Environmental and Sustainability Indicators 28 (2025) 100944

Contents lists available at ScienceDirect

Environmental and Sustainability Indicators

journal homepage: www.sciencedirect.com/journal/environmental-and-sustainability-indicators

Assessing the economic impact of insect pollination on the agricultural sector: A department-level case study in France

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ARTICLE INFO

Keywords:
Pollinators
Economic value
Vulnerability ratio
Dependence ratio method
Agriculture
Policy

ABSTRACT

Pollination is a critical ecosystem service for agriculture, with 76 % of European food crops and 80 % of wild plants depending on it. However, bee populations are declining due to diseases, pesticides, and climate change, with major economic and environmental impacts. In France, pollination services are valued between 2,3 and 5,3 billion euros annually, but detailed data at the department scale (NUTS 3) is lacking. This study aims to fill this gap by quantifying the economic value of crop production (EVCP), the economic value of insect pollination (EVIP), and agricultural vulnerability to pollinator loss across all French departments. We analyzed data from 2022 for 34 major crops, of which 26 are pollinator-dependent, applying the dependence ratio method to estimate pollination contributions. We also developed a generalized additive model (GAM) to identify the main drivers of spatial variation in EVIP per hectare. We estimate France's economic value of crop production at 34,8 billion € and economic value of insect pollination at 4,2 billion €, with an agricultural vulnerability rate of 12 %. The highest economic value of insect pollination per hectare was recorded in Loire-Atlantique (19302,5 €/ha) and the lowest in Seine-Saint-Denis (575,5 €/ha). By analyzing crop-specific dependencies and regional production patterns, the study reveals that southern and western France, particularly departments specialized in fruit and vegetables, are most economically dependent and vulnerable to pollinator decline. The GAM explained 97.6 % of the variability in EVIP per hectare, revealing that fruit and vegetable cultivation strongly drives pollination value. The results highlight spatial disparities in pollination dependency and underscore the need for territorially targeted conservation strategies. Compared to previous studies, our findings suggest a significant underestimation of pollination value, highlighting the need for fine-scale entomological research and territorially targeted conservation strategies to support sustainable agricultural development. However, the study has some limitations: certain crop prices had to be approximated, dependence ratios were fixed and do not account for local ecological conditions, and some minor crops were excluded. Despite these constraints, the results remain robust and provide a reliable basis for territorialized conservation policies.

1. Introduction

Pollination is a vital ecological process that ensures plant reproduction, supports agricultural productivity, and maintains biodiversity (Katumo et al., 2022). Nearly 87,5 % of flowering plants and about 75 % of the most important global food crops depend, at least partially, on animal pollinators, highlighting their indispensable role in ecosystems and in securing global food supply (Ollerton et al., 2011; Klein et al., 2009). Pollinators include a wide variety of animals such as insects (bees, butterflies, beetles, flies), birds, and even some small mammals (Katumo et al., 2022; Ollerton, 2017). Among these diverse pollinators, insects, particularly bees, are especially valuable for agriculture due to their efficiency in pollinating crops and their significant contribution to agricultural economies (Leonhardt et al., 2013; Klein et al., 2006;

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https://doi.org/10.1016/j.indic.2025.100944
Received 2 September 2025; Received in revised form 22 September 2025; Accepted 25 September 2025
Available online 29 September 2025

Senapathi et al., 2021; Ollerton, 2017). In fact, pollination directly enhances the quality and nutritional value of many vital food sources, notably fruits, vegetables, and oilseeds (IPBES, 2016). These nutrient-rich foods are fundamental components of balanced human diets, significantly contributing to nutrition and food security worldwide (IPBES, 2016). In other words, pollination is recognized as a valuable ecosystem service that contributes broadly to human well-being, providing benefits such as medicinal plants, ornamental aesthetics, genetic diversity, and enhanced ecosystem resilience (Millennium Ecosystem Assessment, 2005). The global economic value of animal pollination services is considerable, estimated at between 127 and 152 billion USD annually (Bauer and Wing, 2016; Gallai et al., 2009). Remarkably, despite their relatively modest share of agricultural land use, fruits and vegetables alone constitute over 30 % of this economic value, highlighting their dependency on pollinators (Gallai et al., 2009). However, despite their critical ecological and economic importance, pollinator populations around the world have been alarmingly declining. Numerous studies have identified multiple interconnected factors responsible for these declines, including habitat destruction, intensive farming practices, widespread pesticide usage, diseases caused by introduced pathogens, invasive species competition, and climate change effects (Potts et al., 2010; Cameron et al., 2011; IPBES, 2016; Katumo et al., 2022). Agricultural intensification, driven by the increasing global demand for food, exacerbates these negative trends. Intensive farming often reduces habitat diversity, encouraging monoculture systems heavily reliant on pollinator-dependent crops, thereby heightening vulnerability to pollinator population declines. The decline in pollinator populations, particularly observed in Europe and North America, poses severe risks to both food security and economic development, especially in regions highly reliant on agriculture (Steffan-Dewenter et al., 2002; Potts et al., 2010).

Several studies report the decline in pollinator populations, particularly in Europe and North America, where the most consistent data have been gathered. In Europe, for example, approximately 25 % of wild bee species have been lost since the 1980s, while in parts of North America, honeybee colony losses frequently exceed 30 % annually (Potts et al., 2010). Such reductions in pollinator abundance have critical implications for agricultural productivity because many fruit and vegetable producing crops depend on animal-mediated pollination services (Klein et al., 2009; Gallai et al., 2009). Modeling exercises indicate that, once wild pollinator densities fall beneath certain thresholds, crop yields do not decrease linearly but instead exhibit rapid collapse (Gallai et al., 2009). Gallai et al. (2009) estimated that a 50 % loss of pollinator species, without compensatory measures, could result in a 5 %–9 % reduction in the total global value of crop production. This nonlinear response arises because crops often require multiple visits by different pollinator taxa to achieve complete fertilization. In regions of southern Europe, where small-scale farmers rely heavily on fruits and vegetables, yield losses of up to 50 % have been projected under severe pollinator decline scenarios, threatening both local food security and rural livelihoods (Potts et al., 2010). The economic consequences of reduced pollination services extend beyond yield loss. Even when managed pollinators (e.g., commercial honeybees or bumblebee colonies) are deployed to partially substitute for wild insects, Europe could suffer from a multibillion-dollar economic loss, particularly in fruit-dominated systems (Bauer and Wing, 2016). To mitigate these risks, integrated landscape-level and farm-level interventions are required. Agri-environmental schemes, such as establishing flower-rich field margins, reducing pesticide usage, and restoring semi-natural habitats, have been shown to increase wild pollinator abundance and diversity. Simultaneously, the protection and expansion of natural areas provide critical nesting and foraging resources that support pollinator resilience amid intensifying agricultural land use (Potts et al., 2010). In addition, the introduction of alternative managed pollinator species (e.g., *Osmia bicornis*) can supplement honeybee services; however, such strategies require careful management to avoid disease transmission and adverse effects on native pollinator communities (Cameron et al., 2011). Failure to implement these measures risks a future in which fruit and vegetable production declines sharply, commodity prices escalate, and rural communities suffer decreased food security and economic stability (IPBES, 2016). Therefore, investments in pollinator-friendly agricultural practices, habitat conservation, and diversification of pollination management are essential to maintain crop productivity and ecosystem health under ongoing environmental change. Addressing pollinator decline requires coordinated international actions, combining existing national and local monitoring efforts into a comprehensive global initiative. Given the multifaceted and interacting threats pollinators face, continuous improvement in our understanding of pollinator health and dynamics at local, national, and global scales remains indispensable. Extensive global and national assessments of pollination's economic value have been conducted (e.g.(Carreck and Williams, 1998; A. Morse and W. Calderone, 2000),), smaller-scale analyses at regional (NUTS 2) and departmental (NUTS 3) levels are relatively uncommon (Borges et al., 2020). These localized assessments are particularly important due to the limited foraging distances of many wild pollinator species, such as solitary bees (Gathmann and Tscharntke, 2002). Precise, smaller-scale evaluations are thus more accurate and relevant for conservation efforts and policy planning.

Consequently, the objective of this study is to perform an economic valuation of pollination services at the departmental level (NUTS 3) in France in order to better assess the contribution of pollinators to local and national economies as well as to better assess the venerability of these regions in an even of a "pollination services crisis". The choice of France as a case study stems from its remarkable agricultural heterogeneity and the availability of detailed crop- and region-specific data. France encompasses a wide range of production systems, ranging from extensive cereal belts in the north to intensive fruit and vegetable zones in the south. This diversity allows for the simultaneous examination of both pollinator-dependent (e.g., fruits, vegetables, nuts) and less-dependent (e.g., cereals) crop categories within the same national framework. Moreover, France maintains comprehensive statistical records at the departmental level through sources such as the Agreste database (Ministère de l'Agriculture), which facilitate the disaggregation of crop-specific values and surface areas. Finally, ongoing national initiatives, such as the "Plan national Pollinisateurs 2021–2026" launched by the French Ministry of Agriculture, underscore the policy relevance of quantifying pollination services in a country where agricultural lobby groups and environmental agencies actively seek to balance productivity with biodiversity conservation. In order to do so, we employ the Dependence Ratio method introduced by Gallai et al. (2009), which assesses the economic contribution of pollinators to agriculture based on crop-specific pollination dependency levels. France offers a suitable case study due to its diverse agricultural practices and a variety of cultivated crops, including cereals, fruits, vegetables, tubers, and vineyards. This research seeks to accomplish four primary objectives. We first derive, for each department, the total economic value of crop production (EVCP). We then calculate the share of this value that can be directly attributed to insect pollination by aggregating crop-level dependency estimates across the chosen cultivated species. Next, we identify those departments whose agricultural output is most reliant on pollination services, thus revealing spatial hotspots of vulnerability. Finally, we explore the underlying drivers of these spatial patterns by correlating departmental pollination values with factors such as crop types, and the proportion of agricultural land. To achieve these objectives, we construct a detailed set of economic indicators and examine their relationships through correlation analysis. Furthermore, we apply generalized additive models (GAM) to investigate non-linear relationships between crop compositions and the economic importance of pollination. By leveraging the results of our study, it becomes possible to guide more effectively the scientific research and financial investment toward French departments where urgent measures are needed to protect pollinators. This approach can help minimize the risks linked to the loss of pollination services (lower agricultural productivity, food insecurity, economic instability in rural areas, etc.).

