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

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1 **Abstract**

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

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

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

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23 **1. Introduction**

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

33 Despite the importance of bees in agricultural production, a substantial decline of bee pollinators
34 has been observed across Europe (Potts et al., 2010a; Goulson et al., 2015; Woodcock et al.,
35 2016). This decline was due to several motives and phenomena such as existing farm practices,
36 particularly the increase in pesticide use (Goulson et al., 2015). Hence, production decisions
37 have serious negative effects on bee pollinators. Moreover, farmers face a dilemma in their
38 decision problems as one input (pesticides) is dangerous for another (pollination services). This
39 phenomenon may be further aggravated as the intensive use of pesticides may cause the collapse
40 of bee pollinators and have serious ecological and economic consequences on human welfare.

41 In this context, the European authorities have mobilized a series of policy measures through the
42 Common Agricultural Policy (CAP) to safeguard the conservation of wild bees and
43 consequently, the provision of pollination services (Batáry et al., 2015). However, recent studies
44 have pointed out that these policy measures seem to be inefficient in guaranteeing the
45 conservation of a strong and diverse number of wild bees, as they mostly focus on the provision

46 of bee species that are already well-established (Senapathi et al., 2015; Wood et al., 2015).
47 Therefore, there is a clear need to further ameliorate the effectiveness of the proposed measures
48 to safeguard the provision of pollination services.

49 This research develops an ecological-economic model to explore the potential impacts of
50 changing policy intervention on the provision of pollination services and on farmers' incomes.
51 Moreover, it uses a mathematical programming (MP) setting to integrate the economic benefit of
52 behavioral interactions among different bee species in farmers' decision problems that have, to
53 the best of our knowledge, not yet been addressed in the literature. Despite growing ecological
54 literature on the importance of these interactions having serious negative effects on crop
55 production (Greenleaf and Kremen, 2006; Brittain et al., 2013), existing economic studies treat
56 managed bees as a perfect substitute for wild ones (Rucker et al., 2012; Kleczkowski et al.,
57 2017).

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

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

69 [DRAAF-Occitanie] – Telerucher¹). This practice has significantly increased farmers' production
70 costs as the rental price per beehive varies between €35 and €75 (Chabert et al., 2015).
71 Therefore, having in mind that similar markets already exist in other French regions (Chabert et
72 al., 2015), it is of great scientific interest to explore the potential impacts of policy changes on
73 the provision of pollination services and on farmers' incomes.

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

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

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

¹ <http://www.drome.gouv.fr/declaration-des-ruchers-a3249.html>

91 hives from beekeepers to sustain sufficient pollination services in their fields (Chabert et al.,
92 2015). Consequently, using managed bees as a substitute for the services of wild bees has
93 increased the production costs of farmers (Allsopp et al., 2008; Winfree et al., 2011). These costs
94 may further rise in the future as managed bees also suffer heavy losses (Potts et al., 2010a), while
95 the production of insect pollinator-dependent crops increases (Aizen and Harder, 2009). In fact,
96 recent studies have already reported differences in the supply of managed bees relative to the
97 demands of pollination services across Europe (Breeze et al., 2014a). Almost all European
98 countries have insufficient managed bee colonies to supply their needs in pollination services
99 (Breeze et al., 2014a). Hence, similar markets may emerge in other countries, like what has
100 happened in the United States (Rucker et al., 2012) and France (Chabert et al., 2015).

101 Apart from biodiversity losses, this progressive substitution of wild bees with managed bees that
102 are more costly may also be ineffective for many crops, where the latter are not perfect
103 substitutes for the former (Garibaldi et al., 2013). Many recent ecological and entomological
104 studies have pointed out that the presence of both bee species on the field is necessary in order to
105 secure a sufficient level of pollination services and optimize crop production (Greenleaf and
106 Kremen, 2006; Brittain et al., 2013). Indeed, the behavioral interactions between managed and
107 wild bees, called bees' complementarity, increase their pollination efficiency (i.e., seed resulting
108 from a single pollinators' visit), which optimizes yield quantity and quality (Bartomeus et al.,
109 2014). Therefore, the provision of both bee species is in the economic interest of farmers as it is
110 important for optimizing production. Considering this information in the development of public
111 policy measures may resolve farmers' decision problems as they face the trade-off between
112 pesticide use to reduce crop damages, and its negative effect on bee pollinators.

