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Towards a Modeling of the Impacts of Road Verge Management on the Pollination Service Using System Dynamics: A Case Study in France

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Abstract

Several research studies have proven that eliciting and predicting the impact of human activity on ecosystem services will be crucial to support stakeholders' awareness and to decide how to interact with the environment in a more sustainable manner. In this sense, the ecosystems known as road verges are particularly important because of their length and surface at an international scale, and their role in mitigating the damage done by roads. Plant pollination by insects is one of the most important ecosystem services. Because of its nature and the fact that they extend across a variety of landscapes, roadside can contribute to the maintenance of healthy ecosystems, under the condition of adapted management practices. This research is the first attempt to develop a System Dynamics-based aiming to estimate the ecological and economic impact of maintenance on the road verge pollination service in France. Maintenance strategies of road verges are simulated to compare their performance. The results show that there are ways to improve current maintenance strategies in terms of pollination value, but also that the model needs to consider other ecosystem services and synergistic effects that could further affect pollination to obtain more accurate estimations.

Keywords

Road Verges, Ecosystem Services, Mathematical Modeling, System Dynamics, Pollination

1. Introduction

Road verges, also called roadside, are vegetated strips of grass, shrubs and trees that separate roads from adjacent ecosystems (e.g. agricultural, forestry, urban) [1] [2] [3]. They contribute to improved road visibility, and pedestrian safety, but can also support biodiversity [4] [5]. Given the extent of the road network, road verges cover 270,000 km^2 globally [6], which would be equivalent to 89% of the area of Italy.

The ecological value of road verges is significant, given that they provide a wide range of ecosystem services (ES), including regulating services (e.g. air filtration, temperature regulation, water purification, carbon sequestration), provisioning services (herbaceous and woody biomass), biodiversity and habitat services, and cultural services (aesthetic benefits) [6] [7]. The set of ecosystem services associated with road verges is partly linked to the decisions of territory managers and planners in terms of maintenance (mowing, pruning, ditch cleaning, etc.) and structure (presence of trees, hedges, ditches, etc.) of these roadsides. Thus, road verges can be considered as a socio-ecological system in the sense that they are sites of complex and dynamic interactions between society and ecosystems.

In this research, particular attention is paid to the pollination ecosystem service. According to the Millennium Ecosystem Assessment, pollination is classified as a regulating ecosystem service [8] and is defined as "the transfer of pollen between the male and female parts of flowers to enable fertilization and reproduction" [9]. Animal pollinators play a critical role in the production of many crops [10] and in the reproduction of many wild plants [11]. Indeed, the pollination service mainly concerns agricultural ecosystems (grasslands, field crops, tree crops). Among crop plants, 60% - 80% of species depend, at least in part, on pollinators for seed and fruit production; this represents 35% of global food production [10] [12]. However, pollination is a subject of current attention because of the decrease in pollinator populations [9] [13] caused in part by the loss and degradation of suitable habitats due to urban expansion and the intensification of agriculture [9]. In Europe, a complete absence of pollinators could decrease crop production by 7%, without considering the effects on wild plants [8].

The effects of roadside management on the pollination service at the territorial level are still to be addressed in the scientific literature. Reconciling the sustainable and safe management of the roadside requires consideration of the dynamics of the socio-ecological system during decision-making [1] [4] [6] [14] [15] [16]. This highlights the importance of simulating different strategies of management and the changes they provoke in the pollination service provided to adjacent ecosystems over time [17]. In other words, the aim is to assess the dynamics of the roadside socio-ecological system over time in order to support policy and decision makers in developing appropriate management plans [17] [18] [19]. Currently, existing valuation models present limitations in considering the changes in ecosystem services over time. Therefore, this research explores system dynamics models to overcome these limitations by simultaneously modelling ecological changes and factors related to socio-economic changes in territories [20].

The main objective of this study is then to develop a conceptual framework and a simplified system dynamics (SD) simulation model illustrating the impacts of roadside maintenance on the pollination service through the simulation of different mowing strategies. The ultimate aim of this article lies more in the logic and awareness of the interactions between maintenance practices, biomass availability and pollinator communities than in the proposed quantitative assessment.

The principal challenges faced when building the model of the present article were 1) the identification of the dynamics of ecosystem services provided by road verges and how they are affected by its characteristics and maintenance, and 2) relevant data and indicators collection for the parameters and initial conditions of the variables integrated in the model and 3) the quantification of the ecological value of the ecosystem services and its translation in economic terms. These challenges are directly linked to the main open questions about ecosystem services within the scientific literature [21], which are related to understanding and quantifying how ecosystems provide services, valuing these ecosystem services, using them in trade-off analysis and decision-making, and financing the sustainable use of ecosystem services.

