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A farm-level ecological-economic approach of the inclusion of pollination services in arable crop farms.

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Abstract

Modern agricultural systems use both managed and wild bees in order to secure the provision of pollination services. However, the decline of both bee species due to the increased use of pesticides raises concerns for the supply of pollination services in agriculture. Because European policies seem ineffective in safeguarding bees as they fail to address farmers' socio-economic issues, farmers' adoption rate of friendlier practices by pollinators remains limited.

This study uses a farm-level ecological-economic model to explore the potential impacts of changing policy intervention on the provision of pollination services and on farmers' incomes in two characteristic farms in Southwestern France. Moreover, it integrates the economic importance of behavioral interactions between managed and wild bees on crop production. The model assesses farmers' adoption decisions about alternative practices under risk aversion through an optimization choice among several crops, practices (novel/conventional), variable inputs, and pollination activity. The results show that a knowledge of bees' complementarity may facilitate farmers' adoption decisions. Furthermore, they highlight that different levels of Agri-Environmental Schemes and penalties can be efficiently targeted to encourage the implementation of new farming practices in order to preserve pollination services and maintain economically viable farms.

Key words: Pollination services, Ecological-economic model, Whole farm model, Policy scenarios, Agri-environmental policy, Farmers' adoption decisions

1. Introduction

Insect pollination provides ecosystem services to agriculture by contributing an estimated US$127 to US$152 billion to global economic welfare (Bauer and Wing, 2016). Pollination services are mostly provided by managed and wild bees (Kleijn et al., 2015). Those from wild bees are provided freely by nature while those from managed bees either come for free by local beekeepers as positive externalities (Carreck et al., 1997), or more recently, are rented or bought by farmers (Allsopp et al., 2008; Breeze et al., 2017). Pollination services can increase the quality and quantity of output in many major crops, including widely grown oilseeds, which are important as an input in food (e.g., confection markets, cooking oils) and fuel industries (biodiesels) all over Europe (Guindé et al., 2008; Iliopoulos and Rozakis, 2010).

Despite the importance of bees in agricultural production, a substantial decline of bee pollinators has been observed across Europe (Potts et al., 2010a; Goulson et al., 2015; Woodcock et al., 2016). This decline was due to several motives and phenomena such as existing farm practices, particularly the increase in pesticide use (Goulson et al., 2015). Hence, production decisions have serious negative effects on bee pollinators. Moreover, farmers face a dilemma in their decision problems as one input (pesticides) is dangerous for another (pollination services). This phenomenon may be further aggravated as the intensive use of pesticides may cause the collapse of bee pollinators and have serious ecological and economic consequences on human welfare.

In this context, the European authorities have mobilized a series of policy measures through the Common Agricultural Policy (CAP) to safeguard the conservation of wild bees and consequently, the provision of pollination services (Batáry et al., 2015). However, recent studies have pointed out that these policy measures seem to be inefficient in guaranteeing the conservation of a strong and diverse number of wild bees, as they mostly focus on the provision of bee species that are already well-established (Senapathi et al., 2015; Wood et al., 2015). Therefore, there is a clear need to further ameliorate the effectiveness of the proposed measures to safeguard the provision of pollination services.

This research develops an ecological-economic model to explore the potential impacts of changing policy intervention on the provision of pollination services and on farmers' incomes. Moreover, it uses a mathematical programming (MP) setting to integrate the economic benefit of behavioral interactions among different bee species in farmers' decision problems that have, to the best of our knowledge, not yet been addressed in the literature. Despite growing ecological literature on the importance of these interactions having serious negative effects on crop production (Greenleaf and Kremen, 2006; Brittain et al., 2013), existing economic studies treat managed bees as a perfect substitute for wild ones (Rucker et al., 2012; Kleczkowski et al., 2017).

We used MP methods (Hazell and Norton, 1986) to elaborate on the above integrated ecological-economic model. The use of such model is essential in addressing the problem of biodiversity conservation alongside issues of economic viability between farmers (Wätzold et al., 2006). Similar approaches have been applied to numerous economic studies at the farm-level by embracing mixed ecological-economic analyses (Mosnier et al., 2009; Ridier et al., 2013). Thus, our model is not largely differentiated from previous modeling attempts, but its characteristics make it original.

The model is numerically developed into two characteristic farms in the Occitanie region in Southwest France. A market for managed pollination services has been established in this region with more than 700 beehives per municipality available for local farmers to rent annually for pollination services (*Direction Régionale de l'Alimentation, de l'Agriculture et de la Forêt*

[DRAAF-Occitanie] – Telerucher[1]). This practice has significantly increased farmers' production costs as the rental price per beehive varies between €35 and €75 (Chabert et al., 2015). Therefore, having in mind that similar markets already exist in other French regions (Chabert et al., 2015), it is of great scientific interest to explore the potential impacts of policy changes on the provision of pollination services and on farmers' incomes.

The first section of the paper recalls the main evidence of the literature to introduce the importance of pollination services on farmers' decision problems, as well as the role of public policy towards their provision. Moreover, it introduces the economic importance of bees' complementarity for crop production and examines its role on farmers' adoption decisions. The second section provides a step-by-step analysis of the methodology on the farm-level ecological-economic model. After presenting the obtained results in the third section, the fourth discusses the main findings. The final section draws the conclusions and summarizes the limitations of the model.

2. Farmers' decision problems and the role of public policy

Modern agricultural systems pose numerous threats to the welfare of bee pollinators, such as the degradation of natural habitats and chronic exposure to agrochemicals and novel parasites (Goulson et al., 2015). The use of pesticides has been proven to be one of the main drivers of the decline of bees (Goulson, 2013; Woodcock et al., 2017). Its continuous use by farmers has driven wild bees into extinction in many European landscapes. Hence, an increasing number of European agricultural systems depend more on the purchase or rental of managed bees to ensure the provision of pollination services (Allsopp et al., 2008; Breeze et al., 2017). In fact, a pollination services market has emerged in France in the last decade, where farmers buy or rent

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[1] http://www.drome.gouv.fr/declaration-des-ruchers-a3249.html

hives from beekeepers to sustain sufficient pollination services in their fields (Chabert et al., 2015). Consequently, using managed bees as a substitute for the services of wild bees has increased the production costs of farmers (Allsopp et al., 2008; Winfree et al., 2011). These costs may further rise in the future as managed bees also suffer heavy losses (Potts et al., 2010a), while the production of insect pollinator-dependent crops increases (Aizen and Harder, 2009). In fact, recent studies have already reported differences in the supply of managed bees relative to the demands of pollination services across Europe (Breeze et al., 2014a). Almost all European countries have insufficient managed bee colonies to supply their needs in pollination services (Breeze et al., 2014a). Hence, similar markets may emerge in other countries, like what has happened in the United States (Rucker et al., 2012) and France (Chabert et al., 2015).

Apart from biodiversity losses, this progressive substitution of wild bees with managed bees that are more costly may also be ineffective for many crops, where the latter are not perfect substitutes for the former (Garibaldi et al., 2013). Many recent ecological and entomological studies have pointed out that the presence of both bee species on the field is necessary in order to secure a sufficient level of pollination services and optimize crop production (Greenleaf and Kremen, 2006; Brittain et al., 2013). Indeed, the behavioral interactions between managed and wild bees, called bees' complementarity, increase their pollination efficiency (i.e., seed resulting from a single pollinators' visit), which optimizes yield quantity and quality (Bartomeus et al., 2014). Therefore, the provision of both bee species is in the economic interest of farmers as it is important for optimizing production. Considering this information in the development of public policy measures may resolve farmers' decision problems as they face the trade-off between pesticide use to reduce crop damages, and its negative effect on bee pollinators.

