep tillage in order to destroy weeds seed banks and/or plantlets before the sowing of winter cereals. These two options are likely to require more work (due to tillage), although this is likely to be more spread out throughout the year with spring crops. On the other hand, it will leave more bare soils prone to erosion and nitrate leaching during winter than with winter crops only (Chikowo et al., 2009).

iii- Expression of technical levers in the scenarios

Three scenarios were identified (Table 3):

- The first scenario (Sc_baseline) shows the current “business as usual” situation for the farmer with the presence of weed resistance to herbicides and the loss of crop contracts as shown in Section 2.2.1.
- The (Sc_Rotation_soil_tillage) scenario aims to test the possibility and impacts of the modification of the cropping system induced by the two technical levers (introduction of spring crops and soil tillage) in order to suppress the herbicide resistant weed populations and avoid further replication of the phenomenon. Spring crops have two main advantages over weed resistance problems for herbicide control treatments. These crops can break the weed cycle by preparing their seed beds (Chauvel et al., 2001), and they mobilize other crop herbicide families than winter cereal/rapeseed herbicides (Zimdahl, 2013).

Table 3

The main resources, biophysical, policy and technical constraints-farm database.

Main resources	Biophysical constraints	Policy constraints	Technical constraints	Soci-economic constraints/incentives
-UAA[a] = 113.98 ha	Soil: Water storage capacity = 162 mm/m	Single farm payments (SFPs) (245 €/ha)	Crop rotations	-Contact for crops based on production (soft wheat “Galibier”)

-Limited access to water (2 irrigated crops)	Irrigation: Irrigated area = 29.5 ha		-Contract for crops based on area (seeds grain maize)
-Family labor (1H.W.U[b])		Irrigated crops: - FS (food soybean); - SGM (seeds grain maize);	Labor availability: 92 days per year
-Permanent labor (1H.W.U)		Soil tillage: SCT (shallow tillage)	

[a] Utilized agricultural area. [b] Human work unit.

The use of soil tillage practices instead of shallow tillage makes it possible to break the weed cycle by burying the weed seeds and preventing and/or reducing their ability to grow during the winter cereal/ rapeseed growing cycle (Nichols et al., 2015).

After a discussion with the advisor and the farmer, this was done by the addition of five alternative activities in the database. They introduced spring crops (e.g. soybean) or forage crops (e.g. alfalfa) in the current cereal/rapeseed rotation as well as deep tillage in winter crops (Table 4). Input quantities, production cost as well as the achievable yield for these 5 new activities were estimated based on the knowledge of the agricultural advisors (Supplementary material 2).

- The third scenario (Sc_ Rotation_soil_tillage_Contract) is identical to the second scenario (Sc_Rotation_soil_tillage) but it includes the possibility for the farmer to enter into contracts for crop products once again, as described in Section 2.2.1.

Table 4

Description of the selected scenarios.

Stages	Description
Stage 1: Define the farmer's challenge (issues, strategies)	- Limit weed resistance to herbicides. - Maintain the farmer income. - Maintain the current level of workforce used (family workorce).
Stage 2: Identify technical and socio-economic levers	- Keep the same levels of current herbicide treatments. - Introduce new activities based on extending current rotations with more spring crops. - Reintroducing deep tillage for winter cereals and rapeseed.
Stage 3: Translate technical and socio- Sc_Baseline economic levers into scenarios Sc_Rotation_soil_tillage	Business as usual - Introduction of five new activities with long rotations which are not currently applied (field scale): + rapeseed _soft wheat_soybeanbean_spring barley + rapeseed _soft wheat_grain maize_spring barley +Sunflower_soft wheat_sunflower_Soybeanbean_soft wheat +Winter peas_soft wheat_winter peas_soybeanbean_ soft wheat +Alfalfa_soft wheat_alfalfa_soybeanbean_soft wheat - Introduction of soil tillage at sowing. This concerns winter cereals and rapeseed.
Sc_Rotation_soil_tillage_contract	This scenario is identical to the scenario (Sc_Rotation_soil.tillage) + the assumption that the farmer could obtain again specific crop contracts due to the limitation of weeds resistance problem.
Stage 4: Simulate scenarios and generate performances indicators (farm scale) using the bio-economic model	**-Socio-economic indicators**: ***Annual farm income (euros/ha):*** This indicator makes it possible to judge whether the farmer's strategic decisions are profitable or not compared to the current situation. ***Total labor use (d/ha :*** This indicator shows the extent to which total family labor does not increase by introducing longer rotations and reincorporating deep tillage. **-Environmental indicators:** total cost of HTFI (euro/ha), quantity of nitrate used (kg/ha) and quantity of water consumed (m^3/ha). By combining chemical control with agronomic control, it is assumed that the current HTFI doses remain the same or even decrease. In addition, there is strong pressure on water and nitrogen in this zone and it is necessary to check to what extent the scenarios tested will modify these two indicators.
Stage 5: Discuss the model results with the actors	-Have a better understanding concerning the functioning of the current production systems with their limitations and strengths; -Select the best alternative production strategy in response to production challenges which the farmer must face; -Propose additional scenarios to be explored which emanate from discussing the results of the tested scenarios;