Recent research focuses on the causal relationships between maintenance practices and ecosystem services provided by roadsides [15]. Furthermore, there are precedents for the application of dynamic systems to achieve the sustainable management of the roadside [22]. Nevertheless, these proposals address the problem as a whole by looking at a bundle of ecosystem services and do not give a detailed and quantitative representation of the environmental changes in the maintained roadside over time in terms of the ecosystem services they provide. Our research seeks to contribute to filling this gap by focusing on one ecosystem service. Through the study of the pollination service, this model is a first step in this direction. It considers the variability of roadside biophysical components involved in the ecosystem service of pollination, the influence of environmental cycles such as seasonal changes, and their impact on the dynamics of biophysical components, as well as the effect of human choices that define how the management is carried out in multiple scenarios. Therefore, this article seeks to build a first road verge model enabling the determination of the value of the pollination ecosystem service according to different road verge management scenarios.

2. Study Area and Methodology

2.1. Overview of the Study Area

The study area is located in France, where the road network of more than one million kilometers is the longest in the European Union (1/4 of the European network). Consequently, France has a considerable surface of road verges. The total surface of the French roadside is estimated at 4500 km^2 [5]. In France, road verges have a variable structure and composition depending on the type of road they follow (width, presence of a ditch, or woody vegetation). The variety of soils, microclimates, relief, and exposure offers a multitude of sites potentially favorable to the development of vegetation beneficial to pollination [23].

These vegetated strips are at the interface between roads and adjacent ecosystems, including agricultural ecosystems, which represent approximately 52% of the French Territory. Road infrastructure fragments the agricultural ecosystem, so roadsides are frequently in contact with this ecosystem. Therefore, the roadside can play a role in the pollination of agricultural areas. This claim is supported by the fact that, although covering less than 0.5% of the agricultural area, the presence of linear green elements increased the visitation probability by 5% - 20% while being the sole providers of pollinators in 12% of the croplands [8].

2.2. Methodology

System dynamics is a modelling approach contributing to the exploratory understanding of complex systems with many interacting components [24] [25]. It allows to understand the behavior of these systems over time. This research uses a system dynamics approach to propose a first model of the pollination service provided by roadsides. The aim is to study, through system dynamics, how the maintenance of roadside vegetation affects pollinators and, indirectly, the productivity of adjacent agricultural ecosystems. Reference [17] explain that "*the system dynamics model can be applied to complex social-ecological systems to consider feedback between the factors that cause change. Therefore, when two or more ecosystems interact, it is an appropriate method for analyzing the landscape change due to anthropogenic factors. The system dynamics model can consider the causes of landscape change in complex social-ecological systems*". This approach should therefore help us to make the dynamics between the system (socio-technical and ecological) understandable by using dynamic feedback loops and nonlinear ordinary differential equations [26] [27] [28].

The main steps in the development of the model are as follows:

- The identification of the main components of the system and the description of their interactions. The information collected comes from the analysis of literature and technical reports (e.g. CEREMA). A schematic conceptual model is then constructed.
- The development of a causal loop diagram showing the causal interconnections between the system variables. It contributes to the articulation of the problem and its conceptualization by describing the complex relationships between all indicators of the system. In this type of diagram, labels (−) indicate that a change in one variable leads to a change in the opposite direction of the affected variable, and labels (+) indicate that a change in a variable lead to a change in the same direction of the affected variable. An example of causal loop diagram is presented in **Figure 1**. In our research, the CLD is a

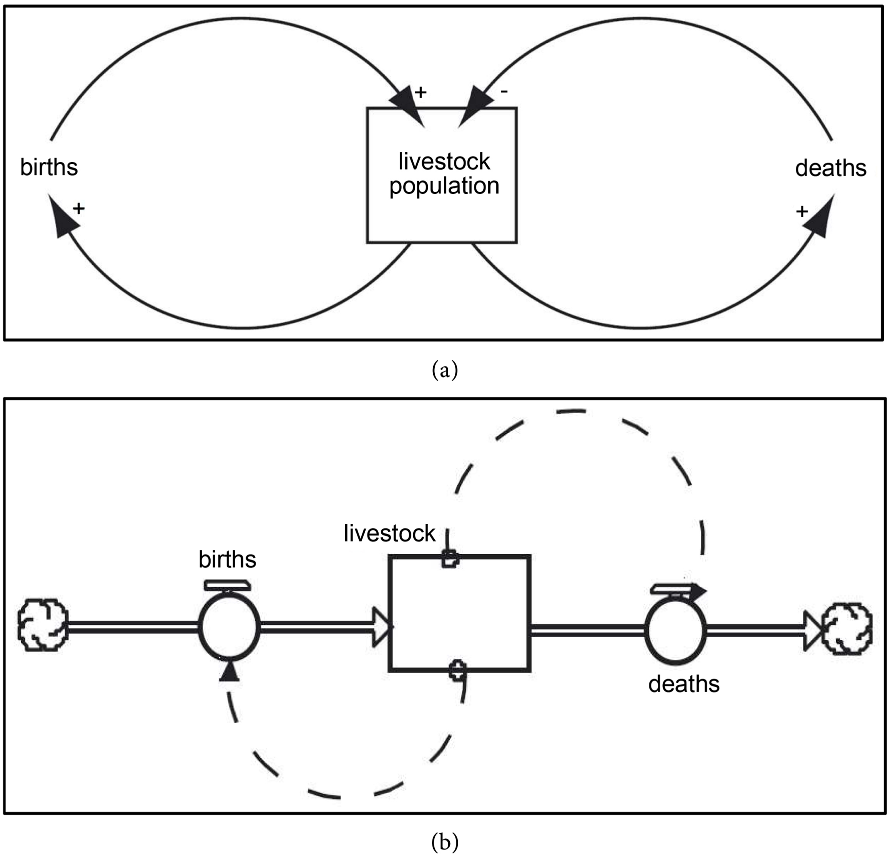

Figure 1. Example of (a) a causal loop diagram (CLD) and (b) Stock-and-Flow Diagram (SFD) stemming from CLD [30].

simplification of the conceptual framework presented earlier. It consists of connected modules that model the system. The CLD of each module is presented in detail.