In general, the awareness of the decline of bees and its negative effect on human food supply (Holden et al., 2006) mobilized a series of policy measures in Europe and France towards their provisions. Since 2013, the European Union has implemented a total ban regulation (EU No 485/2013) on three neonicotinoids related to the decline of bees. Moreover, many Agri-Environmental Schemes (AES) encourage the adoption of friendlier practices towards the provision of pollination services (Batáry et al., 2015).

However, recent studies have indicated that these policy measures seem to be inefficient in guaranteeing the conservation of a strong and diverse number of wild bees. In fact, the study of Hesselbach and Scheiner (2019) revealed that the implementation of the Neonicotinoids regulation forced farmers to search for alternative chemical compounds, which may be equally lethal for bees, rather than adopting the practices of pollinators. In addition, there is a debate concerning the effectiveness of AESs towards the conservation of bee pollinators (Kleijn and Sutherland, 2003; Whittingham, 2011). For instance, the study of Senapathi et al. (2015) suggested that AESs may be beneficial for well-established common species (bumblebees and honey bees), but not for a wider pollinator diversity. Similarly, the study of Wood et al. (2015) concluded that current AESs are focusing on the preservation of pollinators, such as bumblebees and honeybees, which have an economic importance on production. As a result, this trend may lead to the extinction of a vast number of species with low or no economic value, which are essential for the ecosystem. Such an extinction will disrupt the ecosystem's resilience and damage the function of the economically important pollinators (Wood et al., 2015).

Regarding France, the majority of AESs includes wild bees in broader biodiversity schemes or focuses on the installation of managed bees in less intensified agricultural systems (Underwood et al., 2017; Decourtye, 2018). These schemes propose the creation of pollination zones within agricultural systems through the installation of beehives. However, they do not include any specific action for the provision of wild bees, such as the preservation of specific natural habitats. Hence, the installation of numerous managed bees without the protection of wild bees may lead to the displacement, and consequently, the extinction of native bees (Thomson, 2006). Moreover, the great majority of French AESs suffers from the low participation of farmers as the proposed measures failed to address their socio-economic issues. Consequently, the adoption rate of friendlier practices from pollinators remained limited (Gaujour et al., 2012; Del Corso et al., 2017).

Apart from the AESs, the French government launched the National Action Plan “Ecophyto”[2] in 2008 through the Sustainable Use of Pesticides Directive (2009/128/EC[3]). This plan aims to reduce the overall use of pesticides in French arable farms by 50% until 2025. In addition, Ecophyto has acknowledged the importance of bee pollinators on crop production and proposed several actions towards their provision since 2018 (Allier et al., 2019). However, despite its promising nature, the first phase of Ecophyto (2008-2018) failed to convince farmers to adopt practices with low-pesticide use. Consequently, a significant number of farmers did not internalize the need for pesticide reduction. This resulted to an increased use of pesticides in arable crop farms in the last decade (Guichard et al., 2017). Therefore, there is a clear need to further ameliorate the effectiveness of all the aforementioned measures towards both the effectiveness of the proposed practices and the number of participants.

In general, the adoption of alternative practices by farmers demands an evaluation of their cost-effectiveness (Sunding and Zilberman, 2001). This means that potential financial gains or the

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[2] http://agriculture.gouv.fr/ecophyto

[3] https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:309:0071:0086:en:PDF

additional production costs of alternative practices should be included as determinants of the farmers' adoption process (Jaffe et al., 2003; Knowler and Bradshaw, 2007). Labor reallocations are also considered another determinant of farmers' adaptation mechanisms. Those with limited labor resources usually prefer not to adopt alternative practices as they tend to deploy their labor forces to standard tasks rather than the management of alternative practices, which may be more technically demanding or labor-intensive (Fuglie and Kascak, 2001; Ridier et al., 2013). Crop rotation is another determinant (Rodriguez et al., 2009). Farmers typically prefer to allocate their land to the most profitable crops (only in terms of price as they do not examine the profit margin) in crop rotation systems. However, alternative practices may propose, for example, higher land allocations of fallows in order to improve soil quality (Nel and Loubser, 2004). Thus, the adoption of alternative management practices is perceived as an increasing risk by farmers (Lien and Hardaker, 2001).

This study aims to explore the potential impacts of changing policy intervention on the provision of pollination services and on farmers' incomes. We assess if the economic benefit of bees' complementarity may facilitate farmers' adoption decisions towards pollinators' friendlier practices, under risk aversion. If we consider that new agricultural practices may be riskier, their adoption can be facilitated due to the bees' complementarity. In this enlarged analytical context, we consider different crop rotation possibilities and the economic impact of labor reallocations that are generally needed for the adoption of these practices. We create a series of hypothetical policy programs to promote various "novel" practices through financial incentives/penalties. These novel practices involve adopting insect pollinator-dependent crops under lower or no pesticide treatment substituting appropriate operations (i.e., field preparation, tillage and monitoring) for pesticides. In order to integrate the economic importance of bees' complementarity, we assume that farmers participating in these novel programs can benefit from the enhanced yield that emerges from interactions between the two bee species and consequently, decrease their input costs.

To elaborate on the above integrated ecological-economic model, we adopt the farm-based modeling approach of Ridier et al. (2013). The objective of this study was to analyze the role of risk attitude and labor constraints on farmers' decisions for the adoption of alternative practices (among them pesticides use reduction). The selection of this model as a base for our modeling attempt was based on several reasons. Firstly, the model examined similar agricultural systems in the same study area. Secondly, it examined farmers' adoption decisions towards rather similar policy measures (low pesticide use practices). Thirdly, it focused on assessing the role of labor constraints on the adoption of alternative practices. Lastly, this model seems suitable for our analysis since the adoption of environmental measures are rather limited in the Southwest of France, mostly due to labor constraints, (Mosnier et al., 2009; Ridier et al., 2001).

However, this study did not take into account the importance of pollination services nor the presence of a market of pollination services in the region. The installation of such a market in combination with the scarce number of wild bees in European landscapes demands a re-orientation of public policy measures. Therefore, it is important to update the model in order to better represent reality and assess the farmers' adoption decisions in the context of a deficit in pollination services. Therefore, we transformed the model of Ridier et al. (2013) by integrating the use of two bee species and the economic importance of bees' complementarity on production. Moreover, we introduce an ecological function in order to integrate the conflict between pesticide use and pollination services. Consequently, our model estimates farmer's production decisions under risk through an optimization choice among several crops, practices (novel and conventional), variable inputs (pesticides, managed bees, and labor), and pollination activity.

3. Methods

In this section we present: i) the MP model and its constrains; ii) construction of farm-types; and iii) proposed policy scenarios.

