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Combining incentives with collective action to provide pollination and a bundle of ecosystem services in farmland

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ABSTRACT

Bee decline and pollination deficit are driven by intensive agriculture and particularly pesticide use. So far policies to halt the decline and reduce pesticides have not unanimously been accepted, because they were not based on win-win solutions for farmers, beekeepers and biodiversity. A co-management of pests and bees is necessary, and in this study we tested if an incentive scheme based on beekeeper-farmer interdependency and collective action can lead to win-win solutions. We built a bioeconomic model to represent the mutual interdependency through pollination in intensive agricultural landscapes and simulate the economic and ecological impacts of introducing two beekeeping subsidies and one pesticide tax for different communication contexts. The model was calibrated using data from a study area in Western France. We showed that incentives affected targeted stakeholders, but also non-targeted stakeholders through a spillover effect, which therefore influenced the magnitude of ecosystem services provided at the landscape scale. We exhibited that communication between farmers and beekeepers amplified this spillover effect. Subsidies on beehives and honey led to win-win solutions for beekeepers and farmers since they had excellent pollination and economic performances, widely improved by communication. However, they were detrimental for other ecosystem services (ES) including pollination by wild pollinators. Conversely, tax on pesticides showed low economic performances, but was beneficial for the environment. Our study illustrates how a collective management of pollination is beneficial but warns against the artificialization of the pollination service that could result.

1. Introduction

Pollination is a critical ecosystem service (ES) for agriculture: 70% of the world's cultivated crops depend on insect pollination, a figure rising to more than 85% in Europe (Klein et al. 2007). For example, the most cultivated oilseed crop in Europe, oilseed rape (*Brassica napus L.*), relies on insect pollination for more than 35% of its production (Perrot et al. 2018; Woodcock et al. 2019). Pollination services have been valued at US$235–577 billion each year (Lautenbach et al. 2012). Both honeybees (*Apis mellifera*), managed by beekeepers, and unmanaged wild bees play a vital role in enhancing seed quantity and quality (Bommarco, Marini, and Vaissière 2012; Garibaldi et al. 2013), but they are threatened in agricultural landscapes, mainly due to intensive pesticide use and the loss of semi-natural habitats (Potts et al. 2010; IPBES 2016; Hallmann et al. 2017; Sánchez-Bayo and Wyckhuys 2019). Multiple efforts have been devoted to protect pollinators from pesticides such as the integrated pest management (IPM; Kogan, 1998), and more recently the integrated pest and pollinator management (IPPM), which proposes a co-management of pests and pollinators (Biddinger and Rajotte 2015). Improving managed insect-pollination while limiting pesticide use is one of possible co-management options, which relies on a collaboration between beekeepers and farmers. However, up to now, no consistent management scheme has been found to motivate both beekeepers and farmers to work together in European agricultural landscapes (Narjes and Lippert 2019; Breeze et al. 2019), especially in the intensive plains that cover most of the productive landscape.

Yet, farmers and beekeepers are mutually interdependent on pollination: beekeepers benefit from farmers and vice versa (Bretagnolle and Gaba 2015; Vialatte et al. 2019). By keeping honeybees, beekeepers are pollination providers. Through crop flower visitation, honeybees have

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been identified as the main pollinators for mass-flowering crops such as oilseed rape (Perrot et al. 2018) and sunflowers (Perrot et al. 2019), resulting in higher yields and incomes (Catarino et al. 2019). In return, these crops provide abundant floral resources for honeybees, therefore ensuring honey production and overwinter survival success (Requier et al. 2015). In this way, farmers are also indirect providers of managed pollination. Consequently, farmers and beekeepers need one another to maximize their benefits – they are mutually interdependent. Their economic decisions, such as land and pesticide use or the number of beehives, may and should influence each other (Barnaud et al. 2018). Hence, incentivizing ones may have beneficial spin-offs on the others, depending on their level of collaboration (the process in which beekeepers and farmers actively meet, work and talk together; Prager, 2015), may create a win-win situation for them, and likely to the entire landscape due to synergistic relationship between pollination and other ES. To our knowledge, no study have explored the economic and environmental consequences of such schemes while accounting for the interdependency between farmers and beekeepers.

There are diverse types of beekeeper/farmer collaboration around the world, ranging from informal arrangements to pollination markets (Narjes and Lippert 2019). In Europe, collaboration is rather scarce, and if it exists it is mainly carried out through face-to-face communication (Breeze et al. 2019; Bareille et al. 2021). This can be measured as the amount of intentionally shared information. For example, beekeepers may inform farmers about their intention to increase beehive capacity, which can impact farmers' land-use decisions. In this context, policies encouraging managed pollination (such as beekeeping subsidies) or discouraging detrimental factors (such as pesticide taxes), may lead to economic spillovers (i.e. indirect economic effects on non-targeted stakeholders) and thus to win-win strategies. The benefits may be conditioned by communication between farmers and beekeepers (Bareille et al. 2021). Beyond economic effects on stakeholders, trade-offs between ES or their drivers may also lead to environmental impacts at the landscape scale (e.g. by reducing pesticide use; Bennett, Peterson, and Gordon, 2009).

In the following, we aimed at evaluating the economic and environmental consequences of incentive-schemes fostering managed pollination in the European context. Exploring such schemes raises two issues. First, the success of the incentives might rely on communication among farmers and beekeepers. Second, as specified in IPPM principles, wild pollinators must be taken into account while co-managing pests and pollinators (Lundin et al. 2021). To account for these issues, we explicitly considered the mutual interdependency between farmers and beekeepers and their level of communication, as well as wild pollinators, using a bioeconomic modelling approach. To evaluate the consequences of such schemes we examined whether incentives motivating one of these ES providers to change ES drivers could lead to the delivery of a bundle of ES, therefore benefiting other stakeholders as well as the landscape. Following recommendations from European beekeepers (Breeze et al. 2019), we simulated (i) subsidies targeting beekeepers, which seem effective for increasing the number of honeybees (Stefanic et al. 2004; Çevrimli 2019) and (ii) a tax targeting farmers aimed at reducing the use of pesticides in rapeseed fields, i.e. a pesticide tax (Skevas, Oude Lansink, and Stefanou 2013; Finger et al. 2017). In our study, we assessed through a multi-criteria analysis the performance of pollination incentives with or without communication from both an economic and ecological perspective.

2. Materials and methods

2.1. Model overview and interdependency

In order to simulate incentive scenarios, we developed a bioeconomic model of an intensive agricultural landscape: 'landscape' being an organisational level where ecosystem services and stakeholders interact (Vialatte et al. 2019). The model is based on the framework of Bretagnolle and Gaba (2015), in which the authors identified the pollination-related ecological and socioeconomic components of a typical intensive agricultural landscape. The development of the framework was made from many empirical studies and observations, conducted in the same landscape over decades (Faure 2021; Gaba and Bretagnolle 2021). They concerned the effects of agricultural practices and landscape on pollinators and the benefits of insect pollination on crop production and farmers' economic performance.

In the model we included two economic activities: agriculture and beekeeping. The economic decision-making model and the ecological model were linked by pollination. The economic model included farmers' strategies on land use and pesticide use, and beekeepers' strategies on the number of beehives. The ecological model predicted populations of honeybees and wild bees. An overview of the model is presented in Fig. 1a, in which arrows represent the mathematical relationships (see below for details). The model also accounted for the mutual interdependency between farmers and beekeepers: farmers depend on beekeepers through pollination by domestic bees, whose abundance is defined by beekeepers by the number of beehives (Fig. 1b), while beekeepers depend on farmers because mass-flowering crops provide important floral resources for domestic bees and because pesticide use directly affects bee survival (Fig. 1b). Lastly, the model included whether or not farmers and beekeepers communicated, as this can affect their respective management decisions and hence the effectiveness of domestic bee pollination.