- The construction of the stock and flow diagram (SFD) in a system dynamicssoftware. It is a translation of the causal diagram into a terminology that facilitates equation writing, so it is a reclassification of elements into stocks, flows and parameters [29]. Stocks are key variables in the system, which "store" or accumulate material, while flows are mechanisms affecting the rate of movement of material into or out of the stocks. Converters are used to link the system variables and also change the rate of the flow variables. An example of stock and flow Diagram is presented in **Figure 1**. The simulation model was built using STELLA Professional software and the simulation period lasts one year with monthly time steps.
- The validation of the model by comparison with experimental data. The data used to calculate the value of the model's parameters came from secondary sources found in the literature and properly referenced throughout the article. The model validation process consists of an expert review of the simulation results to compare them with their theoretical and empirical knowledge.
- Thanks to this model, two results can be achieved: 1) a model of the current

dynamics of the roadside and an assessment of the roadside pollination ecosystem service, and 2) a simulation of the influence of maintenance operations and an estimation of the associated value of the pollination service.

3. Result

This section presents the different stages of construction of our model, from conceptualisation to validation.

3.1. Conceptual Framework of the Roadside Pollination Ecosystem Service

Pollinators require suitable habitats for feeding larvae with nectar and pollen [31] [32], for breeding, nesting, and overwintering [1]. The floristic composition of semi-natural habitats influences the availability of foraging resources (nectar and pollen) and of places for pollinators to lay their eggs [33]. Research conducted by [1] found that the density and species richness of flowers and pollinators on the roadside are generally similar to or greater than other habitats in the surrounding landscape. Reference [34] found densities of bumblebees, butterflies, and hoverflies at least three to four times higher than in the field core and most semi-natural habitats.

The efficiency of the animal pollination service depends primarily on the composition and structure of wild pollinator communities [35]. In temperate regions, pollinators are almost exclusively insects, belonging mainly to four orders: Hymenoptera, Diptera, Lepidoptera, and Coleoptera [36]. Seed or fruit production depends on the amount of pollen received by flowers [37] [38] and on the abundance of pollinators, which influences the number of visits to flowers [39]. However, other characteristics of pollinator communities can affect pollination efficiency [40]; for example, including plant dependence on pollinators and specialization to pollinators [10], which can be different between plant species.

The structure and composition of pollinator communities depend on several factors, in particular 1) biotic interactions, especially between pollinators themselves or with pathogens, and 2) environmental variables, among which the presence of semi-natural habitats (forests, edges, grasslands, etc.) and management practices carried out on them [41]. Semi-natural habitats, such as grasslands, are often a source of food and nesting sites; their loss is generally associated with a decrease in pollinator abundance and diversity [42]. Although crop fields may provide food to pollinators as eusocial bees, they are suboptimal pollen and nectar sources [43]. Semi-natural habitats are also used for endangered species as nidification areas because of the native vegetation that remains there. Most pollinators are in semi-natural habitats adjacent to agricultural ecosystems, such as road verges [44].

Roadside pollinators can impact nearby agricultural ecosystems [1]. Indeed, there is a negative relationship between distance from semi-natural habitats and pollinator abundance, diversity, and pollination efficiency [45]. They also conclude that, in agricultural ecosystems, this effect includes a negative relationship between distance to semi-natural habitats and pollinator abundance, diversity, and pollination efficiency.

However, pollinators attracted to the road verges for foraging, breeding, nesting, and overwintering can be affected by pollution, vehicle collisions, introduction of invasive species, road verge maintenance, and climate [1], which can result in net harm (referred to as ecological traps [46]) to these species at the landscape scale. This research focuses on the impact of road verge maintenance on the pollination ecosystem service (ES). This maintenance can benefit pollinators by creating, restoring, and maintaining high-quality habitats, but it can affect the ability of roadside habitats to support pollinators [1]. Inspired by the work of [40], **Figure 2** shows the main biophysical determinants and exogenous factors involved in pollination ES provision.