3.1 Structure of the MP Model

The optimization model maximizes the expected net income over one growing season for two characteristic farms located in the Occitanie region of France. In general, because pesticides have been considered an important component in reducing risks of yield loss, many risk-averse farmers are usually using them as insurance (Mumford and Norton, 1984; Lefebvre et al., 2015). In order to consider farmers' risk attitude towards the proposed practices, we modeled yield risk due to changes in climate conditions and pollination levels. To combine the events coming from a specific climatic condition and the levels of pollination services, we used the study of Tuell and Isaacs (2010). This study examines the weather effects on yield outcomes of blueberries due to changes in pollination activity. According to the findings, good or bad weather conditions affect the efficiency of pollinators (higher rate of wild bee visits). Consequently, they increase crop's yield quantity and quality, and decreases its yield variability. More specifically, the results showed that in terms of weather conditions, the yield outcomes of blueberries may increase up to fourfold during good seasons due to higher pollination activity. Despite the fact that this study focuses on blueberries, the authors insist that their findings could be generalized for the majority of insect pollinator-dependent crops. Therefore, by adopting the conclusion of this study regarding the relationship between good weather conditions and higher pollination activity, we assumed that observed yields during good seasons were partially due to higher pollination activity

We suppose that yield risk per crop is normally distributed and prices also follow the normal distribution with parameters estimated by the time series of 2008 to 2018.[4] In economic analysis, decision-making under uncertainty is often modeled following the expected utility hypothesis (Lien and Hardaker, 2001). Thus, the expected utility of farmers' net incomes is the arithmetic mean of utilities from the revenues for various states of nature following a probability distribution.

There is evidence that farmers are risk-averse[5], a behavior that may either remain unchanged for local income changes or attenuated for significant increases in income value (constant or decreasing risk aversion respectively). One way to express this behavior is through an E-V context, which translates to preferences for higher expected income and lower variances of this income. A farm production plan is a portfolio of cropping enterprises; its efficient diversification requires knowledge of covariance among the enterprises. In the presence of numerous activities, the variance-covariance matrix V is derived from the variability of individual activity returns related to one another.

A specification of the E-V rule mentioned by Hazell and Norton (1986) refers to the mean-standard deviation model. The standard deviation is the root of variance, thus the (E, σ) model results in an efficient set of cropping plans that should be identical to the one derived by the E-V model. The function $E(I) - \varphi\sigma$, where φ represents the risk aversion coefficient, has the

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[4] While we ignore market risks here, we take into account estimations of the unpredictable variations in crops' prices by including the price variability parameter (p) of each crop calculated in a 10-year period.

[5] Risk aversion in farmers is persistently reported in the agricultural economics literature. Recently Bougherara et al. (2017), elicit agriculture preference parameters in intensive farming in North-Eastern France using state-of-the-art methodology. They observe risk aversion that can vary depending on internal and external factors, for instance more educated farmers that are active in cooperative context manifest less risk aversion.

advantage of being expressed in the same monetary units as the income itself since it contains the standard deviation, not the variance of income. This facilitates the interpretation of results in case of maximization under constraints in mathematical programming formulated problems. Moreover, according to the interpretation of Baumol (1963), for each value of φ $E(I) - \varphi\sigma$ identifies a particular fractile of the farm plan income distribution, assuming that income is normally distributed. For instance, for φ equal to 1.5, the $E(I) - 1.5\,\sigma$ identifies the 6.7% income fractile. This value can be interpreted as follows: The decision maker with this objective function is likely to adopt such a plan exceeding this income 93.3% of the time. Lower φ values, like those equal to 1, would be translated to an aspiration of income exceeding that value with a probability of 84%. This means less risk aversion. The value of φ is estimated in the literature from a direct elicitation of the farmers' preferences. Others imputed its value by solving farm models so they reproduce observed crop mix results. In other words, farmers' risk preferences are assessed using a revealed preference approach (Chavas and Holt, 1996).

In order to estimate the risk aversion coefficient for our case study, we tested different possible values of φ distributed on an interval of {0.5, 1.5}, as most values reported in the literature vary within this interval (Hazell and Norton, 1986, p. 93). As a result, the elicited coefficient minimizes the sum of the absolute deviations between the observed and predicted land allocations. To validate our model, we used the Percentage of Absolute Deviation (PAD; Ridier et al., 2013) as an indicator. The PAD takes the following form and evaluates the representativeness of our model by calculating crop-pattern variability:

$$PAD = \frac{\sum_{crop=1}^{n} |\bar{X}_{crop} - X_{crop}|}{\sum_{crop=1}^{n} \bar{X}_{crop}}$$

where, index $crop$ is the proposed crops for selection, $\bar{X}_{crop}$ is the value observed, and X_{crop} is the value simulated.

Finally, from the methodology, we retained a value of φ equal to 1 for the two examined farms. According to the study of Hardaker et al. (2004), this value corresponds to a moderate risk aversion attitude among values empirically elicited that vary from 0.5 to 1.5.

The farmer's net income was calculated by adding the revenues from the crop production under novel and conventional practices, and the first pillar CAP subsidies minus the production costs. Moreover, according to the implemented scenario, subsidies or penalties were added or subtracted from the revenues accordingly.

$$R \;=\; \sum\nolimits_{crop}[x_c(\tilde{y}_c\tilde{p}_c - \; w_c - penalty) + \; x_n(\tilde{y}_n\widetilde{p_n} - \; w_n + AES)] - wages \cdot \text{workers}_{\text{hours}} + \bar{S}CAP, \qquad (1)$$

In this formula, the indices c and n represent conventional and novel practices, respectively (Ridier et al., 2013). Variables include crop areas cultivated under conventional practices, x_c, crop areas cultivated under novel practices, x_n, and hired labor time $\text{workers}_{\text{hours}}$. The parameters are specified as follows:

- $\tilde{p}_{c\ or\ n}$ is the vector of market price of crops;
- $\tilde{y}_{c\ or\ n}$ is the stochastic yield per crop;
- w is the variable cost per hectare of crop;
- x is a vector representing the area in hectares per crop;
- CAP is a scalar representing the CAP's 1st pillar subsidies per hectare in euros. It is attributed to the whole farming area $\bar{S}$;

- *AES* is the subsidy in euros attributed to each hectaure using novel practices. These subsidies are part of the Agri-Environmental Policy in the European Union; while *penalty* is the charges in euro attributed to each hectares using conventional practices;

Yield variability, that is, yield standard deviation, is the main source of risk in the model. It is assumed to be lower in pollinator-dependent crops under novel practices, than non-pollinator-dependent crops under conventional practices.[6] This is because the enhanced production arising from interactions between managed and wild bees will partially compensate for yield losses due to low pesticide use (Greenleaf and Kremen, 2006; Garibaldi et al., 2011; Bartomeus et al., 2014).

Furthermore, the new farming practices examined in this study assume lower pesticide use than conventional practices, implying better pollination levels and lower yield variability for pollinator-dependent crops (Garibaldi et al., 2011; Bartomeus et al., 2014). Finally, to obtain the optimal solution for the MP model, CONOPT and SBB solvers were used.

3.2 Constraints of the MP model

The main constraints of the model are related to agronomic, environmental, and economic resources, and linked to the existing public policy:

Land constraint:

This refers to the available farmland of each farm-type. Each farm-type has a different composition of soil types (muddy-clay and sandy-clay soils; *Chambre Régionale d'Agriculture*

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[6] Supplementary material, Table S1

Occitanie [CRAMP][7]). Hence, the total cultivated land must not exceed the total available farmland for every soil type.

$$\sum_{crop,soil} X_{crop,soil} \leq LAND_{soil} \tag{2}$$

where, $\sum_{crop,soil} X_{crop,soil}$ is the total cultivated area under the selected crops for every soil type; $soil$ is the variable for the two soil-types; and $LAND_{soil}$ is the total available farmland for every soil type.