2. Material and methods

2.1. Study area

France was selected as the location of interest for two reasons. First and foremost, detailed data concerning agricultural production at the departmental level, with indicators like total quantity, yield, and surface cultivated, is available and easily accessible. Secondly, and due to its geography, France is rich in terms of biodiversity. It is bordered by the Mediterranean Sea to the south, the Atlantic Ocean to the west, and the English Channel to the north. Its diverse topography includes mountains, forests, rivers, lakes, and plains. Thus, its agriculture sector benefits immensely from its biodiversity, especially from the wide range of pollinators it provides. For that reason, France is a suitable candidate for this research. According to data.gouv.fr, France is divided into 13 regions and 96 departments (excluding overseas territories). In the results part, calculated values will be grouped into departments for comparison and modelling purposes.

2.2. The dependence ratio method

The dependence ratio (DR) method is widely used to estimate the economic benefits of pollination services, as it adjusts crop values by their biological reliance on insect pollinators. Earlier studies often equated the full market value of pollinated crops with pollination benefits, leading to inflated estimates. The DR method corrects this by applying crop-specific dependence ratios, which represent the percentage reduction in yield that would occur in the absence of animal pollination (IPBES, 2016; Breeze et al., 2016).

For each crop i, the dependence ratio D_i was obtained from published meta-analyses (notably (Klein et al., 2009; Layek et al., 2023)). These ratios are fixed coefficients derived from experimental or expert-based assessments, and they reflect potential yield losses without pollination, regardless of production system or variety.

Mathematically, the contribution of pollinators to crop i in department x is:

$$\mathrm{EVIP} = (P_i \times Q_{ix} \times D_i)$$

where:

- P_i = producer price of crop i (€/ton),
- Q_{ix} = quantity of crop i produced in department x (tons),
- D_i = dependence ratio of crop i.

This approach is scalable to small geographical units, such as the 96 French departments, but it does not account for interactions with other agronomic or ecological factors, which may still bias estimates upward.

2.2.1. Economic value of crop production

The first indicator is the Economic Value of Crop Production (EVCP), which measures the gross market value of crop outputs in each department. It is calculated as:

$$\mathrm{EVCP} = \sum_{i=1}^{I} (P_i \times Q_{ix})$$

where:

- P_i = producer price of crop i (€/ton),
- Q_{ix} = quantity of crop i produced in department x (tons),
- I = total number of crops considered.

Here, crop production quantities (Q_{ix}) were obtained from official statistics for the year 2022. They are reported in physical units (tons), which already integrate yields per hectare and the cultivated area of each crop. Thus, no assumption per acre or hectare was made, values are directly based on production volumes at the departmental level.

2.2.2. Economic value of insect pollination

The Economic Value of Insect Pollination (EVIP) represents the fraction of crop value attributable to pollinators. Following Layek et al. (2023) and Gallai et al. (2009):

$$\mathrm{EVIP} = \sum_{i=1}^{I} (P_i \times Q_{ix} \times D_i)$$

This equation parallels EVCP but multiplies by the dependence ratio D_i. EVIP thus measures the monetary value that would be lost if pollinators were absent.

2.2.3. Vulnerability ratio

After calculating the EVCP and the EVIP for each department, we move to understand the degree of dependence of the department on pollinators and pollination services. Following Gallai et al. (2009), the vulnerability ratio (VR) is the ratio of the economic value of insect pollination and the economic value of crop production. A low VR suggests that the agriculture sector is resilient to pollinator's decline, and a high VR implies the opposite, which means that there is a significant dependence of the agriculture revenue on insect's pollination. The equation can be found below.

$$VR = \frac{EVIP}{EVCP}$$

2.2.4. Economic value of insect pollination per hectare of land

While EVIP provides the absolute monetary contribution of pollinators, it is influenced by the scale of production. To normalize across departments of varying agricultural land area, we calculate EVIP per hectare (EVIP/ha):

$$EVIP \Big/ ha = \frac{\mathrm{EVIP}}{\sum \mathrm{Agricultural\ Land}}$$

This measure allows meaningful comparisons across regions. For example, a small department with limited farmland but high-value crops (e.g., orchards) may show high EVIP/ha despite lower absolute EVIP. Thus, EVIP and EVIP/ha were considered separately: one captures total economic contribution, while the other adjusts for land area to highlight intensity of pollination dependence.

2.3. Data collection

To analyze crop dependence on pollinators, three main datasets were compiled.

The first dataset contains crop production figures by department for the year 2022. These data were collected from the French Ministry of Agriculture's official database ('Agreste, La Statistique Agricole', n.d.). In this source, crops are grouped into five major categories: Fruit, Vegetables, Tubers, Vineyards, and COP (cereals, oilseeds, and proteinaceous).

The second dataset includes crop-specific pollination dependence ratios. These values were taken from Appendices 1 and 2 of the work by Klein et al. (2009), which classifies crops based on their level of reliance on animal pollinators.

The third dataset concerns crop prices, which required a more nuanced approach. Most price data were retrieved from the ('FAOSTAT', n.d.) platform, complemented by information from the ('European Commission's Eurostat', n.d.) database.

For several crops, we attempted to obtain specific 2022 price data from ('IndexBox Platform', n.d.), however these figures were behind a paywall and not publicly accessible. As an alternative, we used the freely available data for production volume and production value from the year 2020 to estimate average unit prices. These 2020 values were then adjusted to 2022 levels using the Index of Agricultural Product Prices at Production (IPPAP) (base 100 in 2020) that we got from the Agreste databases, following this formula:

$$2022\ Price = \frac{2020\ Price \times IPPAP\ 2022}{100}$$

For others, such as tomatoes and sunflowers, we applied a different method, given the unavailability of data for these crops. We used the producer price index (2014–2016 = 100) for 2022 and the producer price in 2015, both available on FAOSTAT. The 2022 estimate was derived using this formula:

$$2022\ Price = \frac{2015\ Price \times IPPAP\ 2022}{100}$$

These procedures allowed us to approximate crop prices with a reasonable degree of confidence. To check the robustness of our estimates, we carried out a sensitivity test by adjusting imputed prices by +-10 % and +-20 % (Table A.4 - appendices). These margins reflect typical price fluctuations in agriculture and provide a reasonable range for uncertainty.

Finally, each crop was assigned a pollination dependence level (no increase, little, modest, great, or essential) corresponding to numeric values of 0, 0,05, 0,25, 0,65, and 0,95. All datasets were consolidated into an Excel file and then imported into RStudio for processing and analysis.

3. Results

3.1. National level

Although we emphasize the significance of small-scale evaluations of pollination services, assessing them at the national level can still provide crucial insights into the overall importance of pollinators to the French agricultural sector.

For the studied crops, in 2022, 34 crops were investigated, of which 26 depend on pollinators in varying degrees, 8 have No Increase, 3 have little increase, 7 have a modest increase, 11 have a great increase, and 5 are essential. 11 crops belong to the fruit category, 9 to the COP, 12 are vegetables, 1 is vineyard, and 1 is tubers.

The total national EVCP is 34,8 billion €, of which 4,19 billion € (EVIP) is directly attributed to pollinators, making the national vulnerability 12 %, and the EVIP/ha equals 591,4 € per hectare. Below is the table (Table 1) for crops identified, including crop type, pollinator dependence, EVCP, EVIP, VR, and EVIP/ha.

3.2. Departmental level

To better understand how pollination services are distributed across French departments, we imported our data into RStudio. We calculated the indicators for each department (EVIP, VR, and EVIP per hectare). We then created maps using Rstudio to visualize the spatial distribution of these indicators and highlight regional patterns.

3.2.1. Economic value of insect pollination

This first map offers a visualization of the Economic Value of Insect Pollination (EVIP) across French departments, expressed in absolute monetary terms. It reveals insights into south/north patterns of agricultural dependency on pollinators, the structure of crop production,

Table 1
Crops produced in France, their dependence on pollinators, and pollination service value.

Crop	Crop type	DR	Dependance	EVCP	EVIP	VR	EVIP/HA
Apricot	fruit	0,65	Great	215911117,83	140342226,59	0,65	12355,16
Eggplant	vegetable	0,25	Modest	52180207,89	13045051,97	0,25	11483,32
Oat	cop	0,00	No increase	84345663,64	0,00	0,00	0,00
Cherry	fruit	0,65	Great	169372311,31	110092002,35	0,65	14593,32
Chestnut	fruit	0,25	Modest	46434047,35	11608511,84	0,25	1290,84
Pumpkin	vegetable	0,95	Essential	235868073,14	224074669,49	0,95	30065,03
Rapeseed	cop	0,25	Modest	3025374540,38	756343635,10	0,25	614,84
Cucumber	vegetable	0,65	Great	163675370,94	106388991,11	0,65	101516,21
Zucchini	vegetable	0,25	Modest	174974488,85	43743622,21	0,25	10763,69
Strawberry	vegetable	0,25	Modest	316490471,41	79122617,85	0,25	20303,47
raspberry	fruit	0,65	Great	54714725,15	35564571,35	0,65	55743,84
Green bean	vegetable	0,05	Little	283654970,87	14182748,54	0,05	451,69
Kiwi	fruit	0,95	Essential	146543511,00	139216335,45	0,95	35433,02
Oilseed	cop	0,05	Little	42636567,52	2131828,38	0,05	73,73
Corn	cop	0,00	No increase	3366165532,94	0,00	0,00	0,00
Melon	vegetable	0,95	Essential	369269128,92	350805672,47	0,95	27992,79
Turnip	vegetable	0,65	Great	15757733,22	10242526,59	0,65	4097,01
Hazelnut	fruit	0,95	Essential	19566651,78	18588319,19	0,95	2460,40
Nut	fruit	0,95	Essential	128452919,25	122030273,29	0,95	4535,94
Barley	cop	0,00	No increase	3283259404,97	0,00	0,00	0,00
peach	fruit	0,65	Great	348428885,16	226478775,35	0,65	19809,93
Small peas	vegetable	0,00	No increase	110203798,82	0,00	0,00	0,00
pear	fruit	0,65	Great	137713670,14	89513885,59	0,65	15159,00
Leak	vegetable	0,65	Great	133342851,11	86672853,22	0,65	16152,23
pepper	vegetable	0,05	Little	40120989,46	2006049,47	0,05	1921,50
Apple	fruit	0,65	Great	950398616,60	617759100,79	0,65	15661,28
Potato	tubercule	0,00	No increase	2964227949,53	0,00	0,00	0,00
plum	fruit	0,65	Great	324088637,64	210657614,47	0,65	14037,29
Grape	vineyard	0,00	No increase	15353138199,59	0,00	0,00	0,00
Rye	cop	0,00	No increase	33494414,92	0,00	0,00	0,00
Soy	cop	0,25	Modest	232947013,45	58236753,36	0,25	316,67
Sorghum	cop	0,00	No increase	67150953,05	0,00	0,00	0,00
Tomato	vegetable	0,65	Great	590379776,10	383746854,47	0,65	76079,87
Sunflower	cop	0,25	Modest	1362521668,40	340630417,10	0,25	391,28
Total	–	–	–	**34842804862,34**	**4193225907,59**	**0,12**	**591,42**