Subsequently, several simplifications were made, our aim being to focus on the roadside/farmland interface in order to concentrate on the role of roadside maintenance in the pollination service. Consequently, the system boundaries were revised, excluding some exogeneous factors (climate, introduction of invasive species, pollution, and habitat fragmentation). The role of invasive plants was also excluded from the analysis, as impacts on ecosystem services differ between invasive plant species [15]. Finally, even though there is an impact of pollinator predators on plant-pollination interactions and vital dynamics [47] [48], no evidence of a relationship between this impact and the maintenance strategies

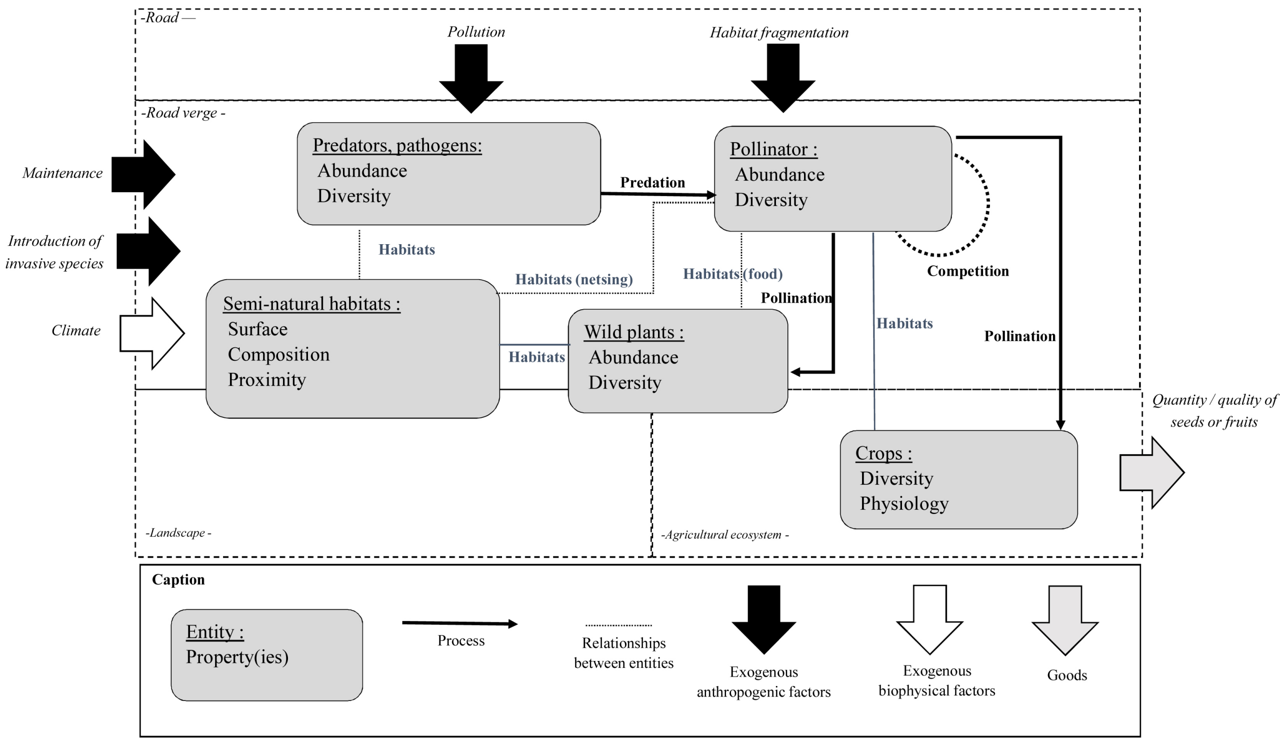

Figure 2. Schematic representation of biophysical determinants and exogenous factors that modulate the pollination ES, inspired by [40].

was found in the literature. Thus, this first proposition of model does not consider all the biophysical determinants and exogenous factors that modulate pollination illustrated in Figure 2. Specifically, it does not consider the interaction between predators and pollinators. This model will focus on pollinator and wild plant abundance, semi-natural habitat composition and adjacent crop diversity.

3.2. Causal Loop Diagram of a Generic Roadside Pollination Ecosystem Services

On the basis of the previous simplifications, the causal loop diagram developed to simulate the impact of roadside maintenance in France on the pollination service is presented in Figure 3. The diversity of vegetation (hedges, trees, grasses, plants, etc.) will have an impact on the vegetation composition of these areas (natural habitats, flowers, etc.). The presence of invasive plants or hedges on the