<u>Irrigation constraint:</u>

For each farm and soil-type, the share of irrigated land is limited. Hence, the sum of the cultivated hectares devoted to irrigated crops must not exceed the irrigated land of every soil-type.

$$\sum_{crop,soil} X_{crop,soil} \leq IR_{soil} \times LAND_{soil} \tag{3}$$

where, IR_{soil} is the percentage of the irrigated farmland per soil-type.

<u>Crop rotation constraint:</u>

A crop rotation constraint was set according to which crop's maximum cultivated area on each soil-type was limited by the total area covered with its allowed precedents in this soil-type (Table S2 and S3). The different precedents for each crop and soil-type were calculated according to the study of Viaux (1999).

$$\sum_{crop.soil} X_{crop,soil} \leq \sum_{previous-crop,soil} X_{previous-crop,soil} \tag{4}$$

where, $\sum_{previous-crop,soil} X_{previous-crop,soil}$ is the total cultivated surface of the precedent crop in each soil-type.

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[7] http://www.chambres-agriculture.fr

Labor constraint:

Labor resource on farms is composed of family workers and additional seasonal workers, which increase the cost of labor. Thus,

$$\sum_{crop,hours} Labor_{crop,hours} \leq family\_available_{hours} + workers_{hours} \tag{5}$$

where, $\sum_{crop,hours} Labor_{crop,hours}$ is the total working hours spent for the cultivation of selected crops; $family\_available_{hours}$ is the total available family working hours per farm-type; and $workers_{hours}$ is the total working hours of seasonal workers.

CAP cross-compliance constraints:

In order for the farmer to receive the entire amount of Basic and Greening payments, he/she has to attain the following requirements according to the European Parliament (2015):

First, the farmer must maintain a permanent grassland with a total surface that should not decrease more than 5%. As a result, the constraint takes the following form:

$$\sum_{crop} X_{"grass"} \geq 0.95 \times \sum_{crop^0} X_{"grass^0"} \tag{6}$$

where, $\sum_{crop} X_{"Fallow"}$ is the total surface of permanent grassland and $\sum_{crop^0} X_{"grass^0"}$ is the total surface of permanent grassland observed in the reference year.

Second, farms with more than 10 hectares of farmland must cultivate at least two crops, while those with arable land exceeding 30 hectares must cultivate at least three. We mathematically expressed the constraints as they were presented in the articles of Cortignani and Dono (2015) and Cortignani et al. (2017). We first identified the main crops in the production systems of our case study.[8] We then introduced two constraints for diversification. The first refers to farms with more than 10 hectares, where each crop must not exceed 75% of the total cultivated land. The constraint takes the following form:

$$\sum_{crop} X_{"main"} \leq 0.75 \times LANDV \tag{7}$$

where, $\sum_{crop} X_{"main"}$ is the total surface of the main crop, and $LANDV$ is the total available farmland including both soil types.

The second constraint refers to farms with more than 30 hectares, which requires the presence of at least three crops, with the surface covered by the two main crops not exceeding 95% of the total cultivated area. The constraint takes the following form:

$$\sum_{crop} X_{"main1"} + \sum_{crop} X_{"main2"} \leq 0.95 \times LANDV \tag{8}$$

where, $\sum_{crop} X_{"main1"}$ is the total surface of the first main crop and $\sum_{crop} X_{"main2"}$ is the total surface of the second main crop.

Third, farms that exceed 15 hectares of farmland have to maintain a 7% rate of Ecological Focus Areas (EFA), which is the last constraint. The 7% rate was selected due to the ongoing debate, at 2017, for increase the rate of EFAs from 5% to 7% (e.g. Cortignani et al., 2017). Moreover, increasing the rate of EFAs is an ongoing goal of the French national action plan “France terre pollinisateur” for the protection of pollinators (Gadoum & Roux-Fouillet, 2016). Thus,

$$\sum_{crop} X_{crop} \leq LANDV - EFA \tag{9}$$

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[8] Farm-type 1: soft-wheat and sunflower; Farm-type 2: maize and soft-wheat; data obtained from the *Chambre Régionale d'Agriculture Occitanie.*

where, EFA is 7% of the total available farmland minus the sum of the areas, E_{efa}, of various features (e.g., fallow, strips, etc.) multiplied by the relative conversion factor (ε_{efa}) and/or the weighting factor (θ_{efa}). Thus,

$$EFA \geq 0.07 \times LANDV - \sum_{efa}(E_{efa} \times \varepsilon_{efa} \times \theta_{efa}) \qquad (10)$$

<u>Wild pollination constraint:</u>

The purpose of this constraint is to force the farmer to secure the sustainability of wild bees by keeping the use of pesticides to a moderate level. To do this, we integrated a simplified wild bees' density function as a constraint. According to this function, the density of wild bees of a farm-type W (wild bees/farm-type) after the cultivation period, equals the initial density of wild bees $\overline{w}$ (wild bees/farm-type) minus the negative impact of pesticides. This negative impact equals the total use of pesticides (*Kg*/farm-type) multiplied by pesticides' residues on pollen resources δ (*mg* of contaminated pollen per *Kg* of pesticides), multiplied by the toxicity of the pesticides g (dead wild bees per *mg* of consumed contaminated pollen).

The estimation of the total pesticide use per farm-type was calculated endogenously by the model according to the farmer's crop selection. According to the study of Thompson (2017), an average of 2.80 *mg* of pesticide residue is retained on pollen resources for every *Kg* of pesticides used, which eventually could be consumed by wild bees during foraging. The average level of initial pesticide toxicity was set at 1 dead bee per 0.75 *mg* of consumed contaminated pollen (Tosi and Nieh, 2019).

The initial density of wild bees ($\overline{w}$) for both farm-types was estimated according to the article of Osborne et al. (2007). This study calculated the average number of wild bees' nests per natural habitat within a farmland. Hence, we estimated the average number of natural habitats within the farmland using data collected from the CRAMP and individual interviews and consequently, the potential number of wild bees' nests. We then extracted the initial density of wild bees for our farm-types following the study of Ellis (2016) on the average number of wild foragers per nest (Kleczkowski et al., 2017).

Finally, the density of wild bees after cultivation period W (wild bees/S) becomes a parameter. Its value varies between farm-types and signifies the minimum number of wild bees which have to survive to secure their reproduction capacity (Osborne et al., 2007). Therefore, the wild pollination constraint takes the following form:

$$\bar{w} - \sum_{crop}(X_{crop} \times Pesticides_{crop}) \times \delta \times g \leq W \tag{11}$$

where, $Pesticides_{crop}$ is the total use of pesticides per crop per ha; $\sum_{crop}(X_{crop} \times Pesticides_{crop})$ is the total use of pesticides (in Kg) in the farm-type; the product $\sum_{crop}(X_{crop} \times Pesticides_{crop}) \times \delta$ calculates the total amount of contaminated pollen resources; and the product $\sum_{crop}(X_{crop} \times Pesticides_{crop}) \times \delta \times g$ calculates the total number of dead wild bees per farm-type.