2.2. Agricultural production

Following the Bretagnolle and Gaba's (2015) framework, three representative crops of intensive agricultural cultivation were modelled (these crops represent more than 80% of existing crops in intensive landscapes[1]; Bretagnolle et al. 2018): wheat for winter cereals (subscript W), temporary grasslands used for hay for meadows (subscript G) and oilseed rape for oilseed crops (subscript OSR). Oilseed rape is largely dependent on pollination (Perrot et al. 2018) and is also the preferred crop of European beekeepers due to its high nectar capacity (Breeze et al. 2019). In the model, each farmer owned her/his farm area (normalized to 1 ha) and cultivated the three crops in the following proportions $x_W \in [0,1]$, $x_G \in [0,1]$ and $x_{OSR} \in [0,1]$ for wheat, grasslands and oilseed rape respectively. In the following, the vector of crop proportions is noted X, corresponding to the land use in the landscape. We imposed a constant acreage, such as $x_W + x_G + x_{OSR} = 1$. In oilseed rape fields, farmers applied pesticides at the rate $x_p \in [0,1]$. Pesticide use in other crops (i.e. in wheat) was assumed invariable because we assumed that this decision was independent from those considered here. The representative farmer's decisions about land use and pesticide use were made to maximize the profit function $\Pi^{(f)}$ (i.e. revenues minus costs, Debertin 2012):

$$\max_{X,x_p}\{\Pi^{(f)}(X,x_p,x_H) = \sum_{i\in\{W,G\}} \eta_i(x_i) + p_{OSR}F_{OSR}(X,x_p,x_H) - C_{OSR}(x_{OSR},x_p) - \tau^{(f)}(X,x_p)\}\ Subject\ to \begin{cases} x_W, x_{OSR}, x_G, x_p \in [0,1] \\ x_W + x_G + x_{OSR} = 1 \end{cases} \tag{1}$$

η_W and η_G are the wheat and grassland benefit functions respectively presented in Table 1 by Eq. (2) and Eq. (3). F_{OSR} is the OSR production function. p_{OSR} is the sale price of OSR seeds (thus $F_{OSR}\ p_{OSR}$ is the OSR revenue), which was assumed to be constant and independent of farmers' decisions (i.e. the farmers are price-takers). The function C_{OSR} represents OSR production costs, and was assumed to be linear with respect to the production factors x_{OSR} and x_p. The function $\tau^{(f)}$ is the

[1] The management of the remaining crops interferes little with the management of cereals, oilseed crops or grasslands (Bretagnolle et al., 2018).

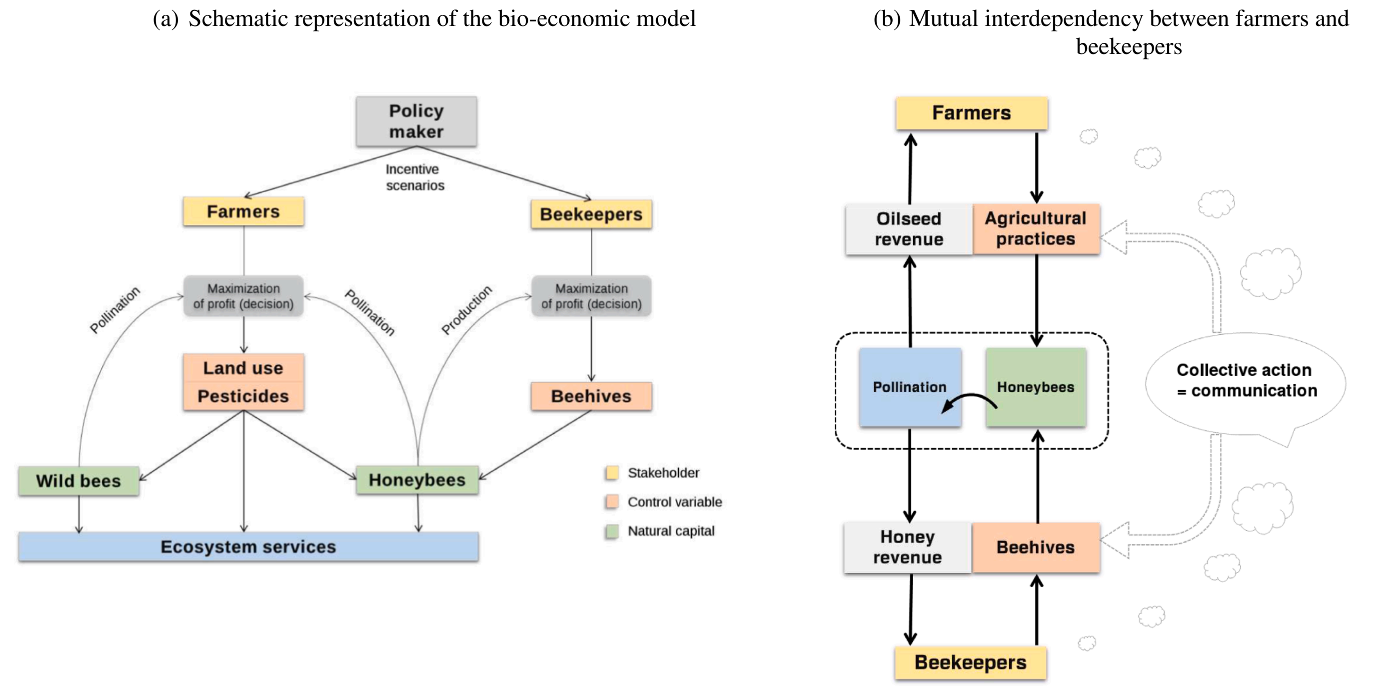


Fig. 1. Model overview. The farmers select the amount of pesticide use and land use allocation that maximizes their profits, while beekeepers choose the number of beehives. These decisions directly impact ES provision and bee populations. The latter affect in turn agricultural production through pollination and honey production through honeybee foraging. This creates a mutual interdependency, represented in (b), based on honeybees. Communication as well as incentives can modify the initial choices of stakeholders.

economic incentive aiming to support pollination (see '*Policy scenarios for improving pollination*' section below). The dependence of farmers on beekeepers is reflected by x_H, which is the number of beehives set up by the representative beekeeper (Fig. 1b). The model implies that farmers adapt their decisions to beehive availability, which has been observed by (Allier 2012) within the same study site. More generally, authors have shown that farmers adapt their oilseed rape-related decisions to yields, and thus to pollination (Breeze et al. 2014; Breeze et al., 2019; Andert, Ziesemer, and Zhang 2021), at least in the medium term, a time frame compatible with the interpretation of our model.

2.3. Crop pollination

In the model, wheat plants do not depend on insect pollination (Klein et al. 2007), and we further assumed that hay production mainly relied on farmers sowing ley meadows that do not depend on pollination by bees. While the yields of non-pollinated crops and honey were simulated using classical agricultural production functions (Cobb-Douglas, Table 1), we used another functional form for the pollinated OSR. The main reason was to best fit with the existing resource competition between managed and unmanaged bees (Mallinger et al., 2017), which was not supported by classical agricultural production functions (Debertin 2012). From the farmer perspective, the two types of bees are substitutes to produce OSR, meaning that a population increase of one class of bees will decrease the marginal product of another. A suitable model in the literature is the one used by (Montoya et al. 2019) and developed in the context of the Bretagnolle and Gaba's (2015). Following Montoya *et al.*, oilseed rape yield was represented by three partially additive yields (Eq. (4) in Table 1): a part dependent on both wild bees and honeybees $f_{OSR,1}$ (Eq. (5) in Table 1), a part dependent on pesticide application $f_{OSR,2}$ (Eq. (6) in Table 1), and a part independent of both bee abundance and pesticide application $f_{OSR,3}$. The first two account for more than 60% of the average yield (Zhang et al. 2017; Perrot et al. 2018; Wang et al. 2019). They used functional response functions of Holling type II that are increasing, concave as classically used in ecology and economics (e.g. for biodiversity-ecosystem function relationship, Paul et al., 2020; bee abundance, Montoya et al., 2019; and yield pesticide-response, Skevas, Oude Lansink, and Stefanou, 2013). The use of saturating functional responses means that crop production increases with inputs, but there is a threshold value for inputs over which crop production remains stable (Debertin 2012).