and potential areas for policy intervention. Departments such as Bouches-du-Rhône (13), Lot-et-Garonne (47), Tarn-et-Garonne (82), and Gard (30) show the highest EVIP values, exceeding 150 million euros, with Bouches-du-Rhône reaching 301 million euros (Map 1). These areas benefit from favorable Mediterranean and Atlantic climates, which promote the cultivation of pollination-dependent crops. Longer growing seasons and higher productivity intensify their reliance on insect pollination. In contrast, departments in northern and central France, characterized by cooler, wetter conditions and a dominance of cereals and livestock, display lower EVIP values.

This spatial distribution reveals that pollination is economically critical in southern and western France, making these regions priority zones for pollinator conservation policies. Maintaining pollination services here is not only an ecological concern but also a strategic economic necessity.

While the absolute EVIP map effectively identifies where the economic stakes are highest, it is highly dependent on land area, which can bias the analysis, so it is essential to complement this perspective with the EVIP per hectare (EVIP/ha) indicator.

3.2.2. Economic value of insect pollination per hectare

To enhance the interpretation of EVIP per hectare (EVIP/ha) across French departments, a quantile-based classification was applied. Given the limited dispersion of EVIP/ha values, using tertiles improved the visualization of spatial contrasts by categorizing departments into high, medium, and low pollination values per hectare.

Unlike the absolute EVIP map, which reflects total economic contributions, the EVIP/ha map (Map 2) emphasizes pollination efficiency relative to cultivated land. This reveals new patterns: western coastal regions, notably Bretagne and Pays de la Loire (e.g., Loire-Atlantiques and Finistère). In these regions, horticulture, floriculture, and market gardening are widespread, often in small plots that require intensive pollination, leading to high economic returns per unit of land. Similarly, Bouches-du-Rhône in the Mediterranean zone exhibits the highest EVIP/ha values as it benefits from favorable climatic conditions and diversified cropping systems, heavily reliant on pollination services.

Conversely, departments within the Île-de-France region (e.g., Seine-Saint-Denis, Hauts-de-Seine, Essonne) display low EVIP/ha values, which illustrate the dilution effect of land pressure and urban expansion. Here, the agricultural footprint is minimal and often fragmented. Similarly, departments in central and eastern France, dominated by cereal and livestock farming, show generally moderate to low values.

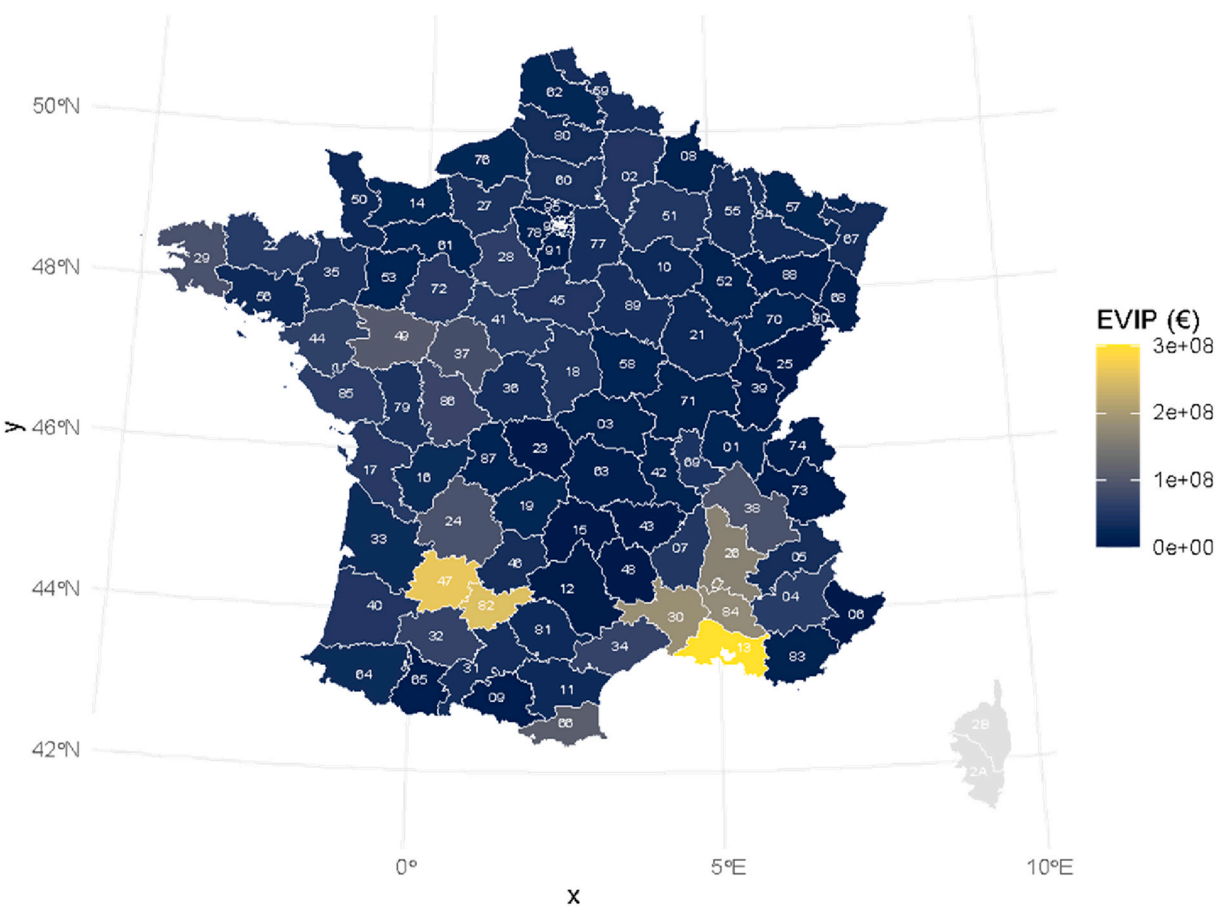
Notably, some departments with high absolute EVIP, such as Lot-et-Garonne (47) or Gard (30), do not necessarily appear in the top tier for EVIP/ha. This discrepancy reveals that their high value stems more from land area than pollination efficiency, emphasizing the need for both indicators in complementary use.

Ultimately, the quartile-based EVIP/ha map illustrates that high pollination value per hectare is not evenly spread across France, but rather clustered in regions where climate, land use, and crop systems create favorable conditions for pollinator-dependent production. It shifts the discussion away from "where is there the most agriculture" to "where does agriculture rely most efficiently on pollinators."

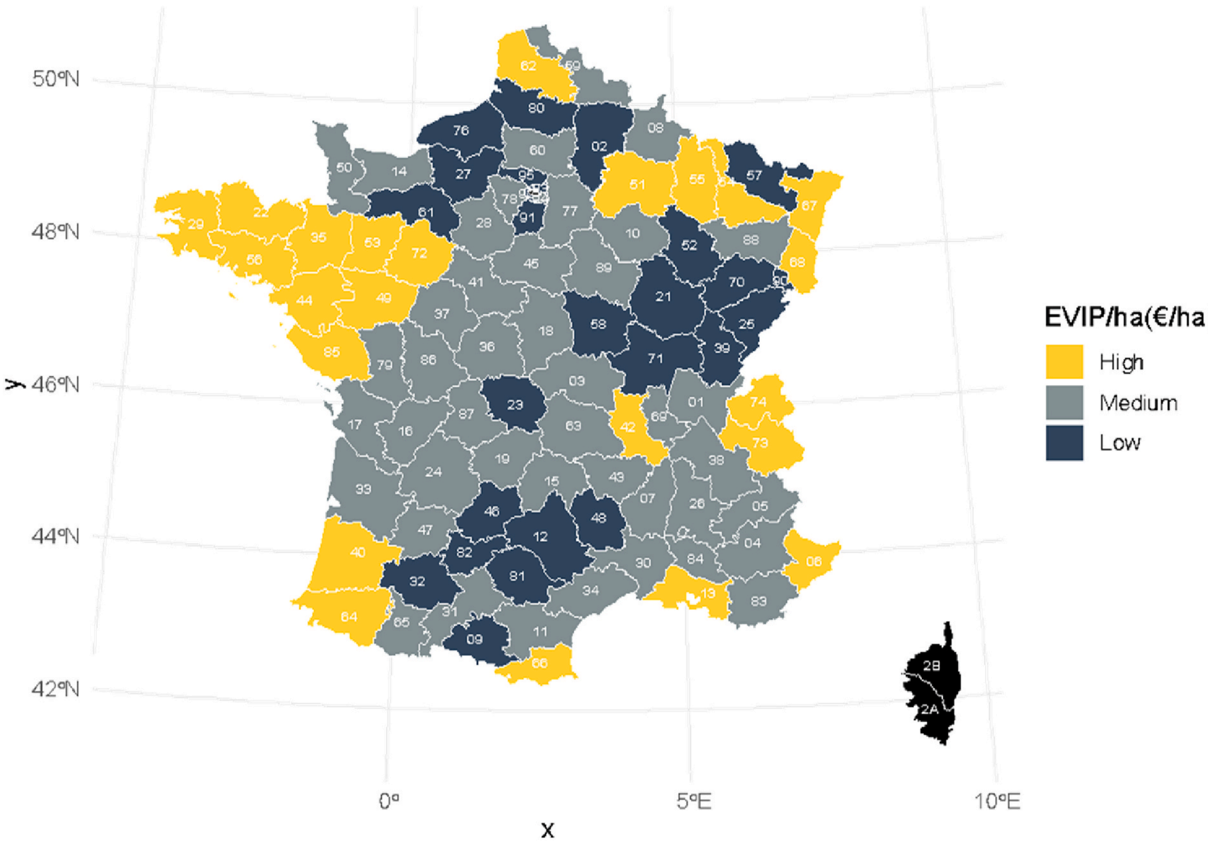
The EVIP/ha map offers a refined lens on where pollination services are most productive per hectare, but it still does not reflect the economic risk associated with pollination dependence. For that, we must turn to the vulnerability rate (VR), which quantifies the proportion of total agricultural value at risk from pollinators decline.