The right-hand side of this constraint, W, represents the supply of an environmental good (Havlík et al., 2005; Sourie and Rozakis, 2001; Guindé et al., 2008). This good is the surviving population of wild bees after one cultivation period. Moreover, W will take the place of $\bar{w}$ in the following cultivation period as the initial number of wild bees on the farmland. Thus, W may signify the available stock of wild bees for the farmer. As a result, it determines the level of supply of wild pollination services in the farmer's production system. Therefore, the dual value of the wild pollination constraint expresses the economic value that the farmer attributes to increase the stock of wild bees by one unit, that is, one wild bee.

Our modeling analysis only takes into account the negative effect of pesticides on wild bees, not on managed ones. In reality, the latter may be affected by pesticides, but to a lower extent than wild bees (Rundlöf et al., 2015), and farmers can act to further minimize their exposure to pesticides (Alaux et al., 2010). However, because there are no data for such practices by farmers, the negative effect of pesticides on managed bees is a limitation of our model. The farm-type model works under the assumption that the farm-type is a closed system (Kleczkowski et al., 2017). This means that neither pesticides nor bee pollinators pass across the boundaries of the farmland. In reality, bees visit the surrounding landscape and as a result, the action of one farmer to bee pollinators may benefit surrounding farmers as well (The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES], 2016). Managed bees from neighboring beekeepers may visit the farm and provide pollination services for free as an externality (Carreck et al., 1997). Similarly, the use of pesticides by one farmer affects the surrounding farmlands as it decreases the available pool of pollination services for all farmers (Moss, 2008). Hence, we do not capture the benefits or costs of these external effects on our farm-type model.

3.3 Farm model data

We based the economic component of farmers' behavior on data extracted from the CRAMP and personal interviews in the river basin called "Gers Amont," belonging to the Adour-Garonne watershed in the Occitanie region. In this landscape, 384 farms exist in a total area of 37,000 hectares where they are using managed bees as an industrialized input to obtain sufficient levels of pollination services (personal interviews; Chabert et al., 2015). The extraction of the farm data refers to the year 2017. This year was selected as the baseline situation as it was the last year Ecophyto (2008-2018) was implemented.

With the help of local extension services (CRAMP), we observed and selected two actual farms which are representatives of hillside land and valley farming systems, respectively. These farms were selected on the basis of their intensification, crop mix, irrigation, rotation systems, labor availability, and use of managed and wild bees' density. Therefore, we assumed that the two observed farms correspond to the main farm-types characterizing the farm population in the study area. Farm-type 1

This farm-type specializes in "dry cereals." It is located in the driest and hilliest areas of the river basin. Its main crop rotation is soft wheat, followed by sunflower, and represents about 35% of the total cropped area. Six different crops can be grown on this type of farm: durum wheat, soft wheat, maize, oilseed rape, sunflower, and soya. Among them, only oilseeds (i.e., oilseed rape, sunflower, and soya) are considered to be pollinator-dependent crops (Klein et al., 2007). In addition, this farm-type disposes a higher family labor availability than farm-type 2. Finally, the density of wild bees in this farm-type is significantly higher than that in farm-type 2 due to the presence of higher levels of natural habitats and permanent grasslands within the farmland (Table 1 and 2).

Farm-type 2

This farm-type specializes in irrigated maize, with widespread maize/maize, maize/soft-wheat, and maize/soybean rotations representing 17% of the total cropped area. The same six crops can be grown in this farm-type as in farm-type 1. Moreover, farm-type 2 is located in valleys with intense agricultural activity in terms of pesticide use, and more irrigated land. While both farm-types use managed bees as an industrialized input, however, it is slightly higher in farm-type 2 (Table 1 and 2). The use of managed bees varies between three to four beehives per hectare, depending on the crop and farm-type. According to the study of Chabert et al. (2015) and information from personal interviews, the average beehive price is fixed at €50 per hive.

Table 1 Farm-type characteristics.

Characteristics	**Farm-type 1**	**Farm-type 2**
Crop pattern (ha)		
Permanent grassland	11	10
Oilseed rape	22	19.59
Sunflower	13	0
Soya	0	0
Soft-wheat	46.75	29.5
Durum-wheat	17.22	0
Barley	0	0
Maize	28.53	52.91
EFAs	10.5	8.4
Pollination services		
Initial wild bees' density ($\overline{w}$)	2,250 (wild bees/farm-type)	1,140 (wild bees/farm-type)
Use of managed bees	3 hives per ha	3 to 4 hives per ha
Other characteristics		
Family labor availabilities (hours/year)	1524.8	1317.2
Total agricultural area (ha)	150	120
% of irrigable soil	8%	40%

% muddy clay soils	80%	20%
% sandy clay soils	20%	80%

Source: CRAMP Occitanie 2017

Table 2 Main economic data for the different crops under conventional practices[9]

	Inflow (€/ton)	Outflows (€/ha)			
	Mean price	Labor	Pesticides	Beehives	Other inputs
Soft-wheat	132	201.4	101.15	0	187.85
Durum-wheat	186	226.5	125.65	0	233.35
Barley	119	198.2	112.7	0	209.3
Sunflower	294	136	71.75	150-200	133.25
Oilseed rape	321	201.2	95.6	150-200	92.4
Soya	319	200.3	42	150-200	78
Maize (dry)	123	237.5	135.8	0	252.2
Maize (irrigated)	123	237.5	135.8	0	252.2

Source: CRAMP Occitanie 2017

3.4 Simulation scenarios of the MP model

Having presented the structure of our model and the examined areas, we discuss the tested policy scenarios in this section. These scenarios propose the adoption of novel low-input practices through financial incentives and penalties. These practices involve farmers' adoption of pollinator-dependent crops under little to no pesticide use. This decrease of pesticide use is compensated by three operations—field preparation, tillage, and monitoring—depending on the crop and proposed scenario[10] (The Andersons Centre, 2014; Movses and Micheli, 2015). Moreover, we assumed that farmers respect and do not use the neonicotinoids mentioned in the

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[9] In Table S4, we present the cost structures per crop for both conventional and novel practices for each scenario.

[10] Details on operations in Table S5

neonicotinoids' regulation of the European Commission (EU No 485/2013[11]). Hence, the decrease of pesticide use refers to pesticides that have been proven to have lethal or sub-lethal effects on bee pollinators(Gill et al., 2014; Byholm et al., 2018). These are the neonicotinoids that have not been included in the neonicotinoid regulation (i.e. Acetamiprid, Thiacloprid, Dinotefuran, and Nitenpyram) and the herbicides glyphosate and bentazone (Zhang et al., 2011; Whitehorn et al., 2012; Goulson et al., 2015).

For the inclusion of these novel practices in the proposed scenarios, two supplementary assumptions were adopted. Firstly, the adoption of novel practices increases the population of wild bees. Additionally, there are no extreme events due to climate conditions or diseases (Lonsdorf et al., 2009). Secondly, the use of incentives for the adoption of novel practices does not have any impact on the sales price of crops (Mosnier et al., 2009; Ridier et al., 2013). Accordingly, three different scenarios were designed:

<ins>Scenario 1:</ins>

This scenario was inspired by the French National Plan, Ecophyto. We included a 50% decrease in the volume of pesticide use for the different crops in the crop options (variables in the model). Following the agronomic literature, this decrease in the use of pesticides was replaced with a threefold or fourfold increase depending on the crop in the above-mentioned operations, including a gross-margin calculation taking into account avoided and associated costs (The Andersons Centre, 2014; Movses and Micheli, 2015). The pesticide reduction is assumed to increase the yield variability of non-pollinator-dependent crops by only 10-15% depending on the crop (The Andersons Centre, 2014), while it decreases the yield variability of pollinator-dependent crops by 10%. This is partly due to enhanced pollination activity from the subsequent

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[11] https://eur-lex.europa.eu/eli/reg_impl/2013/485/oj

increase in wild pollinator populations and the bees' complementarity (Greenleaf and Kremen, 2006; Bartomeus et al., 2014). Finally, the implementation of these novel practices by the farmers is supported by an AES payment (Table 3).