2.4. Honey production

The honey production of each beekeeper depended on the number of beehives set up, or x_H. We assumed that beekeepers' labour capacity was constant, with the number of beehives limited to $\overline{x_H}$ per beekeeper. The representative beekeeper chose x_H beehives to maximize his/her profit $\Pi^{(k)}$ in function (Fig. 1a):

$$\max_{x_H}\left\{\Pi^{(k)}\left(x_H, x_{OSR}, x_p\right) = p_H F_H\left(x_H, x_{OSR}, x_p\right) - C_H(x_H) + \tau^{(k)}\left(x_H, x_{OSR}, x_p\right)\right\}$$
$$\text{Subject to}\ \{\, x_H \in \left[0, \overline{x_H}\right] \tag{9}$$

where F_H is the honey production function, p_H the price of honey, and C_H the cost function of the inputs, which were assumed to be linear with respect to the number of hives. $\tau^{(k)}$ is the economic incentive function and depends on the policy (see '*Policy scenarios for improving pollination*' section below). Honey production followed a Cobb-Douglas function with x_{OSR} and x_H as inputs (Eq. (7) in Table 1). To account for competition for floral resources between colonies (Champetier, Sumner, and Wilen 2015), the marginal productivity of beehives decreased (elasticity less than 1). The area of oilseed rape in the landscape was included in the production function as honey production varies widely with the amount of mass-flowering crops (Free 1993). As has been empirically shown by (Chambers et al., 2019), the use of pesticides implies losses in honey production due to honeybee mortality. We included this damage (i.e. the negative effect of pesticides) through $\mathfrak{D} \in [0, 1]$ in the honey production function; Eqs. (7) and (8) in Table 1. The dependence of beekeepers on farmers is reflected by x_{OSR}, which is the main source of nectar for

Table 1
Functional forms used in the production model.

Stakeholder	Function	Equation		Description
Farmer	Wheat benefits	$\eta_W = \chi_W x_W{}^{\varepsilon}$	(2)	Cobb-Douglas function, exhibiting usual properties of production functions: positive and diminishing marginal productivity of the production input. χ_W is the gross margin of wheat, ε is the input elasticity.
Farmer	Grassland benefits	$\eta_G = \chi_G x_G{}^{\varepsilon}$	(3)	Cobb-Douglas function. χ_G is the gross margin of hay, ε is the input elasticity.
Farmer	OSR production	$F_{OSR} = x_{OSR}\sum_{j=1}^{3} f_{OSR,j}$	(4)	Linear combination of three partial yields $j \in \{1, 2, 3\}$ (giving total yield), times OSR area (Montoya et al. 2019).
Farmer	Bee-dependent crop yield	$f_{OSR,1} = \alpha_1 \frac{\overline{B}}{\beta_1 + \overline{B}}$	(5)	Functional response function of Holling type II, describing the saturating uptake of resources (Holling 1973), broadly inspired from the model of Montoya et al. (2019). $0 < \overline{B} < 1$ is the total bee abundance. $\alpha_1 > 0$ is a parameter related to the level of dependence, and $0 \leq \beta_1 \leq 1$ is a parameter of bee efficacy.
Farmer	Pesticide-dependant crop yield	$f_{OSR,2} = \alpha_2 \frac{x_p}{\beta_2 + x_p}$	(6)	By extension, functional response function of Holling type II, describing the saturation of pesticides. Widely used in crop response models (Fernandez-Cornejo, Jans & Smith 1998; Skevas et al., 2013). $\alpha_2 > 0$ is a parameter related to the level of dependence, and $0 < \beta_2 \leq 1$ is a parameter of pesticide efficacy.
Beekeeper	Honey production	$F_H = f_H x_{OSR}^{\gamma_1} x_H^{\gamma_2} \mathfrak{D}$	(7)	Cobb-Douglas function with OSR area and beehives as inputs, following the Siebert's (1980) model. $0 < \gamma_1 < 1$ and $0 < \gamma_2 < 1$ are the partial elasticities of production. f_H is a production constant, $\mathfrak{D}$ is linked to yield losses caused by pesticides (Eq. 7).
	Damage function	$\mathfrak{D} = 1 - \delta x_{OSR}\left[x_p\right]^{\nu}$	(8)	Complementary of honey and wild bee losses. $\delta > 0$ and $0 < \nu < 1$ are constant parameters calibrated with recent studies (Chambers, Chatzimichael & Tzouvelekas 2019; Wintermantel *et al.* 2020)

honeybees, and by $\mathfrak{D}$, which is the pesticide damage to honeybees (Fig. 1b).

2.5. Bee populations

The honeybee population varied with the number of beehives (x_H). The parameter k_H is the carrying capacity per hive, comprising a survival rate that was assumed to be constant (Eq. (10)). We assumed that there were no 'empty hives', a phenomenon reported by Stokstad (2007), which is already included in the carrying capacity of honeybees. In addition, literature showed that honeybees forage on weeds found in wheat fields, especially during the dearth period (Requier et al. 2015). However, we did not include it for two main reasons: (i) beekeepers can provide extra food during this period which reduces drastically the bee mortality, and (ii) honeybees mainly forage on weeds in cereal fields after the oilseed rape flowering period. Hence, in considering these two effects, oilseed rape yields may not be significantly impacted by wheat management. Following (Kleczkowski et al. 2017), Eq. (10) shows that the wild bee population size depends on the area of grassland because grasslands provide nesting sites. The bees' carrying capacity k_w is assumed constant, leading to constant nesting resources. Both types of bees are affected by pesticide use. Since the beehive number is derived from economic decision-making (Eq. (9)), it already includes the pesticide effect (Eq. (7), Table 1). In accordance with Chambers et al. (2019), we computed and evaluated the rate between honey yield and domestic bee losses (Appendix S1). The total population of bees is:

$$B(x_H, x_G, x_{OSR}, x_p) = \overbrace{x_H k_H}^{honeybees} + \overbrace{x_G\, k_w \mathfrak{D}(x_{OSR}, x_p)}^{wild\ bees} \tag{10}$$

2.6. Policy scenarios for improving pollination

In a recent survey, European beekeepers viewed financial incentives to encourage beekeeping activity (e.g. to increase the number of hives) and reduction of pesticide use as effective ways to support honeybees and enhance crop pollination ES (Breeze et al. 2019). We thus simulated three financial incentive scenarios aiming to increase pollination: two using beekeeping subsidies and one imposing a pesticide tax.

- Scenario HS: in this scenario a *per hive subsidy* (HS) was implemented, formulated as amount $\tau^{(k)} = z_{HS} x_H \geq 0$, which was granted to each beekeeper proportionally to the number of beehives set up. z_{HS} is the sum granted per beehive.
- Scenario PS: in this scenario a *price subsidy* (PS) was implemented, formulated as amount $\tau^{(k)} = z_{PS} F_H \geq 0$, which was granted to the beekeeper for each kilogram of honey sold. z_{PS} is the sum granted per kilogram of honey.
- Scenario PT: in this scenario a *pesticide tax* (PT) was implemented, formulated as amount $\tau^{(f)} = z_{PT} x_{OSR} x_p \geq 0$, which was levied on farmers according to the level of pesticides applied on their oilseed rape fields. z_{PT} is the tax per hectare of oilseed rape.

These scenarios were compared to a *business as usual* (BAU) control scenario with no economic incentive ($\tau^{(f)} = \tau^{(k)} = 0$).

2.7. ES governance effectiveness and bioeconomic indicators

We defined ES governance effectiveness as the simultaneous increase in pollination and a Pareto improvement (Just et al., 2005). The latter is defined as a situation that makes at least one stakeholder better off without making any other stakeholder worse off. We use as an indicator the total economic outcome with respect to the Pareto optimum situation in which full economic efficiency would be reached (i.e. all decision makers cooperate; Table 2). In addition, we extended our analysis on ES governance sustainability using three other ES indicators (food

Table 2
Bioeconomic indicators.