3.2.3. Vulnerability ratio

The third map (Map 3) representing the absolute vulnerability ratio provides a continuous view of the proportion of agricultural value



Map 1. Mapping the Economic Value of Insect Pollination in French departments.



Map 2. Mapping the Economic Value of Insect Pollination per hectare of agricultural land in French departments.

dependent on insect pollination within each French department. Unlike EVIP or EVIP/ha, the VR reflects the structural exposure of agricultural systems to potential pollinator decline, independent of the total or per-hectare value.

Departments such as Alpes-de-Haute-Provence (04), Hautes-Alpes (05), Corrèze (19), and Tarn-et-Garonne (82) exhibit the highest vulnerability rates, exceeding 0,4 and reaching up to 0,58. These regions, often characterized by mountainous or Mediterranean climates, have fragmented agricultural landscapes dominated by high-dependence fruit and vegetable crops, such as apricots, apples, or melons. In contrast, departments in northern and central France, where urbanization, cereal production, and livestock farming prevail, show lower VR values. These systems are typically more mechanized and less reliant on ecological services like pollination.

Interestingly, while Tarn-et-Garonne (82) appeared among the top departments in both EVIP and VR, others like Corrèze (19), with modest absolute EVIP, rank high in VR due to their structural crop dependency. These high vulnerability rates are not necessarily correlated with total agricultural output or land area. Many of the most vulnerable departments have limited agricultural surfaces, but are highly specialized in pollination-sensitive production.

The VR map thus highlights structural vulnerabilities that could result in significant economic impacts if pollination services decline, particularly in regions with small-scale, specialized agriculture. Moreover, combining VR analysis with climate and land use data reveals that Mediterranean and mountainous areas, already prone to climatic stresses like drought and frost, face compounded risks, reinforcing their critical dependence on maintaining pollinator populations.

3.2.4. Implications and key insights

The combined analysis of EVIP, EVIP per hectare, and vulnerability rate (VR) offers a detailed view of how insect pollination supports agriculture across French departments. It shows that pollination services do not carry the same weight everywhere. In southern and western regions, especially under Mediterranean and oceanic climates, the absolute EVIP is highest, reflecting the large-scale production of fruit and vegetables that heavily depend on pollinators. However, when looking at EVIP per hectare, coastal regions like Bretagne and Pays de la Loire emerge, where smaller but more diverse and intensive cropping systems make pollination services highly valuable per unit of land.

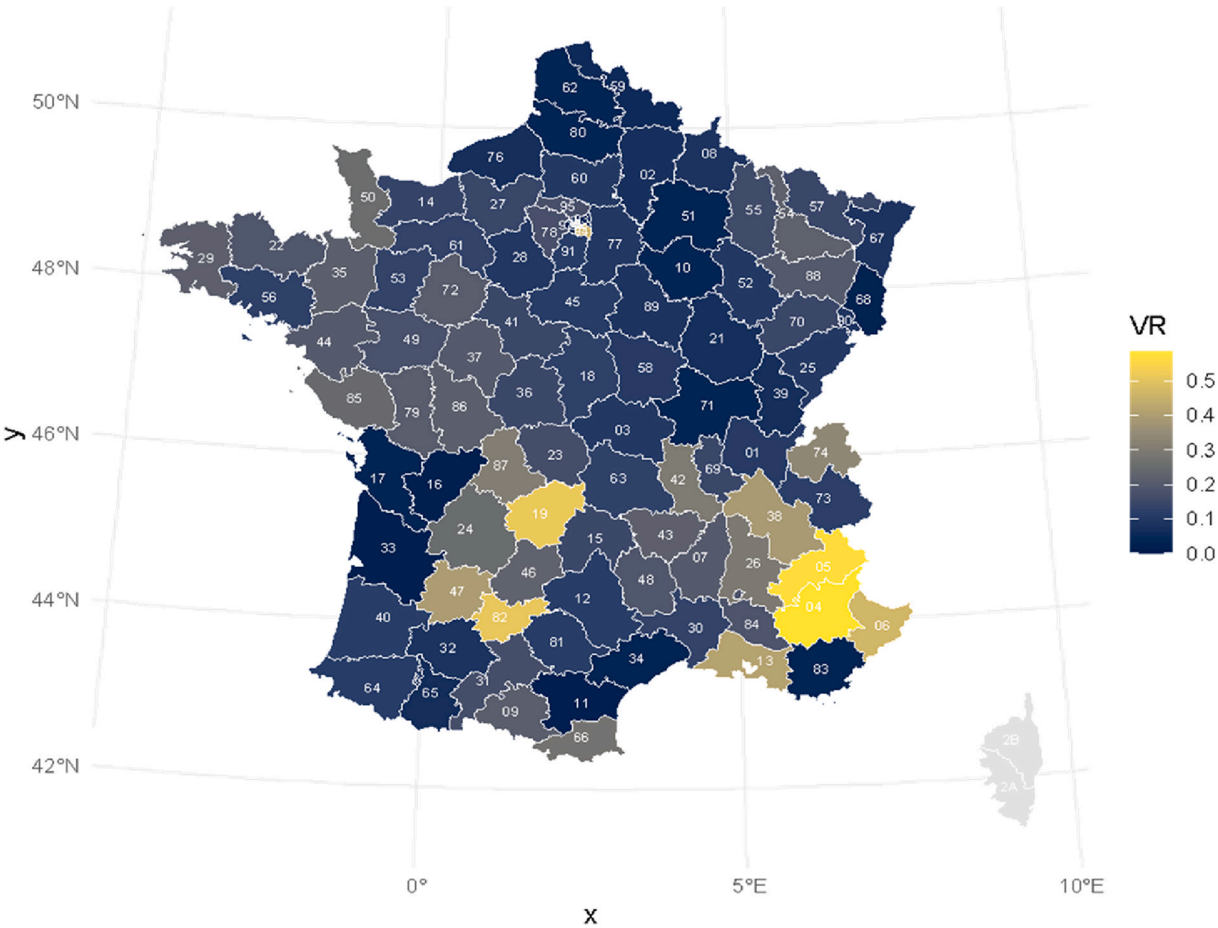
The VR indicator brings another dimension: it highlights areas such as Alpes-de-Haute-Provence and Corrèze, where even modest agricultural sectors are structurally very dependent on pollinators, making them more vulnerable to their decline.

Together, these three perspectives show that pollination's economic role varies by both scale and intensity, shaped by climate, crop diversity, land use, and regional specialization. These findings make clear that protecting pollination services requires targeted, region-specific strategies, balancing both economic importance and ecological risk to support sustainable agriculture.

3.3. Identifying departments where pollination has a significant importance to the agriculture sector

3.3.1. Correlation matrix

3.3.1.1. Correlation matrix of crop types and pollination indicators. The correlation matrix analyzes the relationships between three major crop categories, FRUIT, VEGETABLE, and COP (Cereals, Oilseeds, Protein crops) *(Vineyard and tuber crops were excluded from the correlation analysis, as their associated EVIP, EVIP* per *hectare, and vulnerability values were systematically zero across all departments, making it statistically impossible to compute meaningful correlations for these categories)* and four key indicators reflecting economic dependency on pollination services:



Map 3. Mapping the Pollination vulnerability in French departments.

- EVCP_tot: total agricultural income,
- EVIP_tot: total economic value of insect pollination,
- EVIP/ha: economic value of pollination per hectare,
- VR_moy: average vulnerability to pollinator decline.

The analysis of the correlation matrix (Fig. 1) reveals important statistical patterns across French departments, shedding light on the differentiated role of crop types in shaping the economic significance and ecological vulnerability of pollination services.

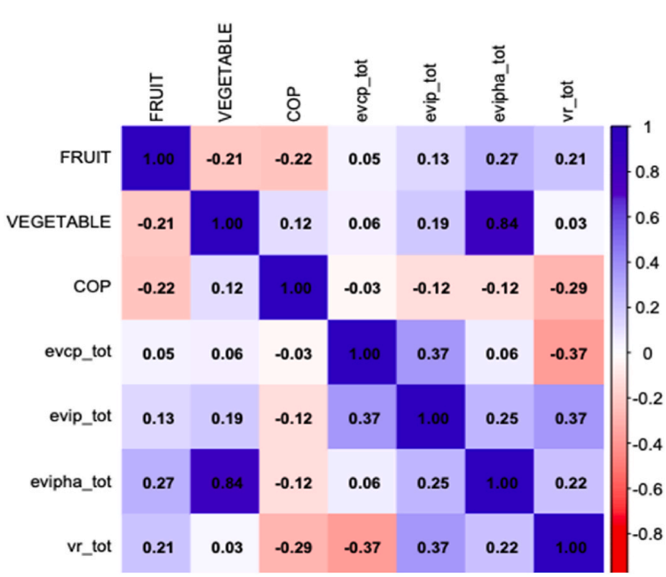


Fig. 1. Correlation Matrix of crop types and pollination indicators.