Scenario 2:

This scenario represents an expansion of the neonicotinoids regulation as it has been adopted by the National Action Plan Ecophyto for the protection of bee pollinators (Allier et al., 2019). It involves a complete restriction of pesticide use linked to pollinators' decline. In this scenario, a 100% decrease in the use of pesticides was facilitated by imposing penalties for their use under common practices (Lefebvre et al., 2015). This decrease was replaced with a fivefold or sixfold increase in the cost of relevant operations depending on the crop, while we assumed that the yield variability of the non-pollinator-dependent crops increases by 20-30% depending on the crop (The Andersons Centre, 2014). Similar to Scenario 1, we also assumed that the yield variability of pollinator-dependent crops remained at the same levels in this scenario due to the increasing number of wild bees and the bees' complementarity (Table 3). This assumption was justified by the study of Motzke et al. (2015), which showed that a strong and diverse number of bees may easily overcompensate for any loss of productivity due to pesticide reduction without harming yield outcomes. Similarly, the study of Gadanakis et al. (2015) showed that it is possible for the majority of British farmers to reduce the use of pesticides without harming their productivity. Therefore, we can assume that yield losses to pollinator-dependent crops remained at the same levels due to the increasing number of wild bees and the bees' complementarity, like in Scenario 1.

Scenario 3:

The last Scenario is identical to Scenario 2 but incentivized changes using an AES subsidy for the adoption of new practices for pollinator-dependent crops, rather than a penalty for pesticide use. This scenario was inspired by an increasing number of studies which demonstrated that the implementation of well-targeted territorialized AESs is a more effective policy mechanism than penalties in convincing farmers to adopt more environment-friendly practices (Del Corso et al., 2014; Lefebvre et al., 2015; Del Corso et al., 2017).

Table 3 Scenario characteristics and their impacts on farm management and risk.

Scenario	Characteristics	Policy measure	Impact on farm management	Impact on risk
Scenario 1	50% reduction on pesticides linked to bees decline	AES premium	Threefold/fourfold increase in the following operations: field preparation, tillage, and monitoring	Pollinator-dependent crops: yield increase (10%), yield variability decrease (10%) Non-pollinator-dependent crops: yield stable, yield variability increase (10-15%)
Scenario 2	100% reduction on pesticides linked to bees decline	Penalty	Fivefold/sixfold increase in the following operations: field preparation, tillage, and monitoring	Pollinator-dependent crops: yield increase (10%), yield variability decrease (10%) Non-pollinator-dependent crops: yield stable, yield variability increase (20-30%)
Scenario 3	100% reduction on pesticides linked to bees decline	AES premium	Fivefold/sixfold increase in the following operations: field preparation, tillage, and monitoring	Pollinator-dependent crops: yield increase (10%), yield variability decrease (10%) Non-pollinator-dependent crops: yield stable, yield variability increase (20-30%)

The aim of this exercise is to examine new modes of the implementation of the National Action Plan Ecophyto. By running the farm model for the aforementioned scenarios, we attempted to provide evidence on the economic and environmental viabilities of the proposed practices for production systems under conditions of farm support, specific to each scenario examined.

Having presented the three scenarios, we must note that the attribution of specific penalties and AES premiums are subject to compliance with the novel farming practices. As a result, the values of penalties and AES premiums have to be sufficient to allow novel practices to be incorporated into the farmers' crop patterns. Moreover, the values of penalties and AES premiums are parameters. Hence, we iteratively solved the model by inserting several values between €0/ha and €200/ha to examine farmers' adoption in the optimal crop mix decisions for different levels of penalties and AESs.

With the introduction of novel practices, we assumed that the use of managed bees for Scenario 1 will be two beehives/ha, while there is no need for managed bees for Scenarios 2 and 3, as farmers will rely exclusively on wild pollinators. In addition, we assumed that the phenomenon of bees' complementarity continues to exist as the total absence of pesticides will lead to an increased and diverse population of wild bees.

4. Results

The results for both farm-types were compared with the 2017 baseline scenario before setting up the policy measures. In the following paragraphs, we analyze the results of different scenario simulations with regard to: i) the impact on expected income and total costs of AES subsidies or penalties on the adoption of novel practices and on crop patterns, and ii) the dual value of the wild pollination constraint.

4.1 Profit and crop patterns changes and the levels of AES subsidies or penalties

In general, changes in crop patterns are reported, while the expected income increases in all scenarios for both farm-types, compared to the baseline. In this section, we present these changes by scenario and farm-type.

Scenario 1

In farm-type 1, a €100/ha AES premium is needed to motivate the farmer to adopt the novel practices in the total cultivated surface under condition to sustain a minimum number of wild bees. Therefore, the farmer is motivated to increase the cultivated area covered by the pollinator-dependent crops (oilseed rape, sunflower, and soya) in the land area of maize and durum-wheat (Fig. 1). This happens for three reasons. Firstly, the adoption of novel practices renders pollinator-dependent crops the most stable in terms of yield variability due to: a) the increasing number of wild bees and effect of bees' complementarity, b) presence of AES premiums, and c) wild pollination constraints. The revised cropping plan leads to a 5.7% increase in the gross margin of farm-type 1 (Table 4). This increase is mainly due to the AES subsidy and the decreasing variable costs of managed bees and pesticides.

In farm-type 2, a subsidy of €123/ha is needed to convince the farmer to adopt the novel practices in the total cultivated surface, mostly due to limited labor availabilities compared to farm-type 1. This happens because farm-type 2 disposes less family labor than farm-type 1 and as a result, a higher AES premium is required to cover supplementary working costs as new practices are more demanding. Consequently, the farmer decreases the surfaces of maize and soft-wheat by more than 50% in the place of oilseeds due to the high labor requirements of the former (Fig. 2). Moreover, the wild pollination constraint is stricter in farm-type 2 than in farm-type 1, as the density of the wild bees of this farmland is significantly lower. Hence, the farmer makes soya the dominant crop in the farmland (40%) instead of maize and soft-wheat to protect wild bees and gain economic benefits from bees' complementarity.

Scenario 2

In farm-type 1, a penalty of €71/ha is sufficient in order to encourage the farmer to adopt the novel practices for all the cultivated crops. Moreover, the gross-margin of farm-type 1 in this scenario increases due to lower variable costs as there is no use of pesticides and managed bees, motivating the farmer to increase the surfaces of oilseed rape and sunflower in the place of durum-wheat and maize. In addition, he introduces soya in the irrigated land of this system in the place of maize, making oilseeds the dominant family crop. Finally, the surface of soft-wheat remains at the same levels as in the baseline scenario (Fig. 1).