Type	Indicator	Expression	Description
Economic	Economic efficiency rate	$E_1 = \dfrac{\Pi^{(f)} + \Pi^{(k)} - \tau^{(f)} - \tau^{(k)}}{\Pi^{(f)^*} + \Pi^{(k)^*}}$	Ratio of total economic outcome in the scenario and in the Pareto optimum situation. The latter is given by maximizing the sum of both farmer's and beekeeper's profits (i.e. the stakeholders cooperate). The associated program is $\underbrace{max}_{X,x_p,x_H}\{\Pi^{(f)} + \Pi^{(k)}\}$.
Ecosystem services	Pollination	$ES_1 = \overline{B}$	Bee abundance
	Food/Feed provision	$ES_2 = \xi_W Y_W x_W + \xi_G Y_G x_G + \xi_{OSR} \mathrm{F_{OSR}} + \xi_H \mathrm{F_H}$	Sum of agricultural/apicultural productions, expressed in units of energy. ξ_i are energy multiplicative shifters of commodities. Y_j are average yields of concerned crops.
	Water quality (pesticides)	$ES_3 = 1 - x_{OSR} x_p - \theta x_W$	Opposite of pesticide quantities in OSR ($x_{OSR} x_p$) and wheat (θx_W). θ is the toxicity index of wheat relatively to OSR. Grasslands are assumed to be pesticide free. This indicator is related to the ES of water provisioning for drinking (Grizzetti et al. 2016).
	Water quality (nutrients)	$ES_4 = 1 - x_{OSR} - x_W$	Opposite of OSR and wheat areas. This underlies that only these crops are chemically fertilized and they are at the same rate. This indicator is related to the ES of water provisioning for drinking (Grizzetti et al. 2016).
Ecological	Wild bee abundance	$BC_1 = \mathrm{x_G} k_w \mathfrak{D}$	See Eq. (9)
	Plant species richness	$BC_2 = x_G^s$	Species-area relationship proxy, a power law with s being the constant slope of the logarithm (Crawley and Harral 2001).

provision, water quality concerning pesticides, and water quality concerning nutrients) and two indicators of biodiversity conservation (wild bee abundance and plant species richness). We also defined marginal indicators at the stakeholder scale to assess the direct effects and indirect effects of the incentives. The latter are named 'spillover'[2] in the following. We calculated input marginal product (output mass per unit area of OSR and per pesticide unit for farmers, output mass per beehive for beekeepers) and output marginal revenue (€.ton^{-1} OSR for farmers, €.kg^{-1} honey for beekeepers; see Appendix S2 for more details).

[2] Spillover is more appropriate than the more generic term 'externality' because it emhpasizes that the effect is caused by the policy incentive, which is not necessarily the case with an externality.

2.8. Communication and decision-making

We modeled the decision making process of the stakeholders, including their degree of collaboration, the latter being the process by which stakeholders talk and work together to satisfy their interests (Prager 2015). Many forms of collaboration exist, the most simple being communication. Feedback from the field showed that farmers and beekeepers sometimes communicate on their strategies, sharing their intentions and coordinating their actions together (Narjes and Lippert 2019). The ensuing change of their productive strategies can then be qualified as a *collective action*. For example, farmers may provide a location for hives next to oilseed rape fields or may reduce pesticide intensity or timing to decrease the negative impact on domestic bees. In exchange, beekeepers may set up more beehives than initially planned (Allier 2012; Breeze et al. 2019). Yet this communication is not always easy, for reasons including a knowledge gap about their common interest (Breeze et al. 2019), social distance, or the lack of an institutional setting (Ostrom 1990; Chwe 2000).

In our model, the decision vector contained the values of the control variables ($x^*_{OSR} x^*_p x^*_W x^*_G$) for the representative farmer and x^*_H for the representative beekeeper, based on maximizing their respective profits. We assumed that the farmer decides first his/her strategy, followed by the beekeeper ('leader-follower' configuration), representing the realistic timing of decisions during a year: sowing period comes before apiary set up. Hence, the decision-making result depends on the communication level, which can be modelled as the quantity of information shared by the beekeeper and owned by the farmer (i.e. the number of beehives actually set up). As described above, communication depends on specific criteria and can be difficult to initiate: in economic terms, communication involves transaction costs for stakeholders. We chose to model two highly contrasting transaction cost situations. The first was a situation in which (i) the costs of communication exceed the benefits so the beekeeper does not share any information about her/his intention. For example, a situation in which farmers are not even aware of the presence of beehives close to their fields, as has been observed in some cases (Allier 2012). The second was a situation in which (ii) communication has no cost so the farmer have complete information regarding the beekeeper's intentions. For example, the farmer and beekeeper are friends and fully share their intentions. From a game theory perspective, these situations are coordination, sequential, non-cooperative games (i.e. separate and individual decision models; Matsumoto and Szidarovszky, 2016) (i) without and (ii) with complete information (Oliver 1993).

We assumed that the BAU scenario decisions depended on the path: farmers and beekeepers have historically adapted their strategies relative to each other and thus are fully informed. Hence, only for incentive scenarios did we differentiate between a case in which the stakeholders (i) do not or (ii) do communicate their intentions, following the model of (Bareille, Boussard, and Thenail 2020). When they do not communicate (i), the farmer ignores that the beekeeper's strategy can be influenced by her/himself, and thus formulates false expectations in considering as fixed the number of beehives, and equals to the BAU level (i.e. $\Pi^{(f)} = \Pi^{(f)}(X, x_p, x_H{}^{BAU})$). When they do communicate (ii), the farmer has rational expectation regarding the beekeeper's strategy, and considers the number of beehives which maximizes the beekeeper's profit (i.e. $\Pi^{(f)} = \Pi^{(f)}(X, x_p, x_H{}^*(X, x_p))$, with $x_H{}^*$ in Eq. S1). We provided a comprehensive mathematical analysis of the decisions in Appendix S3. To sum up, stakeholders consider both direct management decision effects, and indirect ecological effects (i.e. consequences on bee abundance) when making their decisions. However, incentive impacts are not clear because of opposite effects at work, and simulations are needed to go further in the conclusions.

For simulations, we used backward induction to maximize their profits, using an analytical formulation of the beekeeper's best-response function (Eq. S1). This analytical expression was then used in the profit maximization procedure for the farmers. The optimums were determined by numerical optimization using the *optim* function in the “stats” package in *R v3.4.4* (R Core Team, 2018).

2.9. Parameter calibration and sensitivity analysis

Our model originates from Bretagnolle and Gaba’s (2015) framework, which show how pollination relates the ecological and socioeconomic compounds (including stakholders) in an intensive agricultural landscape. This work was achieved in the Long-Term Social-Ecological Research (LTSER) Zone Atelier Plaine & Val de Sèvre, an research infrastructure where more than 12 empirical studies have been published on pollination in the past years (Gaba and Bretagnolle, 2021). The parameter values for oilseed rape production were estimated using the study of (Perrot et al. 2018) conducted in the LTSER as well as a dataset from LTSER used by (Catarino et al. 2019)[3]. For other parameters related to agricultural or honey production, we took local references when available, or else national-scale references of the same type of production (Appendix S4). Economic data such as prices and costs were retrieved from national reports and ecological parameters from scientific studies (Appendix S4). As suggested by Muradian and Rival (2012), we implemented realistic rather than Pigouvian levels of incentives (Pindyck and Rubinfeld 2018). For the subsidy calibrations, the amount granted to each beekeeper was fixed at €5000, corresponding to a realistic budget for a professional beekeeper in France in 2020 (Ministry of Agriculture Food 2020). To compare the two subsidy scenarios, subsidies were set so that the total amount allocated to the beekeeper was equal to €5000, allowing €27.hive^{-1} for the hive subsidy and €1.10.kg^{-1} for the honey price subsidy. The tax per hectare was fixed at €50.ha^{-1} for the maximal agrochemical application rate ($x_p = 1$), in accordance with pesticide taxation literature (Jacquet, Butault, and Guichard 2011; Skevas, Oude Lansink, and Stefanou 2013; Böcker and Finger 2016). Model computation was made at stakeholder scale. Then we summed the effects to grasp them at the landscape scale. More precisely, we defined the landscape scale as follows: in Deux-Sèvres (France), the average area per farm is 95 ha and we assumed that the modelled landscape consisted of 570 ha of agricultural lands, with $n = 6$ farmers and $m = 1$ beekeeper. A sensitivity analysis was performed on incentive amounts (Appendix S5), on the oilseed rape price (Appendix S6) and on pollination-dependency parameter (Appendix S6bis).