113 In general, the awareness of the decline of bees and its negative effect on human food supply
114 (Holden et al., 2006) mobilized a series of policy measures in Europe and France towards their
115 provisions. Since 2013, the European Union has implemented a total ban regulation ([EU No](#)
116 [485/2013](#)) on three neonicotinoids related to the decline of bees. Moreover, many Agri-
117 Environmental Schemes (AES) encourage the adoption of friendlier practices towards the
118 provision of pollination services (Batáry et al., 2015).

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

133 Regarding France, the majority of AESs includes wild bees in broader biodiversity schemes or
134 focuses on the installation of managed bees in less intensified agricultural systems (Underwood
135 et al., 2017; Decourtye, 2018). These schemes propose the creation of pollination zones within

136 agricultural systems through the installation of beehives. However, they do not include any
137 specific action for the provision of wild bees, such as the preservation of specific natural
138 habitats. Hence, the installation of numerous managed bees without the protection of wild bees
139 may lead to the displacement, and consequently, the extinction of native bees (Thomson, 2006).
140 Moreover, the great majority of French AESs suffers from the low participation of farmers as the
141 proposed measures failed to address their socio-economic issues. Consequently, the adoption rate
142 of friendlier practices from pollinators remained limited (Gaujour et al., 2012; Del Corso et al.,
143 2017).

144 Apart from the AESs, the French government launched the National Action Plan “Ecophyto”² in
145 2008 through the Sustainable Use of Pesticides Directive (2009/128/EC³). This plan aims to
146 reduce the overall use of pesticides in French arable farms by 50% until 2025. In addition,
147 Ecophyto has acknowledged the importance of bee pollinators on crop production and proposed
148 several actions towards their provision since 2018 (Allier et al., 2019). However, despite its
149 promising nature, the first phase of Ecophyto (2008-2018) failed to convince farmers to adopt
150 practices with low-pesticide use. Consequently, a significant number of farmers did not
151 internalize the need for pesticide reduction. This resulted to an increased use of pesticides in
152 arable crop farms in the last decade (Guichard et al., 2017). Therefore, there is a clear need to
153 further ameliorate the effectiveness of all the aforementioned measures towards both the
154 effectiveness of the proposed practices and the number of participants.

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

² <http://agriculture.gouv.fr/ecophyto>

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

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

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

180 complementarity, we assume that farmers participating in these novel programs can benefit from
181 the enhanced yield that emerges from interactions between the two bee species and consequently,
182 decrease their input costs.

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

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

203 (novel and conventional), variable inputs (pesticides, managed bees, and labor), and pollination
204 activity.

205 **3. Methods**

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

208 *3.1 Structure of the MP Model*

209 The optimization model maximizes the expected net income over one growing season for two
210 characteristic farms located in the Occitanie region of France. In general, because pesticides have
211 been considered an important component in reducing risks of yield loss, many risk-averse
212 farmers are usually using them as insurance (Mumford and Norton, 1984; Lefebvre et al., 2015).

213 In order to consider farmers' risk attitude towards the proposed practices, we modeled yield risk
214 due to changes in climate conditions and pollination levels. To combine the events coming from
215 a specific climatic condition and the levels of pollination services, we used the study of Tuell and
216 Isaacs (2010). This study examines the weather effects on yield outcomes of blueberries due to
217 changes in pollination activity. According to the findings, good or bad weather conditions affect
218 the efficiency of pollinators (higher rate of wild bee visits). Consequently, they increase crop's
219 yield quantity and quality, and decreases its yield variability. More specifically, the results
220 showed that in terms of weather conditions, the yield outcomes of blueberries may increase up to
221 fourfold during good seasons due to higher pollination activity. Despite the fact that this study
222 focuses on blueberries, the authors insist that their findings could be generalized for the majority
223 of insect pollinator-dependent crops. Therefore, by adopting the conclusion of this study
224 regarding the relationship between good weather conditions and higher pollination activity, we