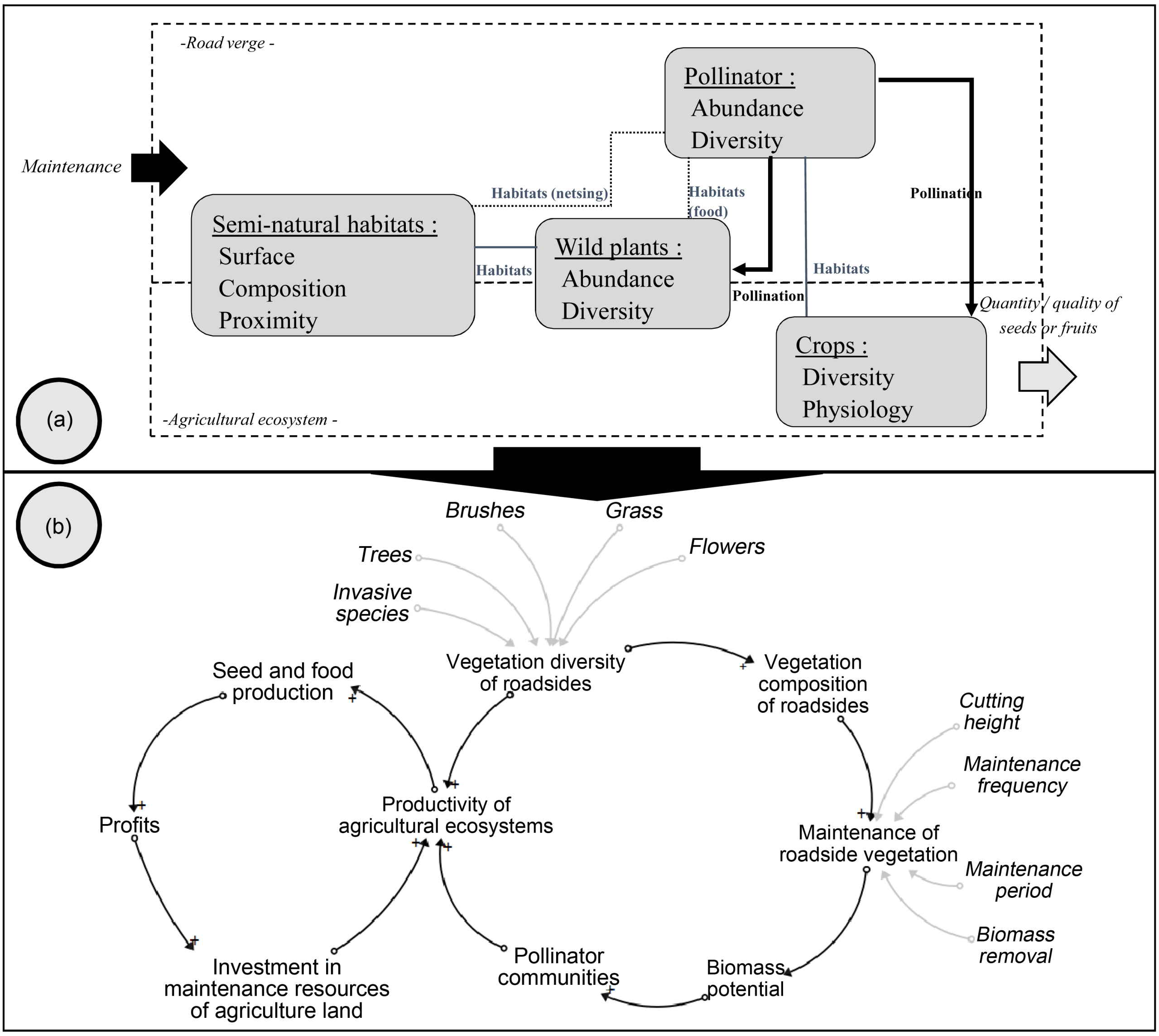

Figure 3. (a) Simplified conceptual model and (b) causal loop diagram.

roadside can have a positive or negative impact on the productivity of adjacent agricultural ecosystems. For safety purposes and to maintain the drainage functions of the road, this vegetation is maintained (mowing, pruning). Intensive maintenance can lead to a loss of biomass, impacting pollinator communities and therefore the productivity of agricultural ecosystems. These ecosystems are able to produce seeds and food, generating profits for farmers who are able to invest in resources to maintain their agricultural land (**Figure 3**).

It consists of connected modules for modelling roadside and biomass vegetation, pollinators and the economic value within the agriculture ecosystem. In the following subsections, the modules dedicated to vegetation and pollinators are described. The equations governing each sub-system have been developed based on the basic equations of the SD approach and the causal loop diagrams of each sub-system.

3.2.1. Roadside Vegetation and Biomass

In the case of the pollination service, the plant species composition of roadsides contributes to the so-called carrying capacity of the ecosystem. The carrying capacity of an ecosystem can be defined as the threshold beyond which an ecological good or service starts to be degraded and can no longer contribute to human well-being [49]. This carrying capacity can be degraded by human activities, in this case the maintenance of roadside vegetation.

Thus, the carrying capacity of the roadside depends on the vegetation present (trees, hedges, grass) that can provide habitats and food for pollinators. Roadside maintenance activities will impact on the natural growth of biomass. Natural biomass growth depends on soil richness, which can be impacted by biomass export decisions. Biomass is governed by actual biomass growth (natural growth impacted by maintenance decisions on cutting frequency, timing and height) and the carrying capacity of the ecosystem. Roadside maintenance activities will impact on the natural growth of biomass. Natural biomass growth depends on soil richness, which can be impacted by biomass removal decisions.

Biomass is governed by actual biomass growth (natural growth impacted by maintenance decisions on cutting frequency, timing and height) and the carrying capacity of the ecosystem. Note that different types of vegetation have different impacts on pollinators, so it is important to consider the pollinator cap in relation to the amount of plant species present. The causal loop diagram for the "roadside vegetation and biomass" module is presented in **Figure 4**.