On the contrary, a penalty of €98/ha is required for the total adoption of novel practices in farm-type 2. The proposed penalty is higher than in farm-type 1. This happens because irrigated maize remains the most profitable crop in the production system. For lower penalty values, the farmer prefers to pay the penalty and cultivate maize under conventional practices, than to adopt novel ones. However, in the presence of the above penalty and the wild pollination constraint and in order to take advantage of the economic benefit of bees' complementarity, the farmer increases the surfaces of sunflower and soya in the place of soft-wheat and maize. Moreover, the surface of oilseed rape decreases in the place of sunflower (Fig. 2). This happens because farm-type 2 disposes lower labor forces than farm-type 1. Hence, the farmer prefers to cultivate crops which are less labor-intensive.

Scenario 3

Finally, by implementing Scenario 3, an AES premium of €110/ha is sufficient in convincing the farmer to adopt the novel practices in the total cultivated surface. Moreover, farm-type 1 reaches the highest gross-margin due to the AES premium and significantly lower variable costs. Regarding the crop patter, the presence of the subsidy and the absence of managed bees (due to an increase in freely available wild pollinators) result in an increase in sunflower and oilseed rape surfaces in the place of cereals. In addition, the high level of AES subsidy facilitates the hiring of more occasional workers and cultivation of maize under novel practices in the irrigated part of the farmland (Fig. 1).

By contrast, an AES premium of €131/ha is required in farm-type 2 to convince the farmer to adopt the novel practices. The difference in the level of the premium between the two farm-types is attributed to different labor availabilities; farm-type 1 disposes higher labor levels than farm-type 2. Consequently, as the novel practices are more labor-intensive, a higher premium is required for farm-type 2 in order for them to be adopted. Finally, the high AES subsidy and wild pollination constraint drive the farmer to significantly increase the surfaces of sunflower and soya in the place of soft-wheat and maize (Fig. 2), while the AES premium facilitates the farmer to employ more workers to increase the surface of oilseed rape in relation to Scenario 2.

Table 4 Economic results of the two farm-types.

	Farm-type 1			**Farm-type 2**		
REF	Gross-margin [€/ha]	GM variation [%]	Cost/ha	Gross-margin [€/ha]	GM variation [%]	Cost/ha

Baseline scenario	132.93		410.25	138.03		456.36
Scenario 1	164.17	5.7	379.5	165.42	4.9	422.22
Scenario 2	174.74	10.7	323.03	197.02	15.5	311.88
Scenario 3	260.05	19.5	330.99	241.93	18.1	342.94

The results are expressed through the use of gross margin and gross margin variation based on the baseline scenario.

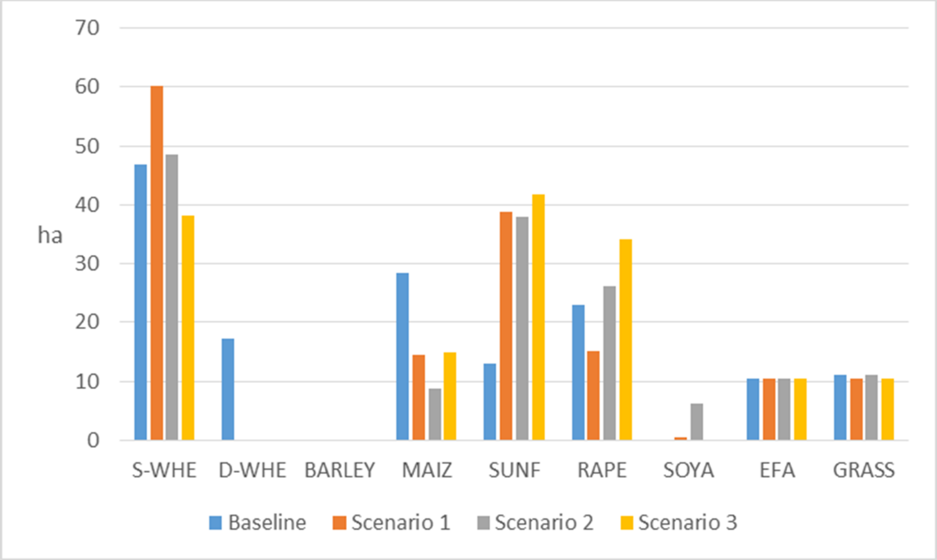

Fig. 1 Changes in crop patterns (in ha) according to the different scenarios for farm-type 1.

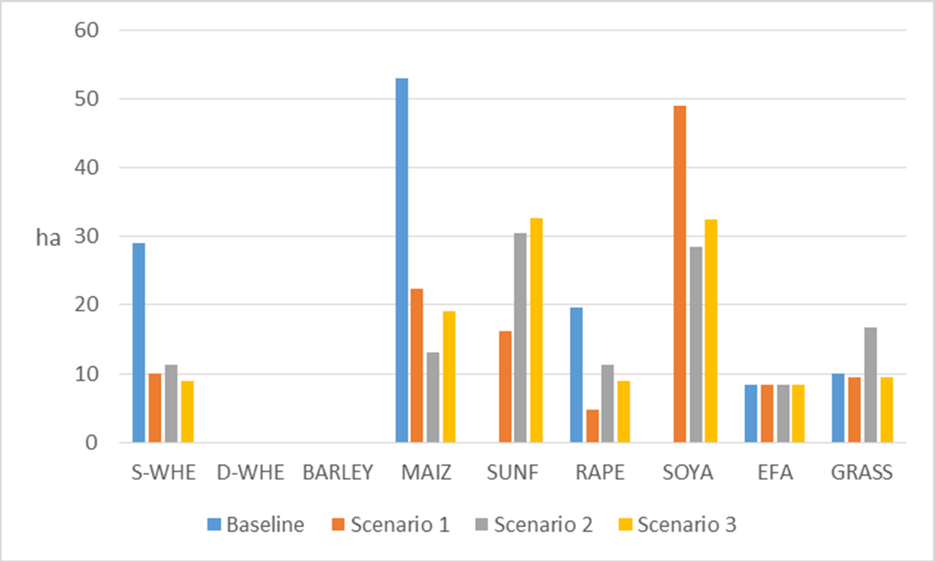

Fig. 2 Changes in crop patterns (in ha) according to the different scenarios for farm-type 2.

These findings are consistent with the model's assumptions; farmers would prefer crops which generate higher gross margins with lower yield variability, better labor allocations (maize and soft-wheat are preferred), and a higher use of wild bees.

4.2 Economic value of wild bees

In this sub-section, we analyze the dual value of the wild pollination constraint (see equation 11) for the two farm-types. The dual value (or shadow price in the terminology of mathematical programming) expresses the potential change in the optimal value of the objective function if one additional wild bee is preserved. According to our findings, farmers attribute significant value to wild bees in both farm-types, as a decrease in the stock of wild bees by one unit has to be replaced by managed bees, resulting in higher opportunity costs. The dual value of wild bees in farm-type 2 is higher than that in farm-type 1 due to the shortage of wild bees in this farmland. In addition, the dual value of wild bees is higher in Scenarios 2 and 3 than in Scenario 1 in both farm-types. Particularly for farm-type 2, the dual value of wild bees almost doubled in Scenarios

2 and 3 in comparison with Scenario 1. This occurs because farmers have replaced the costs of pesticide and managed bees with supplementary labor and wild pollination services, which come freely from nature, in Scenarios 2 and 3. In addition, the absence of pesticides and managed bees in these scenarios increase the value of the sustained stock of bees and the resulting pollination services for their production systems increases. Therefore, the dual value of wild bees varies between the two farm-types and the different scenarios (Table 5).