3. Results

3.1. Economic effectiveness and spillover effects

In order to grasp if incentives and communication between farmers and beekeeper would result in economically effective ES governance (i.e. all stakeholders win to communicate), we simulated the effect of the three defined scenarios on the economic performance of agriculture and beekeeping as well as on public finances (Fig. 2). As expected, the latter decreased with hive and price subsidies (as subsidies generate public expenses, Fig. 2a) and increased in the pesticide tax scenario (as taxes generate public gains, Fig. 2b and c). However, the effect of public policies on the private sector was more complex. While the subsidy scenarios targeted only beekeeping, they also benefited farmers, revealing a spillover effect (Fig. 2a and b). This was accentuated by communication between stakeholders: for example, communication increased agricultural wealth by more than €4000 with the hive subsidy – i.e. 48% more than without communication (Fig. 2a). We also found an increase in the beekeeper’s wealth when the stakeholders communicated, so communication seemed to be a win-win strategy. This suggests that a combination of subsidies and communication allow effective polycentric pollination governance since it is in the interest of beekeepers and farmers to communicate, resulting in a Pareto improvement: the highest economic efficiency rates were reached by a combination of subsidies and communication; Fig. 2, table). In contrast, in the tax scenario, which targeted only farmers, we observed a spillover effect that was negative for both the farmers and the beekeeper (Fig. 2c). In this scenario, communication benefited beekeeping by buffering the losses (by 50%, Fig. 2c). Hence, the tax scenario was not economically effective, as shown by the economic efficiency rates which were the lowest (Fig. 2). All results were robust against ecological uncertainty (sensitivity analysis on pollination-dependency; Appendix S6bis). While the incentive economic effectiveness depended on the incentive-scheme, communication always benefited to stakeholders. A sensitivity analysis on incentive levels showed similar patterns for subsidies. When pesticide tax reach high amounts (i.e. 60€.ha^{-1}), beekeepers go out of the business because of a too low OSR area and thus too scarce nectar resources (Appendix S5).

Using a mathematical analysis, we further show that four conditions need to be met for an economically effective combination of incentives and communication (Appendix S7): (i) the productive change caused by incentives has to be large enough; (ii) the mutual benefits should be high; (iii) the interdependency has to be strong (i.e. economic activities are exclusively dependent and there exists few alternatives to be independent from the other) and (iv) the communication level between stakeholders has to be high.

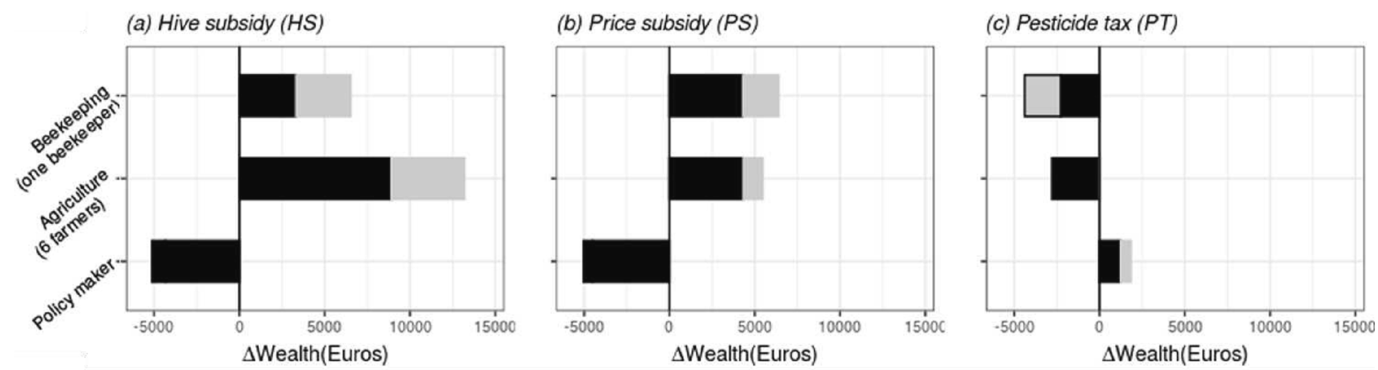
3.2. Bioeconomic performance of the three policy scenarios

In order to assess if the incentives would lead to environmentally sustainable ES governance, and if it was shaped by communication, we also assessed the bioeconomic performance of the three policy scenarios. Compared to the BAU scenario, when stakeholders communicated (Fig. 3a), only subsidy policies increased the pollination service, with the highest increase achieved by the hive subsidy scenario (+62%), followed by the honey price subsidy scenario (+26.8%). Surprisingly, the pesticide tax scenario actually decreased pollination (-7%). Also surprisingly, the increase in pollination services decreased the overall environmental conditions of the landscape in subsidy scenarios. The subsidies reduced the magnitude of water quality services by 4.6% and 3% for pesticides, and by 24.8% and 15.1% for nutrients. Subsidies also had a negative effect on wild bee abundance (-29.8% hive subsidy and −18.2% price subsidy) and plant species richness (-6.9% HS and −4% PS). In contrast, the pesticide tax increased water quality services (i.e. by 5.5% and 10.4% for the pesticide and nutrient indicators) as well as wild bee abundance (+15.3%) and plant species richness (+2.5%). Only the subsidy scenarios increased the economic efficiency rate (+3.7% HS and + 1.7% PS), contrary to the tax scenario, which slightly reduced it (-0.8%) (Fig. 3a).

The absence or presence of communication between the stakeholders generated differing bioeconomic performance (Fig. 3b). Without communication, the positive effects of pollination gains were lowered by 21.5% and 20% in hive and honey price subsidy scenarios, and divided by two in the pesticide tax scenario. Indicators related to production (food provision) and economic performance (stakeholders’ and total wealth) were also lower in the absence of communication in both subsidies and the tax scenario. Benefits to total wealth decreased by 46% in hive and 40% in price subsidy scenarios. Conversely, environmental indicators (pesticide and nutrient pollution reduction, wild bee abundance and species richness) increased, showing a trade-off between collaboration between beekeepers and farmers and natural ecosystem services. Compared to the BAU scenario, subsidies had similar environmental performance for these indicators except for wild bee abundance which was unmodified compared to BAU.

To sum up, only the subsidy scenarios increased pollination services; however, these scenarios presented lower environmental performance than the pesticide tax. Conversely, the pesticide tax had negative

[3] The dataset is available at https://zenodo.org/record/3386708#.Yjrc5vvjJw0.



	BAU	HS	PS	PT
With com.	0.918	0.952	0.934	0.911
Without com.	0.918	0.937	0.928	0.904

Fig. 2. Economic performance of scenarios. Gains and losses without communication (black) and with communication (grey) modelled for each sector (with $n = 6$ farmers and $m = 1$ beekeeper) and for the policymaker for the three scenarios. Economic efficiency rates (see E_1 in Table 2) have been computed for each case (table).