These two scenarios were compared with the current situation (Sc_baseline) by calculating 3 different types of indicators. These indicators were selected in consultation with the agricultural advisor and the selected farmer:

- Socio-economic indicators: annual farm income (euro/ha) and total labor used (d/ha) per period P1, P2 and P3 (see Section 3.3). The farmer would like the proposed solutions to maintain, as far as possible, the current level of workforce used. Despite being very limited, the analysis of the workforce per period aims to determine the periods which are likely to require the most significant increase in comparison to the current situation.
- Environmental indicators:

- Total cost of HTFI (euro/ha): the assumption here is that the more resistant weeds develop, the more the costs of HTFI as well as the

Table 5
Simulated socio-economic and environmental indicators at farm level.

Indicators		Sc_ Baseline	Sc_ Rotation_soil_tillage	% difference[a]	Sc_ Rotation_soil_tillage_contract	% difference[b]
Farm income (€/ha)		613	656	7	115	10
Total labor (d/ha)		66.8	78.7	15	70.9	−10
Labor per period[c] (d/ha)	P1	38.8	48.9	21	42.6	−13
	P2	17	17	0	16.21	−5
	P3	11	12.8	14	12.1	−5
HTFI cost (€/ha)		116	98.6	−15	115	17
Irrigation water use (m^3/ha)		24	30.7	22	29.5	−4
Nitrate use (kg/ha)		124	102.6	−17	116.8	12

[a] is the difference (in %) between the Sc_Rotation_soil_tillage and the Sc_Baseline scenarios. [b] is the difference (in %) between the Sc_Rotation_soil_tillage_contract and the Sc_Rotation_soil_tillage scenarios. [c] P1, P2 and P3 are respectively the periods from September to January, from February to June and from July to August.

environmental impacts of herbicides are important.

- Amount of nitrogen used (kg/ha): Being located in a nitrate vulnerable area, it is essential to analyse the effects of the scenarios tested for nitrate consumption on that farm beyond the HTFI.

- Amount of water used for irrigation (m^3/ha): being located in an area with limited access to water, the alternative activities should not contribute to the increase in the total irrigation water on that farm.

3.5. Simulating and reporting scenarios

The Sc_Rotation_soil_tillage which proposes longer rotations and a reversion to tillage for winter cereals (except rapeseed) has induced the following changes in comparison with the Sc_Baseline (Tables 5 and 6):

– An increase in the farmer's income (+7%) (Table 5). This result can be explained by a reduction in the area allocated to spring crops (−20%) at the expense of the more profitable winter crops (winter cereals + rapeseed: +20%) (Table 6). It can also be explained by the adoption of the longer rotation type rapeseed_winter cereals_spring crops_winter cereals (32 ha instead of 0 ha for the Sc_Baseline) associated with deep tillage which has allowed the farmer to reduce the occurrence of weed resistance to herbicide (in average +11% of yield increase for winter_cereal).
– An increase of 15% in the total workforce due to a rise in workforcerequirements during period P1 (from September to January: + 21%) and period P3 (from July to August: +14%) (Table 5). This result can be explained by three simultaneous effects: (i) for periods P1 and P3: by the increase in the area allocated to winter crops in comparison with spring crops. P1 and P3 represent the two periods of sowing and harvesting for winter crops, (ii) by the disappearance of the area allocated to grassland which required very little

Table 6
Cropping pattern for the selected scenarios.