3.2.2. Pollinators

The pollinator community is governed by the number of births and deaths, *i.e.* through the birth rate and the average life span of the pollinating insects. The birth rate (natural growth rate) plays a role in the increase of pollinators and the pollinator population has a role in the births. The same applies to the decrease in pollinator populations, which is linked to limited plant resources. Therefore, the pollinator community is highly dependent on the carrying capacity of the ecosystem. The causal loop diagram for the "pollinators" module is presented in

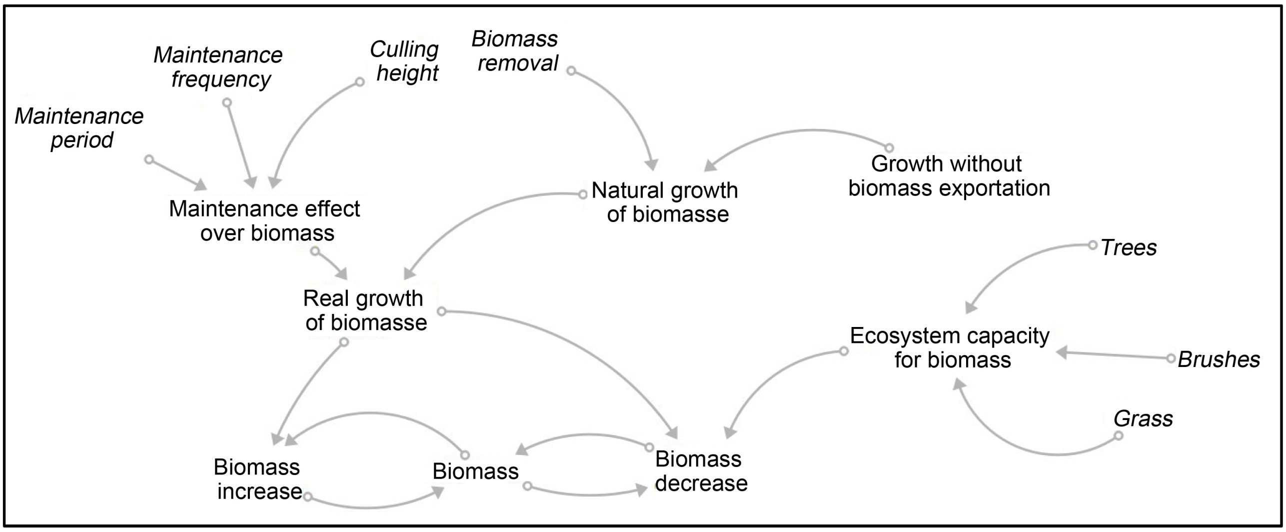

Figure 4. Causal loop diagram for "roadside vegetation and biomass" module.

Figure 5.

3.3. Stock-Flow Diagram of a Generic Roadside Pollination Ecosystem Services

In this section, all equations governing the model have been developed based on the basic equations of the SD approach. The ecosystem service of pollination depends on the pollinator population abundance $P(t)$ and on the amount of biomass $M(t)$ present on the roadside (**Figure 3**). Thus, it is necessary to describe the dynamics of these components and their interactions over time. These two variables follow a variation of the logistic equation, which is standard in population growth dynamics modeling scenarios [50]. Some examples of this approach can be seen in [51] [52] [53]. This system of equations involves two state variables: the pollinator population P and the amount of available biomass M. These two variables have two general dynamics: they increase due to natural birth and growth and decrease due to limitations of natural resources and human activity.

3.3.1. Roadside Maintenance

This paper focuses exclusively on the effects of roadside maintenance on the pollination service. Roadside maintenance impacts the provision of the pollination service through decisions about cutting the height of vegetation (C_H, cm), maintenance frequency (F, times per year), maintenance period (P, month of the first operation), and percentage of biomass removed (E). Regarding the impact of maintenance on pollination some dynamic assumptions are made:

A.1.: A too low cutting height can decrease the amount of floral resources (Johnson 2008) by decreasing the available biomass, therefore limiting the capacity of the ecosystem to carry pollinators.

A.2.: The impact of maintenance is felt on the ecosystem each time that the maintenance is carried out.

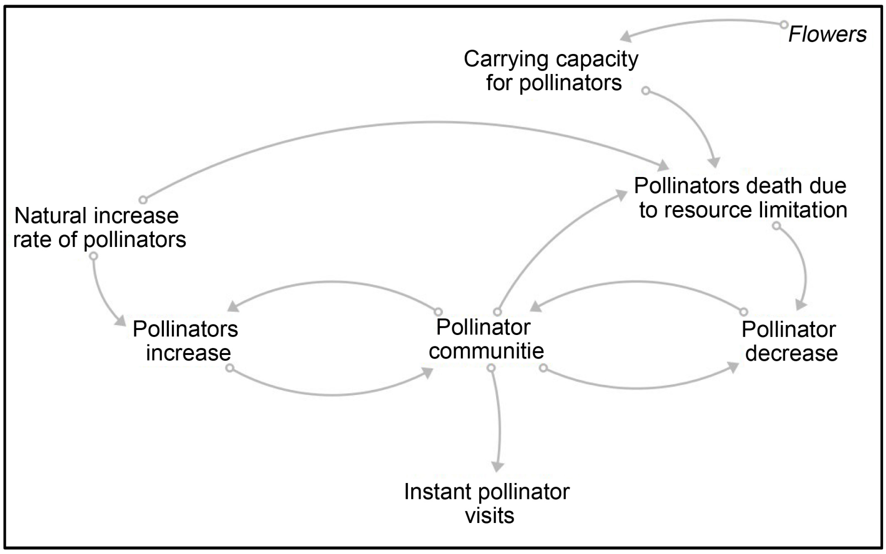

Figure 5. Causal loop diagram for "pollinators" module.