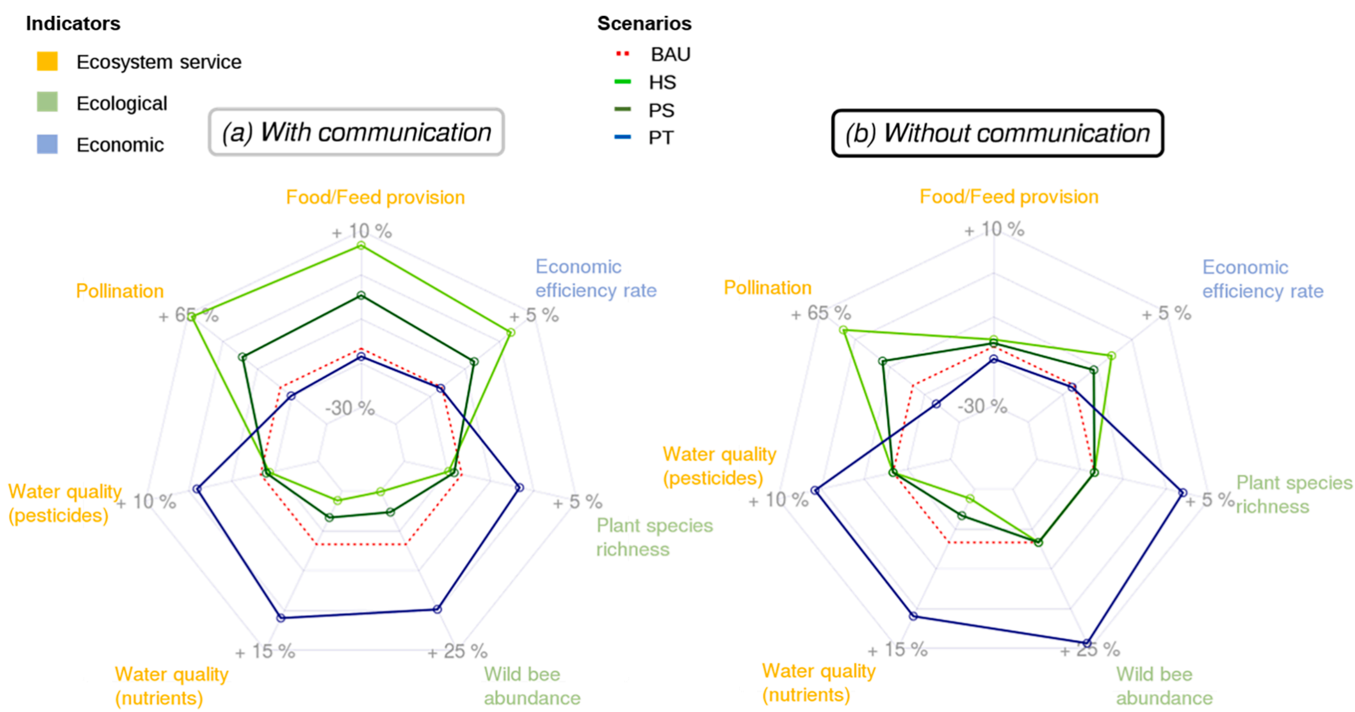


Fig. 3. Bundles of indicators. Magnitudes of ES (orange), biodiversity conservation indicators (in green) and economic indicators (blue) for each scenario with communication (a) and without (b), shown relative to BAU (0%) (red dashed line). The HS (hive subsidy, light green), PS (price subsidy, dark green) and PT (pesticide tax, blue) scenarios are represented by solid lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

economic impacts, while subsidies had high economic performance. Once again, these results were robust against ecological uncertainty (Appendix S6bis). Communication between farmers and beekeepers on their intended strategies alongside pollination policies had a positive effect on the policy's economic performance, but a negative impact on its environmental performance, showing a trade-off between collaboration between beekeepers and farmers and natural ecosystem services.

3.3. Land use change

In an additional step, we computed the land use change associated with all four scenarios including BAU, when agents communicated (Fig. 4). The land use in the BAU scenario was 45.6% winter cereals (wheat), 28% grasslands and 26.4% oilseed crops. In the subsidy scenarios, the proportion of oilseed rape increased up to 46.4% with the hive subsidy and 36.3% with the price subsidy, while the proportion of winter cereals and grasslands decreased by up to 32.6% and 21.1% respectively with the hive subsidy and by up to 39.6% and 24.1% with the price subsidy. In the pesticide tax scenario, the proportion of oilseed rape decreased by up to 16.1%, while the proportion of wheat and grasslands increased by up to 53% and 30.9%. Our sensitivity analysis on the oilseed rape price showed that land use was widely dependent on

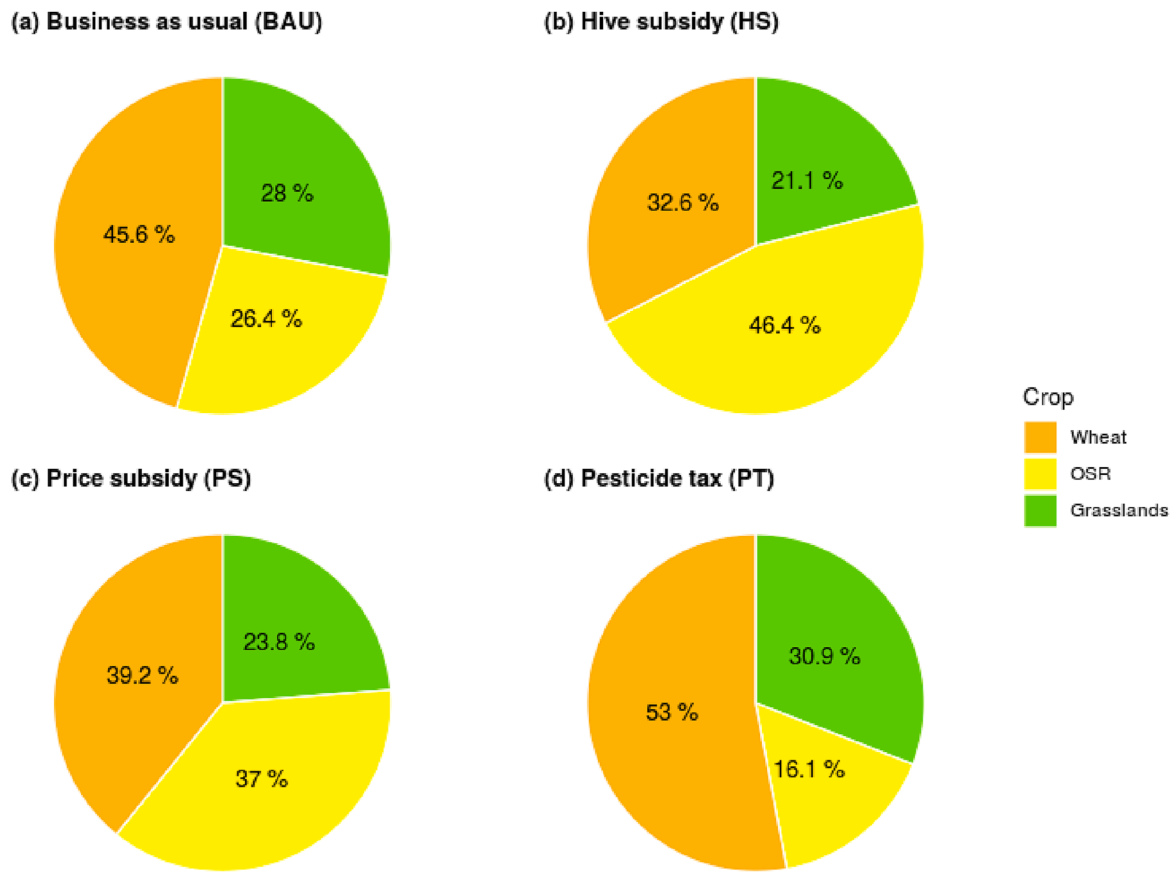


Fig. 4. Land use in the four scenarios. Land use in the business as usual (BAU, a), hive subsidy (HS, b), honey price subsidy (PS, c) and pesticide tax (PT, d) scenarios, with communication. The cropping mix is composed of wheat (dark yellow), oilseed rape (light yellow) and grasslands (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

price level (Appendix S4).