Table 5 Dual value of wild pollination constraint for the different scenario simulations.

Case studies	**Scenario simulations**	**Wild pollination dual value (€/wild bee)**
Farm-type 1	Scenario 1	7.95
	Scenario 2	7.99
	Scenario 3	8.419
Farm-type 2	Scenario 1	6.419
	Scenario 2	13.42
	Scenario 3	13.87

In Table 5, the value that farmers attribute to wild bees varies between 7.95€/wild bee and 13.87€/wild bee. Previous studies (Rucker et al., 2012; Chabert et al., 2015) that evaluated the economic contribution of bees on crop production, as well as the existing marketed value of managed bees in Southwest France (BEEWAPI[12]) report somewhat lower values.

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[12] http://www.beewapi.com/

We should retain that findings derived from the present model to reflect the importance that farmers attribute towards wild bees. However, one should be cautious in comparing the values provided by different models in terms of context and specification that may not be logical.

5. Discussion

The simulations performed by the use of this model for two different farm-types regarding the adoption of novel practices under various policy measures (AES/penalty) highlight different results. We showed that different levels of AES premiums or penalties can be efficiently targeted in order to encourage reluctant farmers to adopt the novel practices in the examined region. However, threshold levels depend on the farms' characteristics, initial stock of wild bees, and labor availability in each farm.

In general, farmers adopted the novel practices in the cultivation of pollinator-dependent crops in significant surfaces in both farm-types throughout the scenario simulations. This occurs as farmers benefit from the decreasing variable costs of managed bees and pesticides. However, the levels of the required AES premiums or penalties are lower in farm-type 1 than in farm-type 2 due to different labor availabilities between the two. In fact, we notice that the main obstacle for the adoption of novel practices in the region is labor re-allocation. Hence, farmers are willing to re-allocate their labor forces towards more profitable crops in terms of price and yield variability. These results are in accordance with Ridier et al. (2013), which showed that the main barrier for the adoption of novel practices in the Southwest of France is available labor force of each farm-type.

The economic benefit of bees' complementarity is a factor which may facilitate farmers' adoption decisions. According to our results, farm-type 1, which disposes a high number of wild bees, easily adopts novel practices as the low variable costs and yield stability that emerge from the presence of bees' complementarity make pollinator-dependent crops the most profitable option. On the contrary, the low initial level of wild bees in farm-type 2 does not permit the phenomenon of bees' complementarity to emerge on a large scale. As a result, maize remains the most profitable crop throughout the scenario simulations. Consequently, a higher AES premium or penalty is required to convince farm-type 2 to adopt the novel practices. Therefore, we can state that the labor availabilities, initial stock of wild bees, and bees' complementarity define the level of the proposed policy mechanism.

These arguments may be further strengthened by examining the dual value of the wild pollination constraint, that is, the economic value that the farmer attributes to increase the stock of wild bees by one unit. In both farm-types, we noticed that farmers attribute high value to the preservation of wild bees. This occurs as both farm-types have to buy more managed bees in order to compensate for any losses from wild pollination density reductions, resulting in higher opportunity costs. Thus, this dual value should be considered in public policy as it is an indicator of two elements. First, it defines the individual opportunity costs of the farmers and as a result, encompasses farmers' adoption decision processes. Second, it is a measure of the economic contribution of wild pollination services on crop production (IPBES, 2016). Consequently, it represents a monetary value that can incite the farmer to preserve wild pollinators (Bauer and Wing, 2016). These findings are in accordance with the study of Havlík et al. (2005), which supported the inclusion of the marginal cost of the supply of the relevant environmental good in effective policy measure.

Towards this direction, our model evaluated the effectiveness of two different policy mechanisms. The scenario simulations showed that AESs in both farm-types seem more effective than penalties in encouraging farmers to adopt new farming practices, improving farming profitability, and protecting pollination services. These results are in accordance with previous findings from Falconer and Hodge (2001), Centner et al. (2018), and Lefebvre et al. (2015), which supported that incentives may achieve better results in farmers' adoption processes than penalties. However, we have to consider that the implementation of AESs is rather costly for society.

The scenario simulation showed that in both farms, the AES premium varies between €100/ha and €131/ha. These values are significantly lower than those proposed in the study of Ridier et al. (2013), which examined farmers' adoption decisions based on the 30% reduction of pesticides proposed AESs in the same region and production systems. In our case, these lower levels of AES premiums are a result of the economic importance that farmers attribute to wild bees. Therefore, these permit us to assume that the sustained stock of wild bees in a farmland and the economic importance of bees' complementarity could significantly contribute towards the decrease of AES costs in the Occitanie region. Moreover, despite our findings being case-specific, considering them in the existing AESs may ameliorate their effectiveness in other French regions where similar trade-offs between pesticides and pollination services exist. This statement can be strengthened by the study of Perrot et al. (2018), which showed that increased production due to the presence of a strong and diverse number of wild bees in French farms could potentially replace policy costs for the management of semi-natural habitats within the farmland.

6. Conclusion and further research

In this study, we analyze the potential impacts of policy changes (AESs and penalties) on the provision of pollination services and on farmers' incomes into two characteristic farms in

Southwest France. In order to explore these impacts, we assess farmers' adoption decisions about alternative practices under risk aversion and bees' complementarity.

The results of our analyses highlight that both AESs and penalties could efficiently be targeted towards the implementation of novel practices and provision of pollination services in the Southwest of France. However, the levels of the proposed policy implementations depend on the labor availabilities of the relevant agricultural system, sustained stock of wild bees, and economic benefits of bees' complementarity. Moreover, we observed that the dual values of the wild pollination constraint vary depending on the policy scenario implemented. Put more simply, they represent the marginal value of preserving wild pollinators. In the event of the damage of wild bees, the economic consequences will be more severe in the cases of Scenarios 2 and 3, eliminating pesticide use driven by subsidy or penalty, respectively. As expected, the wild bee economic value is related to scarcity. Therefore, in farms with abundant starting populations, the dual values are significantly lower for all policy scenarios.

The above-mentioned findings are subject to several simplifications. Firstly, the density of wild bees was calculated using data from the literature, but their reproduction capacities were not considered (Kleczkowski et al., 2017). In reality, the different species of wild bees have different reproduction abilities and life patterns, and they respond differently to pesticides (Cox-Foster et al., 2007; Rundlöf et al., 2015). Hence, the model's accuracy would increase greatly with proper pollinator monitoring and an increased understanding of the reactions of pollinator populations to pressures would further provide relevant information for policy-making (Carvell et al., 2016).

Secondly, we only assumed that the farm is a closed system and there are no external effects regarding pesticide use and pollination services from surrounding farmers. Therefore, it is important to examine the effectiveness of our policy measures at a regional level in order to capture the external effects. This way the indicative results based on two farms of distinct profile, nevertheless arbitrarily selected ones, could be projected to an operational scale. Most importantly, these schemes have to be territorialized in order to include the majority of the implemented actors and treat the landscape as a whole (Prager et al., 2012; Del Corso et al., 2017).

Finally, an important issue for further research stems from the fact that we consider tillage as an operation which can replace pesticides. However, extensive tillage operations may harm beneficial soil insects and consequently, decrease soil quality (Pearsons and Tooker, 2017). Further field experiments in the soils of each case study are necessary in order to find the optimum balance between pesticide use, crop rotations, and tillage practices.

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