A.3.: The moment of the year in which the maintenance is carried out affects its impact, because the damage can be worst if it interrupts the life cycle of the flowers [54].

A.4.: Removing the cut biomass impacts soil fertility, encouraging slower growth and more diverse species that require less management to grow [54].

The set of maintenance decisions modulates the impacts on pollination and takes the form of converters in the final model.

3.3.2. Roadside Vegetation and Biomass

The roadside has woody, floral and herbaceous vegetation. The variables T, B, G represent the proportion of the road verge that has trees, bushes, and grass; M is the amount of biomass in kilograms; and γ represents the proportion of flowered biomass in order to consider the impact on pollinators of plant composition on the road verge.

Roadside vegetation is a dynamic variable that changes over time and with the seasons.

Consequently, the carrying capacity to provide resources for biomass K_m changes throughout the seasons, *i.e.* it is a temporal function with a 12-month period. References [55] [56] present some examples of population modeling with changing carrying capacity. Thus, in order to consider seasonal changes in the dynamics of natural populations, the carrying capacity of the biomass K_m is defined by the following formula, K_{m0} to K_{m3} (here 900, 2500, 1800 and 1100). This parameter determines the shape of the model. The assigned values are calculated following the approach applied in [57], which considers the load capacity by season. Parametric identification was then used to estimate the production in tons, with the production of rapeseed as a reference (see **Appendix 4**). The obtained parameters were thus used in Equation (1) to calculate the estimation error as a validation approach (see **Appendix 5**)

$$K_m = \begin{cases} K \\ K_{m0} \left[\frac{t}{3} \right] = 0 \bmod (4), \\ K_{m1} \left[\frac{t}{3} \right] = 1 \bmod (4), \\ K_{m2} \left[\frac{t}{3} \right] = 2 \bmod (4), \\ K_{m3} \left[\frac{t}{3} \right] = 3 \bmod (4). \end{cases} \tag{1}$$

Figure 6 shows the behavior of K_m and its seasonal periodicity.

Although these equations are not taken directly from the literature, they are variants of well-established equations. In the original logistic model for a species proposed by [58], the main idea specifies that while populations grow logarithmically, the resources on which they depend remain constant or only increase arithmetically [59]. To model pollinator population changes as a function of the human impact on biomass, we consider that the biomass resource also increases logarithmically, but with a defined maximum value and a different growth rate. Reference [60] adopted the same strategy using a logistic equation for biomass to model the impact of human and animal consumption on this. Thus, the human impact on biomass can be represented by a *triangular periodic pulse waveform* $h(t)$ with period $\frac{12}{F}$ and volume of each pulse $Vol(h)$ defined as follows, where the parameters C_H and F indicate the cutting height and frequency of the maintenance:

$$Vol(h) = \begin{cases} -\upsilon(15 - C_H), & \text{if } |P - 6| > 2, \\ -\omega(15 - C_H), & \text{if } |P - 6| \leq 2, \\ 0, & \text{i.o.c.} \end{cases} \tag{2}$$

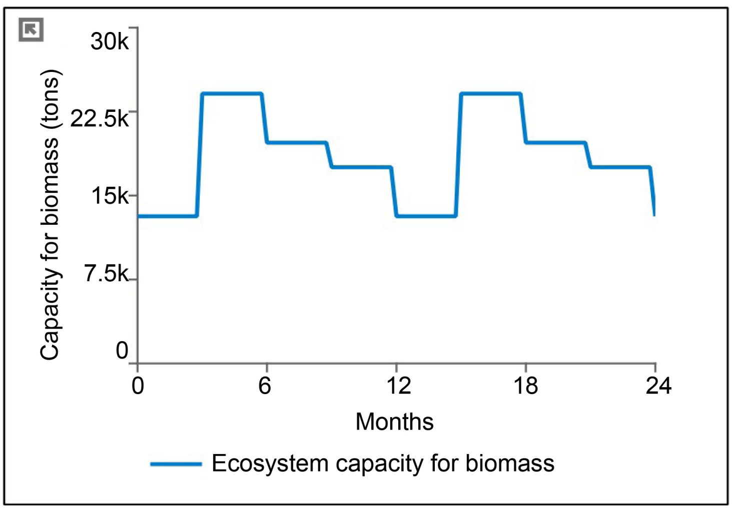

Figure 6. Maximum amount of biomass at a given time over a period of 24 months.