3.4. Decisional cascade and agro-ecological interdependency

Fig. 5 illustrates the decisional cascade leading to the spillover effects and environmental impacts of the policies. The implementation of a particular subsidy or tax generates changes in stakeholders' decision-making that affect ecological and economic processes acting at the scale of the stakeholder and the landscape. An analysis of the decisional processes highlighted the crucial role of pollination as the keystone of the mutual interdependency between the two economic activities. The increase in beekeepers' revenues in the subsidy scenarios was generated by an increase in marginal revenue from honey (37% for HS and 17% for PS), which affected decisions about the number of beehives (Fig. 5a). In turn, the increase in the number of beehives increased pollination (Fig. 5b), which resulted in an increase in oilseed rape productivity of 5.9% for the hive subsidy and 2.8% for the price subsidy (Fig. 4c). Conditional to communication between farmers and beekeepers and given this higher productivity, farmers increased the area of oilseed rape and decreased their use of pesticides with respect to BAU (Fig. 5c). Due to farmer/beekeeper interdependency through pollination, farmers' decisions generated an increase in marginal revenue from honey, which translated into an increase in the number of beehives, which then benefited farmers, and so on. In the pesticide tax scenario, taxation decreased farmers' revenues and marginal revenue from oilseed rape (-2.3%) (Fig. 5d). This caused farmers to modify their practices by reducing pesticide use on oilseed rape (-38.9%) and reducing the cultivated area of oilseed rape. The result was a landscape with lower pesticide damage (-4.4%) and higher pollination (+4.4%, Fig. 5e). However, the lower pesticide use was not enough to counterbalance the reduction in floral resources (less mass-flowering crops) and so beehive productivity decreased by 10%. Conditional on communication, this led beekeepers to decrease their production by decreasing the number of beehives by 15% (Fig. 5f), decreasing oilseed rape marginal revenue, and so on.

4. Discussion

Promoting Integrated Pest and Pollinator Management (IPPM) based on beekeeper-farmer collective action, through monetary incentives, is a promising lever to overcome the pollination deficit and generate win-win solutions. We used an original bioeconomic model to simulate the economic and ecological impacts of two types of beekeeping subsidies and one pesticide tax aiming at fostering managed pollination. Our simulations indicated that subsidies involved a win-win strategy for both beekeepers and farmers, accentuated by a good communication. However, the tax had a negative economic effect. Overall, none of the schemes was sustainable, i.e. was win-win for farmers, beekeepers and for biodiversity at the same time.

A key highlight is that a combination of beekeeping subsidies and communication was more effective than subsidies on their own to support pollination and the economy. Another finding was that public expenditure was also largely exceeded by private benefits, implying a cost-effective policy (OECD 2013). These results are consistent with Breeze et al. (2019), who hypothesized that communication benefits both beekeepers and farmers. Our results are also in line with the study by Opdam et al. (2016) and Bareille et al. (2021) that showed that ES provided at landscape scale (such as pollination) were improved by collaboration between multiple land users. In the beekeeper-farmer case, subsidies encourage beekeepers to increase their beehive

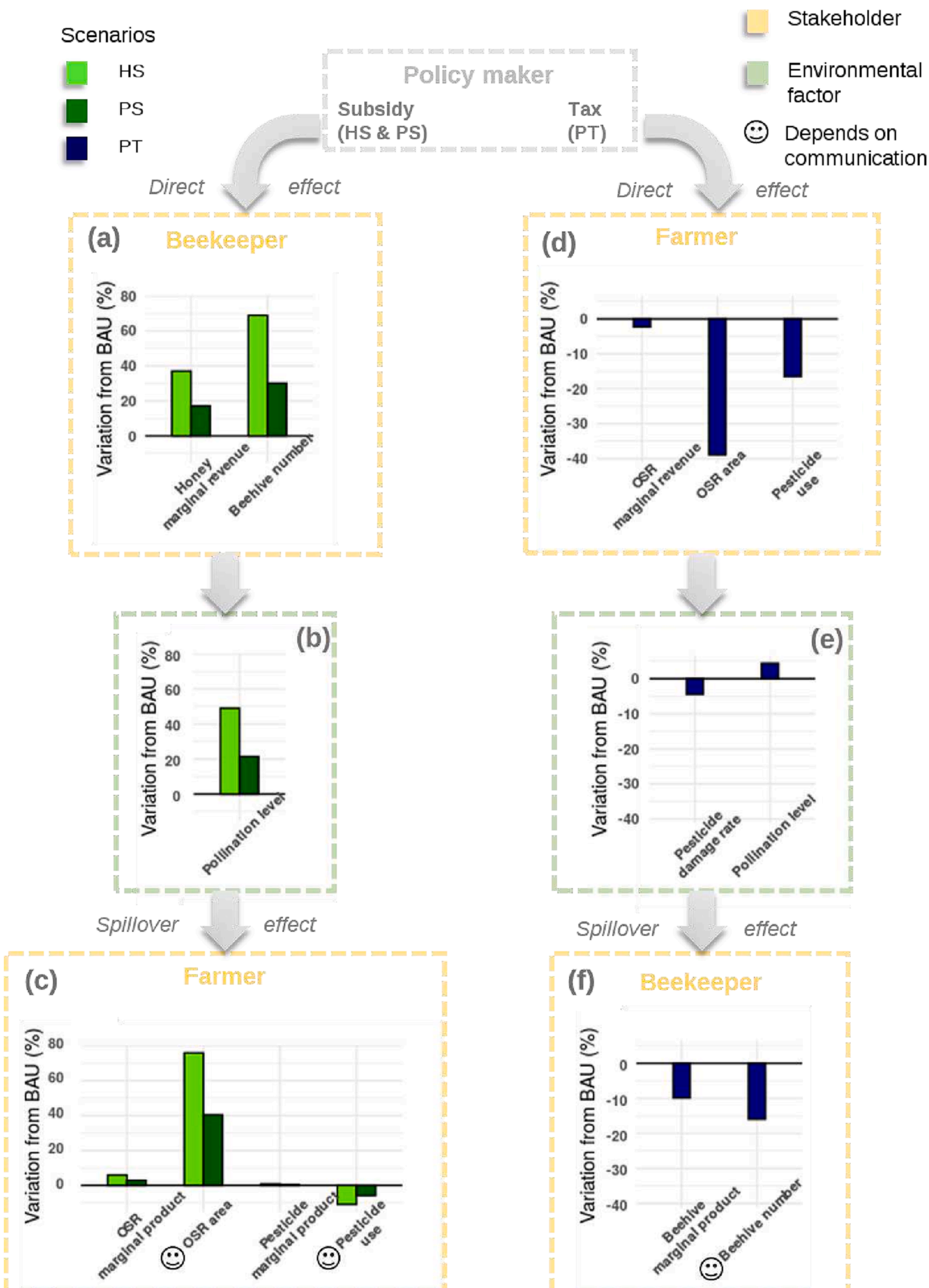


Fig. 5. Decisional cascade and agro-ecological interdependency. Variation from the BAU scenario in terms of marginal economic and environmental indicators for the subsidy scenarios (a, b, c: HS in light green, PS in dark green) and the tax scenario (d, e, f: PT in blue). The first row (a, d) shows how the marginal revenue of outputs (honey and oilseed rape seeds) is impacted by the policy (a: the beekeeper and d: the farmer). The second row (b, e) illustrates the effects of the management changes on pollination, which is the keystone of the interdependency. The third row (c, f) shows how the marginal product of each productive input for the non-targeted stakeholder is indirectly affected (c: farmer and f: beekeeper). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

capacity. This in turn increases OSR yield, increasing production and creating additional revenue for farmers. This spillover effect arises whatever the communication level and is inherent to any positive externality (Meade 1952; Pindyck and Rubinfeld 2018). However, our simulations showed that if beekeepers communicated about their new beehive strategy, farmers increased the area of OSR and decreased their pesticide use per hectare. This strategy has been empirically observed in oilseed rape grown for seeds (Allier 2012). Consequently, the new farming strategy benefited bees, pollination and beekeepers. In turn, the latter decided to further increase beehive capacity. In this way, communication increased production capacity, a benefit of collective action that has often been hypothesized, but rarely showed (OECD 2013; Bareille et al. 2021). We showed that the reciprocal relationship between farmers and beekeepers accentuated the chances of economic success of incentives. As highlighted by (Barnaud et al. 2018), the existence of a shared economic interest promotes successful collective action. Nevertheless, collective action can be advantageous even without pecuniary benefits, as stakeholders may not be solely motivated by profit (Ostrom 2010).

Beyond pollination, these mechanisms could be generalized to study other regulating ES that underlie mutual interdependency between stakeholders (e.g. biological control, water quality). In the case of biological control for example, incentives for semi-natural habitats combined with more communication between farmers could lead to more effective ES governance (Salliou, Muradian, and Barnaud 2019; Opdam et al. 2016). In that context, actions facilitating the dialogue between stakeholders are thus worthwhile, such as organizing local and national-scale workshops, or creating an app to connect them. Latter ones have been realized in France for example (ADA FRANCE, 2020).