Crops	Area per crop (ha)		
	Sc_Baseline	Sc_Rotation_soil_tillage	Sc_Rotation_soil_tillage_contract
Durum wheat	8.5	14.9	0
Seeds durum wheat	0	0	9.93
Soft wheat	42.17	16.5	12.29
Soft wheat « Galibier »	0	0	28.67
Seeds grain maize	0	0	1.5
Winter Barley	0	0	17.5
Rapeseed	0	32.3	0
Soybean	24	30.7	0
Food soybean	0	0	28
Sunflower	35.1	15.3	16.09
Grassland	4.3	0	0
Sorghum	4.58	4.6	0
Total farm area (ha)	113.97	113.99	113.98

workforce, and by (iii) the reversion to deep tillage for part of the winter crops grown under long rotations.
– An increase in the amount of water used for irrigation (+22%)(Table 5). This can be explained by the increased soybean production, from 24 ha in the Sc_baseline to 30.7 ha in the Sc_Rotation_soil_tillage.
– A reduction in the costs of HTFI (−15%) (Table 5). This result is mainly due to the substitution of winter cereals (durum wheat and soft wheat) mostly grown under biennial rotation with rapeseed grown over a longer rotation and whose HTFI per hectare are lower; i.e. 160, 130 and 115 euros/ha for the monetary value of HTFI for durum wheat, soft wheat and rapeseed respectively.
– A reduction in the amount on N used (−17%) as a consequence oftwo changes (Table 5): (i) the substitution of soft wheat which is more N-demanding (170 kg/ha) for rapeseed (148 kg/ha), and (ii) the choice of rotation for which the rapeseed_soft wheat_soybean_spring barley_winter barley only requires 125 kg/ha/year on average in comparison with the 145 kg/ha/year required by the rapeseed_soft wheat_spring barley_winter barley_barley_durum wheat rotation (data not shown).

By allowing the farmer to establish specific contracts for certain crops (Sc_Rotation_soil_tillage_contract), the average income increased by 10% in comparison with Sc_rotation_soil_tillage following the 60% increase in contract crops of total farm area (Table 6).

Nevertheless, the total workforce has dropped by 10%. This drop concerns the three periods P1 (−13%), P2 (−5%) and P3 (−5%). This decrease in workforce is notably the result of the simplification of crops and rotations practiced in comparison with the Sc_Rotation_soil_tillage scenario and of the disappearance of tillage at the expense of shallow tillage. 60% of the farm area is covered by winter cereals (durum wheat grain, soft wheat "Galibier", etc.) and 40% by spring crops. The rotations mainly consist in winter cereals_spring crops (84%) and winter cereals_winter cereals (19%) (Supplementary material 3).

The average cost of HTFI and the average quantity of nitrate per hectare have risen by 17 and 12% respectively in comparison with the Sc_Rotation_soil_tillage following the increase of cereal winter crops, i.e. seed durum wheat (+10 ha), soft wheat "Galibier" (+29 ha) and winter barley (+17 ha) (Table 6).

3.6. Discussion results with the farmer and the agricultural advisor

A meeting involving the concerned farmer with 2 agricultural advisors was organized in order to report the main simulation results as presented in Section 3.5. Two main reactions from the agricultural advisors are to be observed and could be classified as:

- Unexpected results: for the agricultural advisors the adoption ofcontractual crops is only seen now, as an opportunity for farmers to guarantee a minimum income, never as a threat to the simplification of rotations. This will really raise the question of how far farmers would be advised to contract without affecting the need for diversified rotations to prevent the resistance problem. Similarly, the adoption of irrigation is only perceived by these advisors as sources of increasing production by reducing the risk of water stress. Mobilizing water as an argument for diversifying crops and reducing the risk of the appearance of resistance seems to them to be rather buoyant with public authorities to promote irrigation in the area.
- Expected results: this work has reinforced their expectation of therole played by agronomic levers (ploughing, longer rotation, etc.) to reduce the effect of resistance. The added value of this work was for them to understand the possible constraints on the adoption of these levers (in particular in relation to available workforce).