225 assumed that observed yields during good seasons were partially due to higher pollination
226 activity

227 We suppose that yield risk per crop is normally distributed and prices also follow the normal
228 distribution with parameters estimated by the time series of 2008 to 2018.⁴ In economic analysis,
229 decision-making under uncertainty is often modeled following the expected utility hypothesis
230 (Lien and Hardaker, 2001). Thus, the expected utility of farmers' net incomes is the arithmetic
231 mean of utilities from the revenues for various states of nature following a probability
232 distribution.

233 There is evidence that farmers are risk-averse⁵, a behavior that may either remain unchanged for
234 local income changes or attenuated for significant increases in income value (constant or
235 decreasing risk aversion respectively). One way to express this behavior is through an E-V
236 context, which translates to preferences for higher expected income and lower variances of this
237 income. A farm production plan is a portfolio of cropping enterprises; its efficient diversification
238 requires knowledge of covariance among the enterprises. In the presence of numerous activities,
239 the variance-covariance matrix V is derived from the variability of individual activity returns
240 related to one another.

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

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.

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

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

$$265 \quad PAD = \frac{\sum_{crop=1}^n |\bar{X}_{crop} - X_{crop}|}{\sum_{crop=1}^n \bar{X}_{crop}}$$

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

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

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

$$275 \quad R = \sum_{crop} [x_c(\tilde{y}_c \tilde{p}_c - w_c - penalty) + x_n(\tilde{y}_n \tilde{p}_n - w_n + AES)] - wages \cdot workers_{hours} +$$
$$276 \quad \bar{S}CAP, \quad (1)$$

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

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

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

290 Yield variability, that is, yield standard deviation, is the main source of risk in the model. It is
291 assumed to be lower in pollinator-dependent crops under novel practices, than non-pollinator-
292 dependent crops under conventional practices.⁶ This is because the enhanced production arising
293 from interactions between managed and wild bees will partially compensate for yield losses due
294 to low pesticide use (Greenleaf and Kremen, 2006; Garibaldi et al., 2011; Bartomeus et al.,
295 2014).

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

300 *3.2 Constraints of the MP model*

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

303 Land constraint:

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

⁶ Supplementary material, Table S1

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

$$308 \quad \sum_{crop,soil} X_{crop,soil} \leq LAND_{soil} \quad (2)$$

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

312 Irrigation constraint:

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

$$316 \quad \sum_{crop,soil} X_{crop,soil} \leq IR_{soil} \times LAND_{soil} \quad (3)$$

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

318 Crop rotation constraint:

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

$$323 \quad \sum_{crop,soil} X_{crop,soil} \leq \sum_{previous-crop,soil} X_{previous-crop,soil} \quad (4)$$

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

⁷ <http://www.chambres-agriculture.fr>

326 Labor constraint:

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

$$329 \quad \sum_{crop, hours} Labor_{crop, hours} \leq family_available_{hours} + workers_{hours} \quad (5)$$

330 where, $\sum_{crop, hours} Labor_{crop, hours}$ is the total working hours spent for the cultivation of selected
331 crops; $family_available_{hours}$ is the total available family working hours per farm-type; and
332 $workers_{hours}$ is the total working hours of seasonal workers.

333 CAP cross-compliance constraints:

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

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

$$338 \quad \sum_{crop} X_{"grass"} \geq 0.95 \times \sum_{crop^0} X_{"grass^0"} \quad (6)$$

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

341 Second, farms with more than 10 hectares of farmland must cultivate at least two crops, while
342 those with arable land exceeding 30 hectares must cultivate at least three. We mathematically
343 expressed the constraints as they were presented in the articles of Cortignani and Dono (2015)
344 and Cortignani et al. (2017). We first identified the main crops in the production systems of our