Starting with vegetable cultivation, we observe a strong and significant positive correlation with EVIP/ha ($r = 0{,}84$, $p = 0 < 0{,}001$), confirming the critical dependence of vegetables such as melon, cucumber and pumpkin on insect pollination. In departments where vegetable farming is prominent, the economic value per hectare is notably high. Additionally, these regions display a weak but statistically significant positive correlation with total EVIP ($r = 0{,}19$, $p = 0{,}03 < 0{,}05$). These areas combine economic efficiency with a certain degree of ecological fragility, especially in the absence of crop diversification.

Fruit crops, although known for their pollination dependency, show a weak but significant correlation with EVIP/ha ($r = 0{,}27$, $p = 0{,}009 < 0{,}01$). Despite high dependency ratios in species like apple, pear, and apricot, their impact remains regionally confined and diluted.

In contrast, COP crops display a moderate and significant negative correlation with VR ($r = -0{,}36$, $p = 0{,}004 < 0{,}01$), confirming their role in providing structural resilience. This inverse relationship is coherent with the biological characteristics of major staples like barley, oats, and sorghum (RD = 0), as well as partially dependent crops like sunflower and rapeseed (RD = 0,25).

Finally, the link between EVIP/ha and vulnerability (VR) is moderate and statistically significant ($r = 0.38$, $p = 0{,}006 < 0.01$). This result points to a clear pattern: departments deriving the highest per-hectare value from pollination services are also among the most ecologically sensitive. This reinforces the need for targeted conservation policies in economically valuable yet ecologically exposed areas.

3.3.1.2. Scatterplot of EVIP/ha vs vulnerability (VR). To better understand the link between the economic value of pollination services and the vulnerability of agricultural systems, we constructed a scatterplot crossing EVIP/ha with the vulnerability rate for each department. This approach allows us to visualize how the value of pollination per unit of land is related to the risk of pollinator decline.

The scatterplot (Fig. 2) plots French departments based on two variables: EVIP per hectare (€/ha) on the x-axis and vulnerability to pollination decline (VR) on the y-axis. Each department is represented by a numerical label (e.g., 006 for Alpes-Maritimes). Overall, we can see from Fig. 2 that the form of the scatterplot is an elliptical cloud with a slight upward trend, indicating a general but non-linear association between EVIP/ha and vulnerability. A dense cluster is visible between EVIP/ha values of 10000–15000 euros and VR levels between 0,3 and 0,4.

At the upper end of the spectrum, departments such as Loire-Atlantiques (044) and Pyrénées-Orientales (066) report both high EVIP/ha values (19303 € and 16879 €, respectively) and high vulnerability rates (VR = 0,41 and 0,44). These results reflect their specialization in high-value, pollination-dependent crops, particularly vegetables (e.g., over 43000 €/ha for VEGETABLE production in Loire-Atlantiques). Similarly, Côtes-d'Armor (022) and Finistère (029) display EVIP/ha values exceeding 17000 €, consistent with their intensive agricultural systems fostered by oceanic and temperate climates. Same thing for Alpes-Maritimes (006), despite a relatively small agricultural base (EVCP ≈ 9 million €), stands out with high vulnerability (VR = 0,48) and a high EVIP/ha (15989 €), reflecting the strong reliance of its Mediterranean horticultural production on pollinators.

At the opposite end, highly urbanized departments such as Hauts-de-Seine (092) and Seine-Saint-Denis (093) exhibit very low EVIP/ha (0 € and 576 €, respectively) and low vulnerability (VR = 0 and 0,10), reflecting the near-absence of productive agricultural land. Territoire de Belfort (090) also reports low EVIP/ha (4618 €) and vulnerability (VR = 0,20), consistent with its small surface area and industrial-economic orientation. Other departments like Essonne (091) and Seine-Maritime (076) present modest EVIP/ha values (8533 € and 8700 €) and moderate vulnerability, linked to the dominance of COP crops and relatively less land of fruits and vegetables.

Between these two extremes, departments such as Cantal (015) and Haute-Loire (043) show moderate EVIP/ha levels (12508 € and 13584 €) combined with lower-than-average vulnerability (VR = 0,31 and 0,33), characteristic of livestock-oriented agricultural systems in the Massif Central.

Southern and western departments, with Mediterranean or oceanic climates, tend to favor intensive vegetable and fruit farming, increasing both EVIP/ha and vulnerability. Northern and eastern departments, where cereals and industrial crops dominate, show a little less reliance on pollination. Mountainous and livestock-oriented areas like Auvergne and the Massif Central lie in a balanced middle zone.

However, the scatterplot as a whole reveals a more nuanced reality: most departments cluster within a relatively narrow range of vulnerability and EVIP/ha values. This indicates that, regardless of crop specialization, the decline in pollination services has the potential to affect nearly all regions to varying degrees. The observed patterns suggest that additional factors, beyond agricultural structure alone, must be considered to fully understand the exposure of each region to pollinator decline.

3.3.2. GAM model

3.3.2.1. Observed vs predicted values of the economic value of insect pollination per hectare of land. Fig. 3 illustrates the relationship between the observed and predicted values of EVIP/ha from the GAM model. The points cluster tightly along the reference line, indicating a highly accurate model fit. The minimal dispersion confirms the strong predictive power of the model, consistent with the adjusted R^2 of 0,97 and the 97,6 % deviance explained. This validates the model's robustness in capturing the underlying structure of the data.

3.3.2.2. Smooth terms: non-linear effects of crop categories. Fig. 4 below displays the estimated smooth terms for the effects of FRUIT, VEGETABLE, and COP crop areas on the log-transformed EVIP/ha.

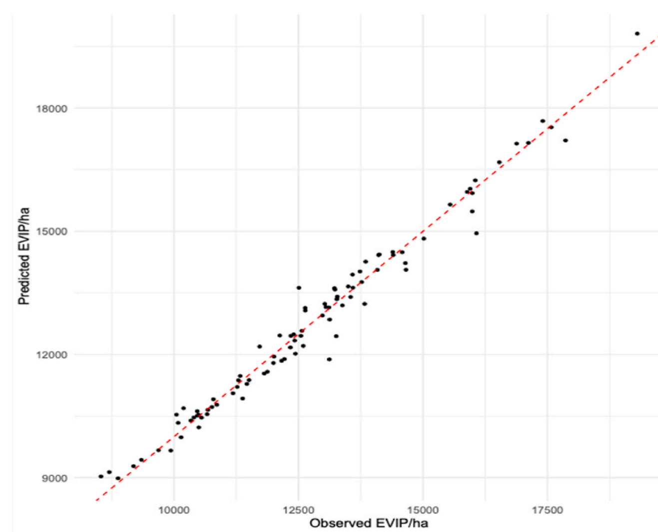


Fig. 3. Observed vs predicted values of the Economic Value of Insect Pollination per hectare of land.

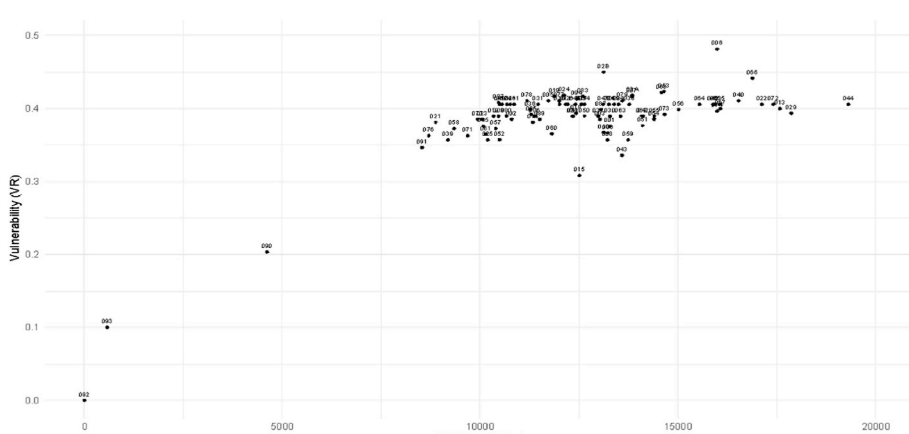


Fig. 2. Scatterplot of EVIP/ha vs Vulnerability (VR).

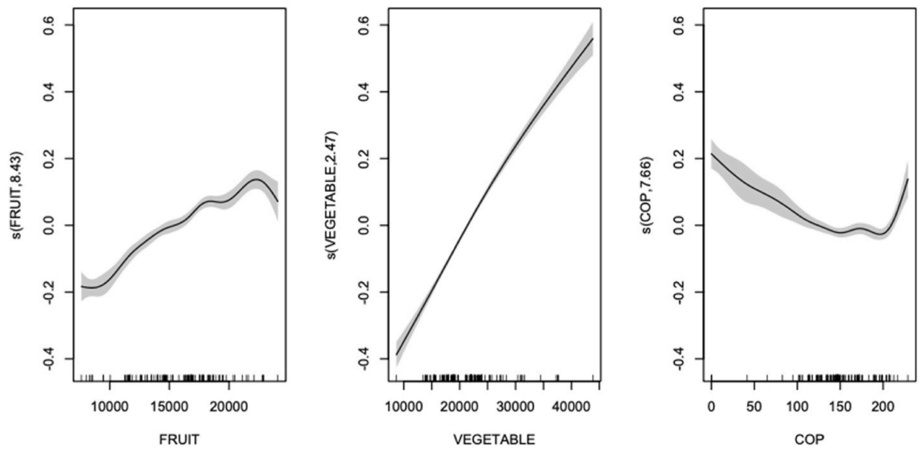


Fig. 4. Estimated smooth terms for the effects of FRUIT, VEGETABLE, and COP crop areas on the log-transformed EVIP/ha.