Overall, three main strategic conclusions were highlighted, to be potentially explored:

1- The necessity for the farmer to practice longer rotations and, every 3–4 years, a soil tillage instead of permanent shallow tillage for winter cereal/rapeseed crops.
2- To explore with other farmers, and with the support of the cooperative represented by the 2 agricultural advisors, the possibility of sharing workers mainly during periods P1 (from September to January) and P3 (from July to August). The practice of long rotations and soil tillage implied, as shown in Section 3.5, an increase in total labor demand mainly in P1 and P3.
3- To explore other scenarios mainly by including additional investment to increase the use of irrigation for profitable spring crops. Access to irrigation by cereal-based farms is very limited today even if shallow water is available in the studied area. Increasing spring crop area is seen by the farmer and the agricultural advisors as a potential solution to contract less winter crops and to practice longer rotations by including legume crops and to then reduce the presence of resistant weeds.

4. General discussion

4.1. Discussion of the results

In this study a bio-economic farm model-based on a regional/farmer database, scenarios of alternative agricultural practices and performance indicators was developed in order to simulate the impacts of strategic decisions of farmers when faced with a problem of weed resistance to phytosanitary treatments.

This bioeconomic model is meant to help agricultural advisors as a decision support tool to advise farmers on the different types of strategic decisions (irrigation, fertilization, etc.).

This analysis reveals that strategically, in accordance with the bibliography (Davis et al., 2012; Lechenet et al., 2016) in order to deal with resistance problems, a reversion to longer rotations and tillage (Sc_Rotation_soil_tillage) could not only contribute to the improvement of the farm income but also to a drop in the quantity (costs) of inputs. Nevertheless, these practices generate an increase in workforce and irrigation. These two indicators are of crucial importance for the decision-making of the farmer. Work is very restrictive in the French context despite high mechanization (Nichols et al., 2015) and water access is often limited with sometimes significant restrictions during base-flow periods (Terresinovia, 2005).

This analysis also reveals that the introduction of specific contracts for certain crops (Sc_Rotation_soil_tillage) has strategically entailed the simplification of rotations for a maximum income. This is the strategy which is currently being adopted by most farmers in the study zone (Meynard et al., 2013). As shown in our study, this strategy involves less total workforce (following the simplification of rotations) but in the long term it can cause more environmental impacts (more nitrates and HTFI) but also the reappearance of the problem of weed resistance to phytosanitary treatments.

4.2. DST: Flexibility and re-usability by agricultural advisors

Most DST based on linear programming in the literature focus on the *ex-ante* assessment of agricultural policy with little attention to agriculture production at farm level with a specific context of land management practices (Ewert et al., 2009; Janssen et al., 2010). It was possible to fill this gap by adopting the Agricultural Activity concept, involving both farmers and agricultural advisors at different stages of the assessment, and using a modelling chain.

From our point of view, the re-usability of the DST developed for cereal farms will mainly depend on the nature of the tested scenarios:

- Scenarios that involve only parameter changes such as fluctuation in price, modification of labor availability, etc. In this case, the agricultural advisor could use the DST itself. We believe that the learning process is not difficult. A one-day training course to present the model, its database, and how to display the results might be enough for such scenarios. In this case, we believe that the advisor would only need to understand the assumptions and simplifications behind the model formalisms (without going into the mathematical equation program).

Nevertheless, it seems important to provide agricultural advisors with a guide to interpreting simulated indicators. As suggested by Mahmood et al. (2017), indicators could be classified into expected or unexpected results. For example, it is expected that by retrieving the contracts the income per farm will fall and the cost of the HTFI will increase.

- Scenarios that lead to partial or total changes in the database or model, such as: expressing crop water requirements on a monthly basis instead of annual or adding new alternative activities. This kind of modification will require the intervention of a modeller. The time needed to adapt the model as well as the database will depend on data availability.