345 case study.⁸ We then introduced two constraints for diversification. The first refers to farms with
346 more than 10 hectares, where each crop must not exceed 75% of the total cultivated land. The
347 constraint takes the following form:

$$348 \quad \sum_{crop} X_{"main"} \leq 0.75 \times LANDV \quad (7)$$

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

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

$$354 \quad \sum_{crop} X_{"main1"} + \sum_{crop} X_{"main2"} \leq 0.95 \times LANDV \quad (8)$$

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

357 Third, farms that exceed 15 hectares of farmland have to maintain a 7% rate of Ecological Focus
358 Areas (EFA), which is the last constraint. The 7% rate was selected due to the ongoing debate, at
359 2017, for increase the rate of EFAs from 5% to 7% (e.g. Cortignani et al., 2017). Moreover,
360 increasing the rate of EFAs is an ongoing goal of the French national action plan “France terre
361 pollinisateur” for the protection of pollinators (Gadoum & Roux-Fouillet, 2016). Thus,

$$362 \quad \sum_{crop} X_{crop} \leq LANDV - EFA \quad (9)$$

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

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

$$366 \quad EFA \geq 0.07 \times LANDV - \sum_{efa}(E_{efa} \times \varepsilon_{efa} \times \theta_{efa}) \quad (10)$$

367 Wild pollination constraint:

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

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

382 The initial density of wild bees (\bar{w}) for both farm-types was estimated according to the article of
 383 Osborne et al. (2007). This study calculated the average number of wild bees' nests per natural
 384 habitat within a farmland. Hence, we estimated the average number of natural habitats within the

385 farmland using data collected from the CRAMP and individual interviews and consequently, the
 386 potential number of wild bees' nests. We then extracted the initial density of wild bees for our
 387 farm-types following the study of Ellis (2016) on the average number of wild foragers per nest
 388 (Kleczkowski et al., 2017).

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

$$393 \quad \bar{w} - \sum_{crop}(X_{crop} \times Pesticides_{crop}) \times \delta \times g \leq W \quad (11)$$

394 where, $Pesticides_{crop}$ is the total use of pesticides per crop per ha; $\sum_{crop}(X_{crop} \times$
 395 $Pesticides_{crop})$ is the total use of pesticides (in Kg) in the farm-type; the product $\sum_{crop}(X_{crop} \times$
 396 $Pesticides_{crop}) \times \delta$ calculates the total amount of contaminated pollen resources; and the
 397 product $\sum_{crop}(X_{crop} \times Pesticides_{crop}) \times \delta \times g$ calculates the total number of dead wild bees
 398 per farm-type.

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

407 Our modeling analysis only takes into account the negative effect of pesticides on wild bees, not
408 on managed ones. In reality, the latter may be affected by pesticides, but to a lower extent than
409 wild bees (Rundlöf et al., 2015), and farmers can act to further minimize their exposure to
410 pesticides (Alaux et al., 2010). However, because there are no data for such practices by farmers,
411 the negative effect of pesticides on managed bees is a limitation of our model. The farm-type
412 model works under the assumption that the farm-type is a closed system (Kleczkowski et al.,
413 2017). This means that neither pesticides nor bee pollinators pass across the boundaries of the
414 farmland. In reality, bees visit the surrounding landscape and as a result, the action of one farmer
415 to bee pollinators may benefit surrounding farmers as well (The Intergovernmental Science-
416 Policy Platform on Biodiversity and Ecosystem Services [IPBES], 2016). Managed bees from
417 neighboring beekeepers may visit the farm and provide pollination services for free as an
418 externality (Carreck et al., 1997). Similarly, the use of pesticides by one farmer affects the
419 surrounding farmlands as it decreases the available pool of pollination services for all farmers
420 (Moss, 2008). Hence, we do not capture the benefits or costs of these external effects on our
421 farm-type model.