- VEGETABLE: The strongest effect is observed for vegetables, with a sharp rise in EVIP/ha up to 20000 ha, before flattening. This supports the finding from the correlation analysis that vegetable area is the primary driver of EVIP/ha, due to the high pollination dependency of many vegetable crops (e.g., melon, pumpkin, tomato).
- FRUIT: The effect is positively non-linear, showing a steep increase up to approximately 10000 ha, followed by a plateau and slight decline beyond 13000 ha. This suggests a diminishing marginal return of pollination services in fruit-dominant departments beyond a certain threshold.
- COP: A negative non-linear effect is observed. EVIP/ha decreases with increasing COP area, then stabilizes. This is consistent with the fact that COP crops (e.g., cereals, rapeseed, oats) have little or no dependence on insect pollination, thus reducing the relative value of pollination services in such areas.

3.3.2.3. Model diagnostics. The figures below (5, 6, 7, and 8) present the standard diagnostic plots used to evaluate the statistical validity of the GAM model:

- QQ plot of deviance residuals (Fig. 5): The residuals align closely with the reference line, suggesting that the normality assumption is satisfied.

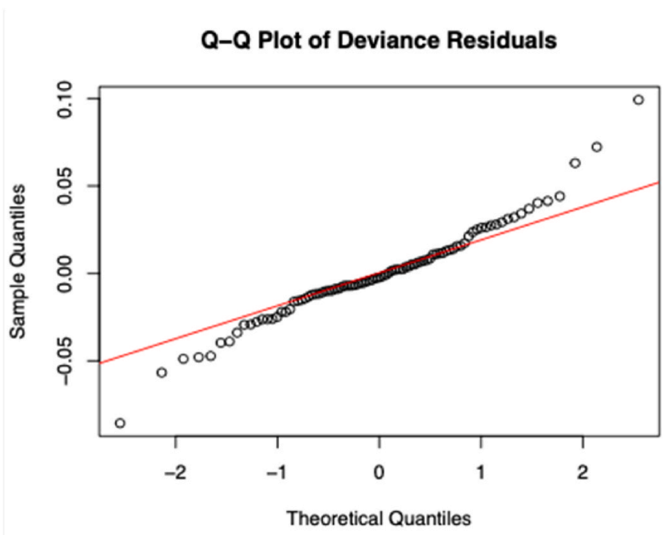


Fig. 5. QQ plot of deviance residuals.

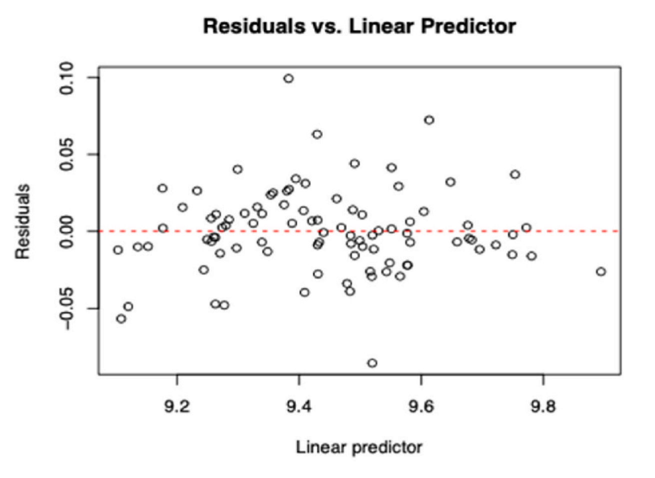


Fig. 6. Residuals vs linear predictor.

- Residuals vs linear predictor (Fig. 6): The residuals are randomly scattered around zero, without any visible pattern, confirming the absence of heteroscedasticity or systematic bias.
- Histogram of residuals (Fig. 7): The distribution appears symmetrical and centered around zero, supporting the normality of errors.

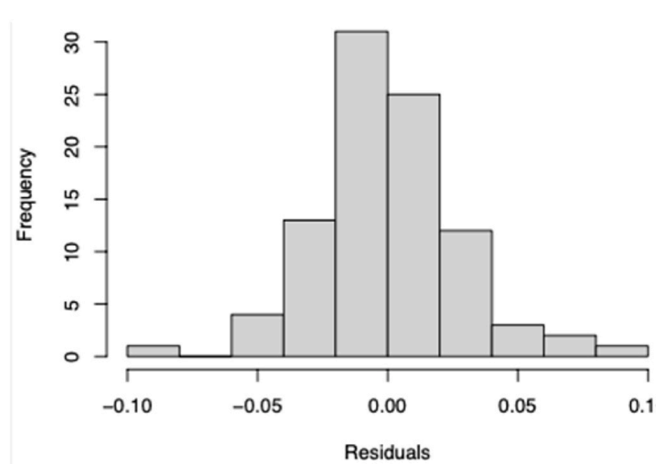


Fig. 7. Histogram of residuals.

- Response vs fitted values (Fig. 8): The observed responses closely follow the fitted values along the diagonal, indicating a nice overall model fit.

3.3.2.4. Implications and key insights. The GAM model predicting the Economic Value of Insect Pollination per hectare (EVIP/ha) shows strong reliability, with an adjusted R^2 of 0,97 and 97,6 % of deviance explained. The close match between observed and predicted values, as well as the good distribution of residuals, confirms the model's robustness.

Smooth term analysis reveals that vegetable and fruit areas strongly increase EVIP/ha, while the expansion of COP crops reduces it. These non-linear effects highlight the critical role of crop composition in shaping the economic value of pollination services. Overall, the model effectively captures the key ecological-economic relationships across departments.

4. Discussion

In this study, we explored the economic importance of pollinators to agriculture using a high-resolution approach at the departmental level across France. Nationally, we estimate the total Economic Value of Crop Production (EVCP) to be 34,8 billion €, the total Economic Value of Insect Pollination (EVIP) to be 4,19 billion €, the average vulnerability ratio (VR) to be 12 %, and the national average EVIP per hectare (EVIP/ha) to be 591,4 €/ha. When compared with the estimates provided by Leonhardt et al. (2013), who valued France's EVIP at 2,1 ± 0,5 billion €, our figure is almost twice as high. The contrast is even more striking with EVIP/ha: Leonhardt et al. report an average of 56,12 €/ha, over ten times lower than our estimate. The vulnerability ratio, however, remains comparable, 12 % in our study versus 9 % ± 1 % in theirs, which reinforces the reliability of this indicator across methodologies.

Several reasons may explain these differences. First, inflation and global price shifts between 2013 and 2022 have increased the market value of pollination-dependent crops. Second, our methodology leverages finer spatial granularity. The departmental approach in our study captures heterogeneity in production systems, crop specialization, and local land use, unlike Leonhardt et al.'s country-level averages. This allows for a more accurate assessment of where pollinators contribute the most. Yet, despite methodological and temporal differences, both studies converge on the central insight: if pollinators were to collapse, France would face a double-digit reduction in crop production value. As a matter of fact, Leonhardt et al. (2013) have stated that given the importance of pollination services, the EU might face a monetary loss due to declining numbers of pollinators, although it is unlikely that the world will lose all pollinating insects. This also aligns with international estimates, which showed that even under assumptions of partial substitution and price adjustments, Europe could suffer from a multibillion-dollar economic loss, particularly in fruit-dominated systems (Bauer and Wing, 2016).

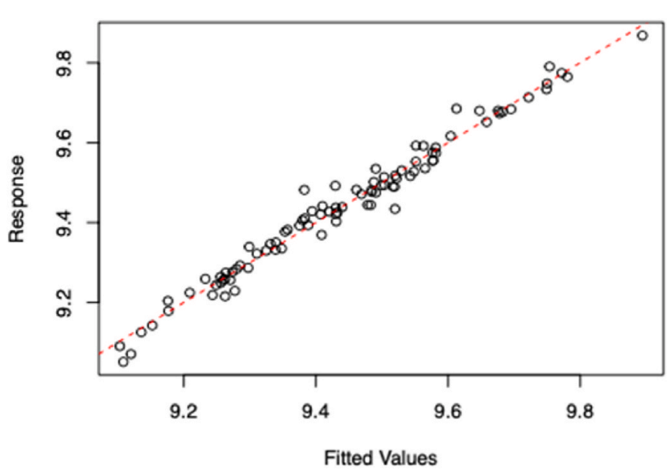


Fig. 8. Response vs fitted values.

In practice, the use of fixed dependence ratios can bias results in both directions. In departments dominated by monocultures with low pollinator diversity, the method may overestimate the contribution of pollinators, since actual pollination efficiency is often below the global average. By contrast, in heterogeneous or pollinator-rich landscapes, it may underestimate the benefits of pollination, as interactions between crops, wild pollinators, and landscape composition can enhance yields beyond fixed coefficients. While this limitation affects absolute values, the relative spatial patterns remain robust because all departments are evaluated under the same framework. A promising avenue for future work is the development of dynamic models that integrate ecological indicators such as pollinator abundance, species richness, habitat diversity, and pesticide use, alongside economic data.

Because some crop prices for 2022 had to be estimated using older data and agricultural price indices, we tested how sensitive our results are to this approximation. In agriculture, producer prices can vary a lot from one year to another, often by more than 10 %. For this reason, we applied two simple bands, +-10 % and +-20 %, which cover the range of typical year-to-year fluctuations. At the national scale, the EVIP ranged from 3,35 billion € (−20 %) to 5,03 billion € (+20 %), compared to our baseline of 4,19 billion €. This means that the total value changes by 7–20 %, which is expected given the price variation. However, because crop prices are national (the same for all departments), this shift applies equally across the country. As a result, the relative positions of departments remain the same. Departments that were identified as high-value or highly vulnerable to pollinator loss remain in those categories. This test shows that even if some prices are not exact, the main results and spatial patterns of the study are robust.