Conversely, the pesticide tax scenario led to losses for both types of stakeholders, indicating ineffective ES governance whatever the communication level. The resulting change in the farmers' strategy (mainly a reduction in the area of OSR) led to a decrease in floral resources for honeybees. This type of behavior has been observed after restrictions on neonicotinoid use, which implied a reduction in OSR area (Zhang et al. 2017). We proved that two factors underlied the failure of the tax policy: first, the benefits caused by pesticide reduction (lower bee mortality and thus higher pollination) were not high enough to counterbalance the cost of paying the tax. Second, farmers had an alternative to avoid the tax (planting more winter cereals and grasslands), which was detrimental for beekeepers because these crops flower less. Hence, conclusions could be different in monoculture of highly pollination-dependent crops, such as fruit production (Hevia et al. 2021). Finally, tax revealed a power asymmetry between farmers and beekeepers: farmers can diversify their activities contrary to beekeepers. These results reveal that a good communication between farmers and beekeepers, as well as a strong interdependency between them can favour the success of pollination incentives.

Our results also found that environmental performance was high with the tax policy, but low for subsidies. Water quality, species richness and wild bee abundance increased in the pesticide tax scenario, while they decreased in both beekeeping subsidy scenarios as the increase in oilseed rape area was mainly at the expense of grasslands. Such substitution is often observed in intensive agricultural landscapes (Holzschuh et al. 2016; Gaba and Bretagnolle, 2021). The lower biodiversity (of plants and wild pollinators) in the subsidy scenarios is therefore not surprising, as plant species richness is generally higher in grasslands (Öckinger and Smith, 2007) and haylands (Gaba et al. 2020), and wild bees require adequate semi-natural habitats (here modelled by grasslands) for nesting and foraging (Bretagnolle and Gaba's, 2015). Moreover, the decrease in wild bee abundance resulting from less grassland can be accentuated by competition between wild and managed pollinators (Lindström et al. 2016). While we did not model direct competition, our results highlighted indirect competition between wild and domestic bees and thus an antagonism between managed and unmanaged pollination ES. To ensure the delivery of pollination ES, a decrease in wild pollinators can be compensated to a certain extent by managed pollinators: availability of managed bees can mask a decrease in wild pollination services that would otherwise encourage farmers to adopt conservation measures (Kleczkowski et al. 2017; Narjes and Lippert 2019). However, some studies have shown that this substitution is partial (Garibaldi et al. 2013). In this case, communication between farmers and beekeepers accentuated this replacement of wild pollination by managed pollination, further impacting the environmental performance. Lastly, we found that environmentally-effective schemes were characterized by incentivized ES drivers that were not detrimental to other ES. This is important as studies have shown that ES-oriented policies can lead to trade-offs in which the provision of one service increases while another declines (Bennett, Peterson, and Gordon 2009). This raises an additional criterion to be met for such pollination incentive regimes to be sustainable: the strategies chosen to deliver an ES targeted by the incentives should account for trade-offs between ES to avoid negative environmental, economic and societal impacts (IPBES 2016). The conclusion would be that beekeeper-farmer communication should take place in a thoughtful hybrid policy context, so as not to penalize wild pollination.

Our results come from an original bioeconomic model focusing on pollination which can be applied to many landscapes. Up to now, few models of this type have been developed. Although, our pollinated yield model is similar to others (Kleczkowski et al. 2017; Kirchweger et al. 2020), our modelling approach differs from others on several issues. First, our model includes decision making, which allows to simulate public policy scenarios. For example, the comprehensive model of Kirchweger et al. (2020) does not model it. Moreover, conversely to other models that include decision making to our knowledge, such as those of Kleczkowski et al. (2017) or (Champetier, Sumner, and Wilen 2015), our model includes the two decision makers related to pollination, i.e. beekeepers and farmers. It is important when studying monetary incentives to model the decisional cascade that they may entail. The only models that include both beekeepers' and farmers' decisions are purely economic models such as those of Meade (1952), or (Narjes and Lippert 2019), but they do not include the ecological component of the agricultural landscape, therefore missing a comprehensive analysis of the consequences of incentives. All in all, our model may be improved to better represent the incentive consequences, by integrating stakeholders' heterogeneity of decision for example.

In this study, the form of collaboration we considered was communication between farmers and beekeepers. Focusing on communication was specific to the European bee management context, and it would be insightful to explore the validity of our results within other contexts such as in the United States. Other collaborative approaches exist, such as collective payments, for example, but feedback from the field showed that collaboration between farmers and beekeepers in Europe usually takes the form of informal arrangements, although few studies have been carried out on this topic. However, it may be valuable to explore other types of collaborative approaches: for instance, collective incentives to promote pollination (Prager, Reed, and Scott 2012). We modelled communication either with or without infinite transaction costs. However, in real life there is typically a mix of the two. Transaction costs of communication between beekeepers and farmers can arise from social distance (e.g. they do not have the same social networks) or from more cognitive factors such as beliefs or status quo biases (Breeze et al. 2019). In Europe, relationships between beekeepers and farmers have been degraded by recent debates on pesticide use, for example. Risk can also be a barrier: oilseed rape is largely avoided by beekeepers because of the perceived pesticide risk (Breeze et al. 2019). A second threat is default risk, which is initially large but decreases with repetition and trust (Ostrom 2010). More generally, ES are characterized by high uncertainty, or asymmetric information, which increases reticence to collaborate (Muradian 2013). Uncertainty reflects the 'noise' underlying biophysical processes and ecological functions (e.g. unstable pollination, Garibaldi et al. 2011), but also socio-economic uncertainties underlying negotiations and markets (Ostrom 2010; Muradian 2013). Including these transaction costs in the model may result in a reduction in the benefits of communication and thus lessen stakeholders' motivation to share information, increasing the realism of the simulation (Olson 2009). In this case, it might be valuable to model and compare institutional forms of organization between beekeepers and farmers that aim at reducing transaction costs (e.g. co-ops or unions). It is likely that the benefits of communication would hold at larger scales of organization if the stakeholders still share a common interest. However, they are still conditioned to a fluent communication at the ecological process scale studied in the paper (i.e. bee foraging scale). Furthermore, the model did not simulate the decision to communicate per se, but only explored two extreme cases. It would be valuable in future studies to include communication in the decision model. The likelihood to act collectively is a rich research field: studies have shown that this decision can be shaped by reputation, trust or reciprocity (Ostrom 2010). Our model did not explore the causal relationship between incentives and communication, but it has been shown that incentives can raise stakeholder awareness about their interdependency and encourage them to collaborate more (Barnaud et al. 2018; OECD 2013).

5. Conclusion – Policy perspectives

Up to now, managed pollination has mainly been supported through pesticide regulation policies in Europe, the most emblematic being the ban on neonicotinoids in 2013 (European Commission 2023). These regulations are still widely debated and are contested by farmers. In this context, finding win-win solutions could ease the situation. This study quantified the economic impacts of domestic bee support and how they are shaped by communication between farmers and beekeepers. We showed that incentivizing beekeeping could be an interesting tool for both beekeepers and farmers, and also allow the opportunity to act collectively to get the best out of such measures. These results are insightful for current and near policies which plan to accentuate the financial support of apiculture in the next CAP. This may be, at the same time, a first step to find more win-win solutions for controlling pesticides, and thus ease the tight situation in Europe. Nevertheless, the sustainability of such financial support was low because the incentivized managed pollination drivers may conflict with the delivery of other ES, notably the unmanaged pollination service. Further research is therefore needed to design sustainable polycentric governance that accounts for the complex interactions between ES providers, and between ES providers and the environment. In light of our results, we claim that diversifying the policy toolbox as it is made in some countries (e.g. France made it in the next pollination policy 2021–2026; Ministry of environment 2021) may be the best solution to reach sustainable goals. Furthermore, engaging a variety of stakeholders to share interest in a policy is inherently challenging and will require support to facilitate collective action. In Europe for example, even if private initiatives flourish, no public initiatives that facilitate farmer-beekeeper dialogue are known.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2023.101547.

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