422 *3.3 Farm model data*

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

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

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

445 Farm-type 2

446 This farm-type specializes in irrigated maize, with widespread maize/maize, maize/soft-wheat,
447 and maize/soybean rotations representing 17% of the total cropped area. The same six crops can
448 be grown in this farm-type as in farm-type 1. Moreover, farm-type 2 is located in valleys with
449 intense agricultural activity in terms of pesticide use, and more irrigated land. While both farm-
450 types use managed bees as an industrialized input, however, it is slightly higher in farm-type 2
451 (Table 1 and 2). The use of managed bees varies between three to four beehives per hectare,

452 depending on the crop and farm-type. According to the study of Chabert et al. (2015) and
 453 information from personal interviews, the average beehive price is fixed at €50 per hive.

454 **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
EFAAs	10.5	8.4
Pollination services		
Initial wild bees' density (\bar{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%

455 Source: CRAMP Occitanie 2017

456 **Table 2** Main economic data for the different crops under conventional practices⁹

	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

457 Source: CRAMP Occitanie 2017

458 3.4 Simulation scenarios of the MP model

459 Having presented the structure of our model and the examined areas, we discuss the tested policy
460 scenarios in this section. These scenarios propose the adoption of novel low-input practices
461 through financial incentives and penalties. These practices involve farmers' adoption of
462 pollinator-dependent crops under little to no pesticide use. This decrease of pesticide use is
463 compensated by three operations—field preparation, tillage, and monitoring—depending on the
464 crop and proposed scenario¹⁰ (The Andersons Centre, 2014; Movses and Micheli, 2015).
465 Moreover, we assumed that farmers respect and do not use the neonicotinoids mentioned in the

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

466 neonicotinoids' regulation of the European Commission (EU No 485/2013¹¹). Hence, the
467 decrease of pesticide use refers to pesticides that have been proven to have lethal or sub-lethal
468 effects on bee pollinators(Gill et al., 2014; Byholm et al., 2018). These are the neonicotinoids
469 that have not been included in the neonicotinoid regulation (i.e. Acetamiprid, Thiacloprid,
470 Dinotefuran, and Nitenpyram) and the herbicides glyphosate and bentazone (Zhang et al., 2011;
471 Whitehorn et al., 2012; Goulson et al., 2015).

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

478 Scenario 1:

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

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

488 increase in wild pollinator populations and the bees' complementarity (Greenleaf and Kremen,
489 2006; Bartomeus et al., 2014). Finally, the implementation of these novel practices by the
490 farmers is supported by an AES payment (Table 3).

491 Scenario 2:

492 This scenario represents an expansion of the neonicotinoids regulation as it has been adopted by
493 the National Action Plan Ecophyto for the protection of bee pollinators (Allier et al., 2019). It
494 involves a complete restriction of pesticide use linked to pollinators' decline. In this scenario, a
495 100% decrease in the use of pesticides was facilitated by imposing penalties for their use under
496 common practices (Lefebvre et al., 2015). This decrease was replaced with a fivefold or sixfold
497 increase in the cost of relevant operations depending on the crop, while we assumed that the
498 yield variability of the non-pollinator-dependent crops increases by 20-30% depending on the
499 crop (The Andersons Centre, 2014). Similar to Scenario 1, we also assumed that the yield
500 variability of pollinator-dependent crops remained at the same levels in this scenario due to the
501 increasing number of wild bees and the bees' complementarity (Table 3). This assumption was
502 justified by the study of Motzke et al. (2015), which showed that a strong and diverse number of
503 bees may easily overcompensate for any loss of productivity due to pesticide reduction without
504 harming yield outcomes. Similarly, the study of Gadanakis et al. (2015) showed that it is possible
505 for the majority of British farmers to reduce the use of pesticides without harming their
506 productivity. Therefore, we can assume that yield losses to pollinator-dependent crops remained
507 at the same levels due to the increasing number of wild bees and the bees' complementarity, like
508 in Scenario 1.

509 Scenario 3:

510 The last Scenario is identical to Scenario 2 but incentivized changes using an AES subsidy for
 511 the adoption of new practices for pollinator-dependent crops, rather than a penalty for pesticide
 512 use. This scenario was inspired by an increasing number of studies which demonstrated that the
 513 implementation of well-targeted territorialized AESs is a more effective policy mechanism than
 514 penalties in convincing farmers to adopt more environment-friendly practices (Del Corso et al.,
 515 2014; Lefebvre et al., 2015; Del Corso et al., 2017).