4.3. Is this type of tool really suitable for agricultural advice?

The participation of agricultural advisors in the elaboration of the database as well as the scenarios will undoubtedly help understand what is really expected from the model and its logical framework. This conclusion has also been confirmed by Delmotte et al. (2016), who suggest the early implication of stakeholders (advisors, farmers) in the process of designing strategic options but also in the development of the optimization model. Moreover, the time required to interact with farmers to build data and scenarios is not-longer than that of other participatory methods which are much more commonly used today. However, we believe that it is not necessary for the advisor to master the codes of this model. It can remain a simple usage provided it is supported by a modeller.
Overall, we suggest that this type of tool should not be used directly as a decision support tool. It must be part of an approach to support strategic thinking by providing simulated options to explore the socioeconomic and environmental impact of agro-ecological production strategies in the face of a changing context (Delmotte et al., 2016; Komarek et al., 2018). These simulation results should help the farmer and his advisor discuss and choose the best possible solutions, by taking into account other “soft” constraints not considered in the model.

5. Conclusion

This study simulated the effects of two scenarios in comparison with the baseline situation on the cereal farm indicators of socio-economic and environmental performances. Our results showed that the introduction of long rotation and tillage increased the profitability of the farm and decreased the amount of pesticide and nitrogen used. However, this solution increased the use of irrigation water and total farm labor. Establishing contracts for specific crops made farm production more profitable but also more specialized in cereal production with the dominance of biennial rotations. This situation can lead to the development of weed resistance to herbicide treatment.
Both results constitute a good basis for agricultural advisors to discuss, in conjunction with farmers, production strategies that could be followed to reduce the risk regarding the problem of weed resistance to herbicide treatments. This strategy should be addressed by considering a trade-off analysis of socio-economic and environmental indicators.
Exploring strategic options to improve the profitability of the cereal farm in an unstable socio-economic context without affecting natural resources is another avenue to explore with further research that the DST can be applied towards. As was the case in this study, the structural nature of the DST can help point out potential constraints that limit strategic options.

The full information of this paper is:

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Abstract: In an uncertain socio-economic and climatic context, sustainable farming is a major challenge for farmers as well as for their agricultural advisors. It is therefore essential to develop a decision support tool (DST) that is likely to be useful to establish and evaluate new production strategies, in accordance with farm sustainability and environmental protection. This paper aims, by using the Agricultural Activity concept, to put forward and test a DST based on mathematical programming used to evaluate strategic production decisions, in conjunction with farmers and agricultural advisors. In the test case, the decisions concern the crop activities and their spatio-temporal combinations in order to reduce both the use of herbicides and the risk of weed resistance to herbicides in cereal-based production systems. Moreover, the DST considers the availability of the workforce during the crop cycle to determine the periods which are likely to require the most significant increase in comparison to the current situation. One scenario showing the current situation (Sc_baseline) and two alternative scenarios have been defined to address the weed-herbicide issue. The comparison of the scenario promoting soil tillage and the introduction of spring crops with Sc_Baseline has shown that the adoption of long-term rotations, the increase in winter crop frequency and the return to deep soil tillage have contributed to an increase in farmer income, total labor and water consumption by 7, 21 and 22% respectively. However, the intensity of pesticide use and nitrate fertilization have dropped by 15% and 17% respectively. By allowing the farmer to establish specific contracts for certain crops, the average income as well as the use of pesticide and nitrate fertilization were increased by at least 10%. This situation is the result of a simplification of rotations with a predominance of winter cereals and the elimination of deep soil tillage. The analysis of these scenarios shows that the use of the DST has made it possible not only to put forward and evaluate alternatives that result in strategic decisions but also to understand, with the concept of Agricultural Activity, the biophysical and technical processes relating to farmer decisions and their impacts at field and farm level. Understanding and sharing this functional chain at farm level is expected to strengthen the farmer-advisor relationship in order to address the complex challenges of farming system sustainability.

Keywords: Strategic decisions; Weed resistance; DST; Mathematical programming; Activity concept