Another limitation of this study is that it focuses on 34 major crops. These crops account for the vast majority of national agricultural production, so adding smaller crops would not substantially change the national EVIP estimates. However, at the departmental scale, the effect could be more significant. In some regions, minor or niche crops such as berries, nuts, or aromatic plants represent an important share of local agricultural income and are often highly pollinator-dependent. Their inclusion could therefore raise the EVIP for certain departments and refine the spatial diagnosis of vulnerability. Future work should extend crop coverage to better capture these local specificities.

The VEGETABLE and FRUIT categories are not only economically important but also sinequanone for nutritional security, which explains why the vulnerability is concentrated in these specific crop types. A decline in pollination services would thus affect both economic output and public health (Breeze et al., 2016; IPBES, 2016). Moreover, spatial analysis through Figs. 4 and 5 demonstrates that southern and western French departments are significantly more reliant on pollination, both in terms of EVIP/ha and VR. This is consistent with studies across the EU, where warmer Mediterranean countries reveal both higher pollination value and greater dependency on pollination services, due to their production of fruit and vegetable-dominated systems (Leonhardt et al., 2013). The correlation matrix in Fig. 1 confirms this connection, revealing that departments with higher EVIP/ha also tend to exhibit greater vulnerability. This suggests that these departments are not only economically reliant on pollination but also structurally exposed to pollinator decline, a concern that Bauer and Wing (2016) further emphasized through macroeconomic simulations, showing how sectoral shocks from pollination loss can amplify regional disparities and threaten rural economic resilience.

Fig. 2 highlights departments where pollination services are concentrated. However, it's important to distinguish between ecological risk and economic vulnerability. A department with a high VR doesn't necessarily mean that its pollinator population is most threatened; it means that the local agricultural economy would suffer the most in the case of a pollination service failure. Nonetheless, we note that in orchard-dominated systems, wild bee richness and abundance are often lower than in more heterogeneous landscapes (Bommarco et al., 2012). This statement raises concerns for French departments with a high VR where FRUIT cultivation predominates, suggesting the need for targeted ecological assessments and conservation action. This is where the EVIP/ha indicator is useful. It reflects the economic return of pollinators per unit of land. It is going to help inform regional subsidy allocation and design incentive schemes to protect pollination services. This said, departments with a high EVIP/ha should be prioritized in pollinator conservation programs, especially when combined with high VR.

Overall, the multi-indicator framework developed in our study offers a nuanced lens through which policymakers and scientists can identify French departments where pollination services are both economically essential and ecologically at risk. Leonhardt et al. (2013) relied on country-wide averages and coarse resolution data to make national-level assessments, but our approach leverages high-resolution, crop-specific production values and recent department-level data to provide a much finer and more accurate spatial diagnosis. This level of detail is important for territorialized policy interventions. In addition to the granularity, our study integrates multiple indicators (total EVIP, EVIP per hectare, and vulnerability ratio), which together offer a multidimensional understanding of how and where pollination matters most.

Moreover, the relevance of our approach is amplified in today's context. Since the study of Leonhardt et al. (2013), agricultural prices have changed due to inflation, market volatility, and the increasing demand for nutrient-dense foods, fruits, and vegetables, for instance, pollinator-dependent crops. Our method provides an updated view and highlights how regions within the same country face disproportionate risks if pollination services continue to decline.

Our findings can also be situated within the broader international literature. For example, Bauer and Wing (2016) simulated the effects of a global pollinator collapse using a computable general equilibrium (CGE) model. Their partial equilibrium approach estimated global direct losses in the crop sector at 138,3 billion $, while their CGE model, accounting for indirect effects on non-agricultural sectors and price changes, estimated total global economic losses at 334,1 billion $. Interestingly, the direct agricultural loss estimated under general equilibrium was much lower (10,5 billion $), illustrating that partial approaches may overstate crop-level risks while underestimating broader economic repercussions. Compared to their global-scale and macroeconomic framework, our study adopts a bottom-up approach. The granularity of our data allows us to identify precise hotspots of economic and ecological risk, particularly in vegetable and fruit-dominated French zones. Our study thus complements the CGE model by giving direct and explicit insights for more territorial policies, while also echoing Bauer & Sue Wing's conclusion that pollinator losses, whether direct or systemic, present serious economic threats.

Ultimately, by combining spatial precision with economic and ecological insight, this framework empowers policymakers to make better-informed decisions in a country, France, for instance. It supports the design of targeted agri-environmental schemes, regional incentive structures, and biodiversity strategies that reflect the current territorial value of pollination, ensuring that interventions are scientifically grounded, economically justified, and socially equitable.

5. Conclusion

Our study advances a detailed, spatialized assessment of the economic significance of insect pollination across French departments, using a multi-indicator framework that integrates the total Economic Value of Insect Pollination (EVIP), EVIP per hectare (EVIP/ha), and the vulnerability ratio (VR). Unlike prior national-scale assessments, our departmental approach captures the spatial heterogeneity of crop systems, pollination dependencies, and ecological risks. By doing so, it provides a clearer picture of where pollination services are economically critical and ecologically fragile.

Our results show that the highest total EVIP is found in southern and western departments, especially those with Mediterranean and oceanic climates. These areas are hubs for fruit and vegetable production, crop types that are highly dependent on pollinators and offer high returns per hectare. When looking at EVIP/ha, departments such as Loire-Atlantiques and Finistère emerge as hotspots of pollination efficiency, where small but diverse plots contribute significantly to national pollination value. Meanwhile, the vulnerability ratio (VR) highlights regions like Alpes-de-Haute-Provence and Corrèze, where the agricultural economy, although modest in scale, is disproportionately reliant on pollination services. These areas would suffer the most from pollinator decline, not necessarily due to scale, but due to structural crop dependency. The positive correlation between EVIP/ha and VR underscores a fundamental tension: the regions that benefit most from pollinators are often the most at risk if those services are lost, and this calls for urgent territorial policy responses.

However, our study is not without limitations. First, the modeling framework assumes a static and linear relationship between crop yield and pollination dependency, which doesn't take into consideration adaptive farming practices (shifting crop types or increasing artificial pollination, for example), nor longer-term ecological feedbacks such as pollinator population resilience or land-use shifts. These complex dynamics could alter the actual impact of pollinator decline on crop yields and economic outcomes. In contrast, the Computable General Equilibrium model (CGE), developed by Bauer and Wing (2016), attempts to simulate these adaptive behaviors and systemic feedbacks at a macroeconomic level, providing a complementary but broader-scale understanding of pollination decline effects. Second, the vulnerability ratio (VR) is a valuable indicator of structural exposure to pollination loss, but it doesn't directly measure pollinator health, abundance, or diversity. In reality, these ecological parameters depend on a multitude of factors, such as pesticide use, habitat conversion, and climate change. As a result, a department may exhibit high vulnerability without necessarily having degraded pollinator populations, and vice versa. Third, due to data constraints, the study does not include the full spectrum of crops cultivated in France. Consequently, some minor or region-specific crops were omitted, possibly leading to a slight underestimation of our numbers. Furthermore, some crop types, such as vineyards and tubers, were excluded from the correlation and modeling analyses. This exclusion was specifically methodological. In our dataset, both grapes (vineyard) and potatoes (tuber) have a dependency ratio (RD) of zero. As a result, their associated EVIP, EVIP/ha, and VR values were systematically zero across all departments. Including these values in the correlation matrix and the predictive model would have introduced statistical noise. Their exclusion ensures a cleaner and more interpretable model structure. Fourth, another source of uncertainty comes from crop prices. For some crops, 2022 producer prices had to be estimated using earlier values adjusted with agricultural price indices. While this approach relies on official sources, it introduces a potential margin of error. A sensitivity analysis with +-10 % and +-20 % price variations shows that national EVIP values range from 3,35 to 5,03 billion €, compared to our baseline of 4,19 billion €. Importantly, these adjustments do not change the relative ranking of departments, which confirms that the spatial patterns remain robust. Fifth, the use of fixed dependence ratios (DR) introduces another limitation. These coefficients are derived from global averages and do not vary with local conditions. As a result, the method may overestimate pollination benefits in homogeneous monocultures with low pollinator diversity and underestimate them in heterogeneous or pollinator-rich landscapes. While this affects absolute values, the relative spatial patterns remain robust since all departments are evaluated with the same framework. Future work should therefore aim to develop dynamic approaches that integrate ecological data such as pollinator abundance, landscape diversity, and pesticide use. Last but not least, the analysis also excludes certain minor or niche crops. While their contribution at the national level is small, they may hold greater importance in specific regions, where their pollinator dependence could affect both local economic resilience and cultural heritage. Including them in future assessments would improve the completeness and territorial sensitivity of pollination value estimates.

Despite these limitations, the framework presented in our analysis offers a tool for territorialized policy planning. By moving beyond national averages and integrating recent, crop-specific economic data, this study updates previous estimates, such as those by Leonhardt et al. (2013).

As for next steps, future research should seek to integrate ecological data on pollinator populations, land-use fragmentation, and pesticide use to better contextualize economic vulnerability. It is also important to couple economic indicators with social and political variables like policy uptake capacity, farmer behavior, and public incentives, which would enhance the operational relevance of decision-making. Additionally, as Bauer and Wing (2016) have demonstrated, the decline of pollinators not only affects the agricultural sector directly, but has consequences that go beyond that. Even modest reductions in pollination services could disrupt food systems and exacerbate regional inequalities. In France, as shown in this study, these risks are unevenly distributed, concentrated in zones where vegetable and fruit production dominate. This calls for the design of agri-environmental policies that are both spatially targeted and economically justified.

In conclusion, safeguarding pollination services in a changing climate and volatile market environment requires more than broad conservation goals. It demands precise, localized, and economically informed actions. The multi-indicator framework developed here lays a foundation for such efforts. It allows for the identification of departments where ecological vulnerability and economic dependency intersect, thereby supporting more effective, regionally adapted, and future-oriented strategies for pollinator protection and sustainable agriculture in France.