516 **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%)

517

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

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

529 With the introduction of novel practices, we assumed that the use of managed bees for Scenario
530 1 will be two beehives/ha, while there is no need for managed bees for Scenarios 2 and 3, as
531 farmers will rely exclusively on wild pollinators. In addition, we assumed that the phenomenon
532 of bees' complementarity continues to exist as the total absence of pesticides will lead to an
533 increased and diverse population of wild bees.

534 **4. Results**

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

540 *4.1 Profit and crop patterns changes and the levels of AES subsidies or penalties*

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

544 Scenario 1

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

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

563 makes soya the dominant crop in the farmland (40%) instead of maize and soft-wheat to protect
564 wild bees and gain economic benefits from bees' complementarity.

565 Scenario 2

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

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

583 Scenario 3

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

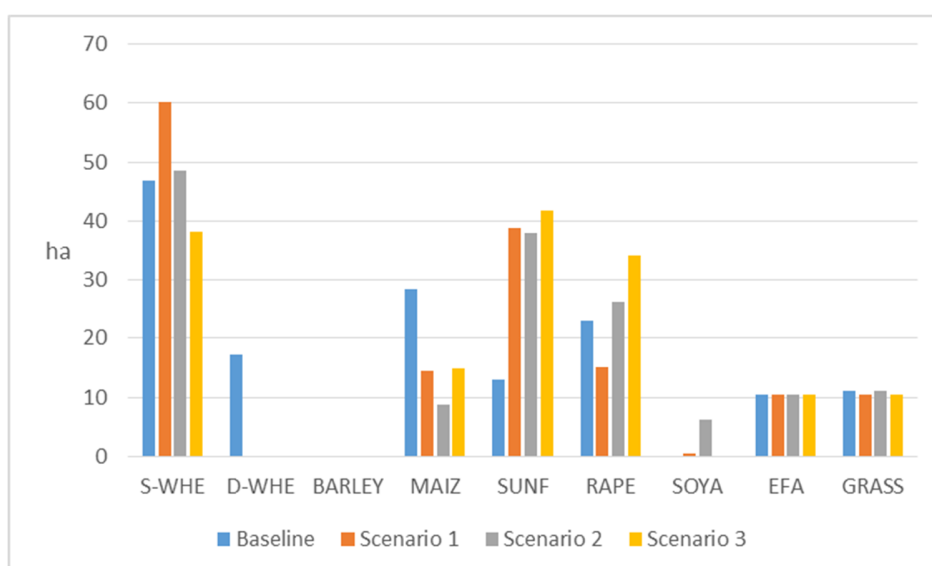
592 By contrast, an AES premium of €131/ha is required in farm-type 2 to convince the farmer to
 593 adopt the novel practices. The difference in the level of the premium between the two farm-types
 594 is attributed to different labor availabilities; farm-type 1 disposes higher labor levels than farm-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

600 **Table 4** Economic results of the two farm-types.

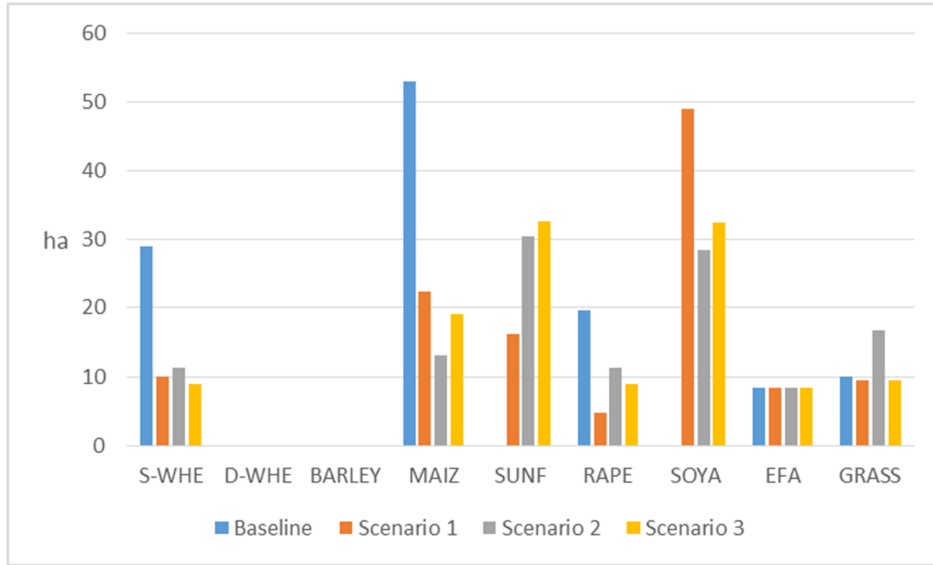
	Farm-type 1			Farm-type 2		
REF	Gross- margin [€/ha]	GM variation [%]	Cost/ha	Gross- margin [€/ha]	GM variation [%]	Cost/ha

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

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



603
604 **Fig. 1** Changes in crop patterns (in ha) according to the different scenarios for farm-type 1.



605

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

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

610 *4.2 Economic value of wild bees*

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

620 2 and 3 in comparison with Scenario 1. This occurs because farmers have replaced the costs of
 621 pesticide and managed bees with supplementary labor and wild pollination services, which come
 622 freely from nature, in Scenarios 2 and 3. In addition, the absence of pesticides and managed bees
 623 in these scenarios increase the value of the sustained stock of bees and the resulting pollination
 624 services for their production systems increases. Therefore, the dual value of wild bees varies
 625 between the two farm-types and the different scenarios (Table 5).

626 **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

627

628 In Table 5, the value that farmers attribute to wild bees varies between 7.95€/wild bee and
 629 13.87€/wild bee. Previous studies (Rucker et al., 2012; Chabert et al., 2015) that evaluated the
 630 economic contribution of bees on crop production, as well as the existing marketed value of
 631 managed bees in Southwest France (BEEWAPI¹²) report somewhat lower values.

¹² <http://www.beewapi.com/>

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

635 **5. Discussion**

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

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

652 The economic benefit of bees' complementarity is a factor which may facilitate farmers'
653 adoption decisions. According to our results, farm-type 1, which disposes a high number of wild
654 bees, easily adopts novel practices as the low variable costs and yield stability that emerge from

655 the presence of bees' complementarity make pollinator-dependent crops the most profitable
656 option. On the contrary, the low initial level of wild bees in farm-type 2 does not permit the
657 phenomenon of bees' complementarity to emerge on a large scale. As a result, maize remains the
658 most profitable crop throughout the scenario simulations. Consequently, a higher AES premium
659 or penalty is required to convince farm-type 2 to adopt the novel practices. Therefore, we can
660 state that the labor availabilities, initial stock of wild bees, and bees' complementarity define the
661 level of the proposed policy mechanism.

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

675 Towards this direction, our model evaluated the effectiveness of two different policy
676 mechanisms. The scenario simulations showed that AESs in both farm-types seem more
677 effective than penalties in encouraging farmers to adopt new farming practices, improving

678 farming profitability, and protecting pollination services. These results are in accordance with
679 previous findings from Falconer and Hodge (2001), Centner et al. (2018), and Lefebvre et al.
680 (2015), which supported that incentives may achieve better results in farmers' adoption
681 processes than penalties. However, we have to consider that the implementation of AESs is
682 rather costly for society.

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

697 **6. Conclusion and further research**

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

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

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

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

720 Secondly, we only assumed that the farm is a closed system and there are no external effects
721 regarding pesticide use and pollination services from surrounding farmers. Therefore, it is
722 important to examine the effectiveness of our policy measures at a regional level in order to

723 capture the external effects. This way the indicative results based on two farms of distinct
724 profile, nevertheless arbitrarily selected ones, could be projected to an operational scale. Most
725 importantly, these schemes have to be territorialized in order to include the majority of the
726 implemented actors and treat the landscape as a whole (Prager et al., 2012; Del Corso et al.,
727 2017).

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

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