CRediT authorship contribution statement

Yasmine Blili: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Elie Abou Nader:** Writing – original draft, Methodology, Conceptualization. **Iciar Pavez:** Writing – review & editing, Validation. **Paolo Prosperi:** Writing – review & editing, Validation. **Rachid Harbouze:** Validation. **Leonidas Sotirios Kyrgiakos:** Validation. **Christina Kleisiari:** Validation. **Marios Vasileiou:** Validation. **Vasileios Angelopoulos:** Validation. **George Vlontzos:** Validation. **Georgios Kleftodimos:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

This article was written entirely by the authors without the use of generative AI or AI-assisted technologies.

Funding

This work was supported by the ALLIANCE Project and has been financed under the European Union's HE research and innovation program under grant agreement N° **101084188**.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2025.100944.

7. Appendices

Table A.1
correlation matrix

	FRUIT	VEGETABLE	COP	evcp_tot	evip_tot	evipha_tot	vr_tot
FRUIT	1	−0,2121	−0,2202	0,0474	0,1302	0,2701	0,2072
VEGETABLE	−0,2121	1	0,0457	0,0952	0,2149	0,8440	0,0697
COP	−0,2202	0,0457	1	−0,0417	−0,1303	−0,1814	−0,2919
evcp_tot	0,0474	0,0952	−0,0417	1	0,3832	0,1494	−0,3338
evip_tot	0,1302	0,2149	−0,1303	0,3832	1	0,2842	0,3809
evipha_tot	0,2701	0,8440	−0,1814	0,1494	0,2842	1	0,2780
vr_tot	0,2072	0,0697	−0,2919	−0,3338	0,3809	0,2780	1

Table A.2
p-value matrix

	FRUIT	VEGETABLE	COP	evcp_tot	evip_tot	evipha_tot	vr_tot
FRUIT	1	0,0424	0,0350	0,6538	0,2162	0,0092	0,0475
VEGETABLE	0,0424	1	0,6620	0,3612	0,0375	0,0000	0,5044
COP	0,0350	0,6620	1	0,6898	0,2106	0,0802	0,0043
evcp_tot	0,6538	0,3612	0,6898	1	0,0001	0,1484	0,0009
evip_tot	0,2162	0,0375	0,2106	0,0001	1	0,0052	0,0001
evipha_tot	0,0092	0,0000	0,0802	0,1484	0,0052	1	0,0064
vr_tot	0,0475	0,5044	0,0043	0,0009	0,0001	0,0064	1

Table A.3
Dependence ratios table from appendices 1 and 2 from Klein and al. (2009)

source	crop	Dependance ratio	Dependance ratio
Appendix 1	Okra, gumbo	modest	0,25
	pigeon pea, cajan pea, congo bean	little	0,05
	jack bean, horse bean, sword bean	modest	0,25
	chile pepper, red pepper, bell peper, green pepper	little	0,05
	quinoa	no increase	0
	chickpea, gram, garbanzo bean	no increase	0
	watermelon	essential	0,95
	cantaloupe, melon	essential	0,95
	cucumber, gherkin	great	0,65
	pumpkin, squach, gourd, marrow, zucchini	essential	0,95
	guar bean, goa bean	little	0,05
	hyacinth bean, horse-gram, lablab	modest	0,25
	buckwheat	great	0,65
	lentils	no increase	0
	tomato	little	0,05
	velvet bean	unknown	unknown
	Kidney bean, Haricot bean, Lima bean, Adzuki bean, Mungo bean, String bean	little	0,05
	Garden pea, Field pea	no increase	0
	Winged bean, Goa bean	unknown	unknown
	Eggplant, Aubergine	modest	0,25
	Cowpea, Blackeye pea, Blackeye bean	little	0,05
	Bambara beans, Bambara groundnuts, Earth pea	little	0,05
	Kiwifruit	essential	0,95
	Atemoya, Cherimoya, Custard apple	essential	0,95
	Tree- strawberry	modest	0,25
	Breadfruit	unknown	unknown
	Jackfruit	unknown	unknown
	Pawpaw, Indiana banana	essential	0,95
	Carambola, Starfruit	great	0,65
	Papaya	little	0,05
	Bergamot, Chinotto, Citron, Clementine Grapefruit, Kumquat, Lemmon, Lime, Manderine, Orange, Pomelo, Tangerine	little	0,05
	Star apple, Cainito	little	0,05
	Azarole, Azzeruolo	little	0,05
	Longan, Lungan	little	0,05
	Persimmon	little	0,05
	Durian	great	0,65
	Loquat, Japanese plum, Japanese medlar	great	0,65
	Feijoa	great	0,65
	Fig	modest	0,25
	Strawberry	modest	0,25
	litchi, lychee	little	0,05
	apple	great	0,65
	Mammee	modest	0,25
	Mango	great	0,65
	Sapodilla	essential	0,95
	Medlar	unknown	unknown
	Rambutan	little	0,05
	Prickly pear	modest	0,25
	Passion fruit, Maracuja	essential	0,95
	Avocado	great	0,65
	Sapote, Mamey colorado	unknown	unknown
	Plum, Greengage, Mirabelle, Sloe	great	0,65
	Peach, Nectarine	great	0,65
	Sweet cherry	great	0,65
	Apricot	great	0,65
	Sour cherry	great	0,65
	Guava, Guayaba	modest	0,25
	Pomegranate	modest	0,25
	Pear	great	0,65
	Black currant, Red currant	modest	0,25
	Rose hips, Dogroses	great	0,65
	Raspberry, Blackberry, Clouderry, Northern Dewberry, Southern Dewberry	great	0,65
	Elderberry	modest	0,25
	Naranjillo	great	0,65
	Rowanberry	essential	0,95
	Service-apple	modest	0,25
	Hog plum, Mombin	little	0,05
	Tamarind	little	0,05
	Highbush blueberry, Lowbush blueberry, Rabbiteye blueberry, Bilberry	great	0,65
	American cranberry, European cranberry	great	0,65
	Table grape, Vine grape	no increase	0
	Jujube	modest	0,25

(*continued on next page*)

Table A.3 (*continued*)

source	crop	Dependance ratio	Dependance ratio
	almond	great	0,65
	Cashew nut, and Cashewapple	great	0,65
	Peanut, Groundnut	little	0,05
	Brazil nut, Para nut, Cream nut	essential	0,95
	Chestnut	modest	0,25
	Macadamia	essential	0,95
	Mustard seeds	modest	0,25
	Rapeseed, Oilseed rape	modest	0,25
	Turnip rape, Canola	great	0,65
	safflower	little	0,05
	Coconut	modest	0,25
	Oil palm	little	0,05
	Soybean	modest	0,25
	Seedcotton	modest	0,25
	Sunflower seeds	modest	0,25
	Flaxseed	little	0,05
	Olive	no increase	0
	Sesame	modest	0,25
	Broad bean, Faba bean, Field bean, Horse bean	modest	0,25
	Karite nuts, Sheanuts	modest	0,25
	coffee	modest	0,25
	cola nut, kola nut	great	0,65
	cocoa	essential	0,95
	grains of paradise	unknown	unknown
	caraway	modest	0,25
	Coriander	great	0,65
	Cumin	great	0,65
	Cardamom	great	0,65
	Star anise	unknown	unknown
	Fennel seed	great	0,65
	Nutmeg	great	0,65
	Allspice, Pimento	great	0,65
	Pepper	no increase	0
	Anise	unknown	unknown
	Vanilla	essential	0,95
Appendix 2	Sugar cane	no increase	0
	Maize, Green corn, Sweet corn	no increase	0
	Wheat	no increase	0
	Rice, Paddy	no increase	0
	Potato	increase-breeding	increase-breeding
	Sugar beet	no increase	0
	Cassava	increase-breeding	increase-breeding
	barley	no increase	0
	sweet potato	increase-breeding	increase-breeding
	Cabbage, Cauliflower	increase-seed production	increase-seed production
	Table Grape, Vine Grape	no increase	0
	Onion, Shallots, Welsh onion (green)	increase-seed production	increase-seed production
	Sorghum	no increase	0
	Yam	increase-breeding	increase-breeding
	Millet	no increase	0
	oat	no increase	0
	Carrot	increase-seed production	increase-seed production
	Lettuce, Chicory	increase-seed production	increase-seed production
	Bean dry like Kidney bean, Haricot bean, Lima bean, Azuki bean, Mungo bean, String bean	increase	increase
	rye	no increase	0
	Pineapple	increase-breeding	increase-breeding
	Garlic	increase-breeding	increase-breeding
	Triticale	no increase	0
	Spinach	no increase	0
	Taro (Coco Yam)	increase-seed production	increase-seed production
	Date palm	no increase	0
	Asparagus	increase-seed production	increase-seed production
	bean, green	increase	increase
	Mixed Grain	no increase	0
	Bamboo shoots	no increase	0
	Beets, Chards	no increase	0
	Capers	increase	increase
	Cardoons	increase	increase
	Celery	increase	increase
	Chervil	increase	increase

(*continued on next page*)

Table A.3 (*continued*)

source	crop	Dependance ratio	Dependance ratio
	Cress	no increase	0
	Fennel	increase	increase
	Horseradish	increase	increase
	Sweet marjoram	unknown	unknown
	Oyster plant	increase	increase
	Parsley	increase	increase
	Parsnips	increase	increase
	Radish	increase	increase
	Rhubarb	no increase	0
	Rutabagas, swedes	increase	increase
	Savory	unknown	unknown
	Scorzonera	increase	increase
	Sorrel	no increase	0
	Tarragon	no increase	0
	Watercress	no increase	0
	Babaco	no increase	0
	Mangosteen	no increase	0
	Arracacha	increase	increase
	Arrowroot	increase	increase
	Chufa	no increase	0
	Sago palm	increase	increase
	Oca and ullucu	increase	increase
	Mashua	increase	increase
	Jerusalem artichoke	increase	increase

Table A.4
Sensitivity analysis of national EVIP under + -10 % and +-20 % price variation

Scenario	EVIP (billion €)
−20 %	3,35
−10 %	3,77
baseline (2022)	4,19
+10 %	4,61
+20 %	5,03

Data availability

i have shared the link to the datasets used for the analysis in the \"attach files\" section.

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