This formula means that the impact of maintenance is represented by a sudden decrease in biomass at the time of cutting, which slowly recovers until it reaches the carrying capacity or the next cut. The impact of the decrease, measured by the weight parameters υ, ω, is determined by the time of the maintenance: if the time of the year when maintenance is performed is in the first or last three months, the impact on biomass will be less severe [54]. The impact also depends on the number of centimeters cut, which is modeled by the $(15-C_H)$ factor. **Figure 7** presents the behavior of $h(t)$ graphically.

The removal of cut biomass has a negative impact on soil fertility, promoting species that grow more slowly [54]. Therefore, the biomass increase rate b_m depends on the removed cut biomass as $b_m = b_{m,0} - b_{m,1} * E$, where E is the proportion of biomass removed. Thus, we assume that:

A.5. The growth rate is a linear function of the extracted biomass.

Therefore, by considering previous elements, biomass dynamics can be represented in the following ordinary differential equation:

$$\frac{\mathrm{d}M}{\mathrm{d}t} = (h + b_m) M \left(1 - \frac{M}{K_m}\right) \tag{3}$$

where b_m is the biomass increase rate, K_m is the carrying capacity for biomass and h is the impact of maintenance over biomass.

3.3.3. Pollinators

The ecosystem carrying capacity for pollinators is not constant, as it is affected by changes in food resource quantity and quality, as well as changes in nesting site availability. To represent this phenomenon, we assume that:

A.6. Each kilogram of each vegetation type (grass, bush, and trees) carries a constant number of pollinators, and the total carrying capacity is the linear combination of this partial carrying capacity weighted by the proportion of each

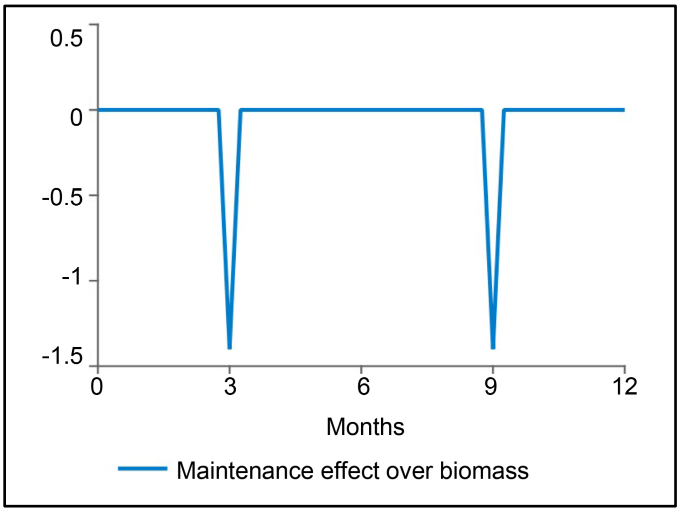

Figure 7. Behavior of the maintenance impact on biomass as a function of time, measured as kilograms of biomass lost due to maintenance.

vegetation type present in the roadside and weighted by the total amount of biomass and by the proportion of flowering biomass.

Thus, the carrying capacity of the ecosystem for pollinators K_p is written as:

$$K_p = \gamma\left(K_T T + K_B B + K_G G\right) M \tag{4}$$

where the parameters K_T, K_B, K_G represent the carrying capacity for pollinators per kilogram of trees, bushes and grass; T, B, G represent the proportion of the road verge that has trees, bushes, and grass; M is the amount of biomass in kilograms; and γ represents the proportion of flowered biomass in order to consider the impact on pollinators of plant composition on the road verge.

By considering previous elements, these pollinator dynamics can be represented in the following ordinary differential equations:

$$\frac{\mathrm{d}P}{\mathrm{d}t} = b_p P\left(1 - \frac{P}{K_p}\right), \tag{5}$$

where b_p is the pollinator birth rate, P the pollinator abundance and K_p the carrying capacity of the ecosystem for pollinators.

3.3.4. Economic Value

The previous modules relate the number of pollinators, the available biomass, the plant composition of the roadside, the growth rate of the biomass, and the impact of maintenance on the ecosystem service. On this basis, an economic evaluation of the pollination service provided by roadside is proposed. The calculation considers the amount of crop produced (kg) through pollination in the field adjacent to the road verge (called C) and the value in euros per kg. We assume that:

A.7. The number of new kilograms of crops produced through pollination per unit of time is proportional to the product of pollinators (P) and flowering biomass (γM).

Thus, the following equation is proposed:

$$\frac{\mathrm{d}C}{\mathrm{d}t} = \alpha\beta P\gamma M \tag{6}$$

The final economic value is:

$$Z = p_{pp}\theta C \tag{7}$$

where θ is the value in euros per kilogram of crops and p_{pp} is the purchasing power parity factor.

Then, roadside model was implemented using a stock-flow diagram as shown in **Figure 8**, in which the assumptions are presented as shaded shapes. **Appendix 1** describes in detail all parameters involved in the system.

3.4. Validation of the Model

In order to validate the model, the results obtained will be compared with those found in the literature, where various models have been proposed for the valuation of ecosystem services; for example, the dependency ratio model [61], the

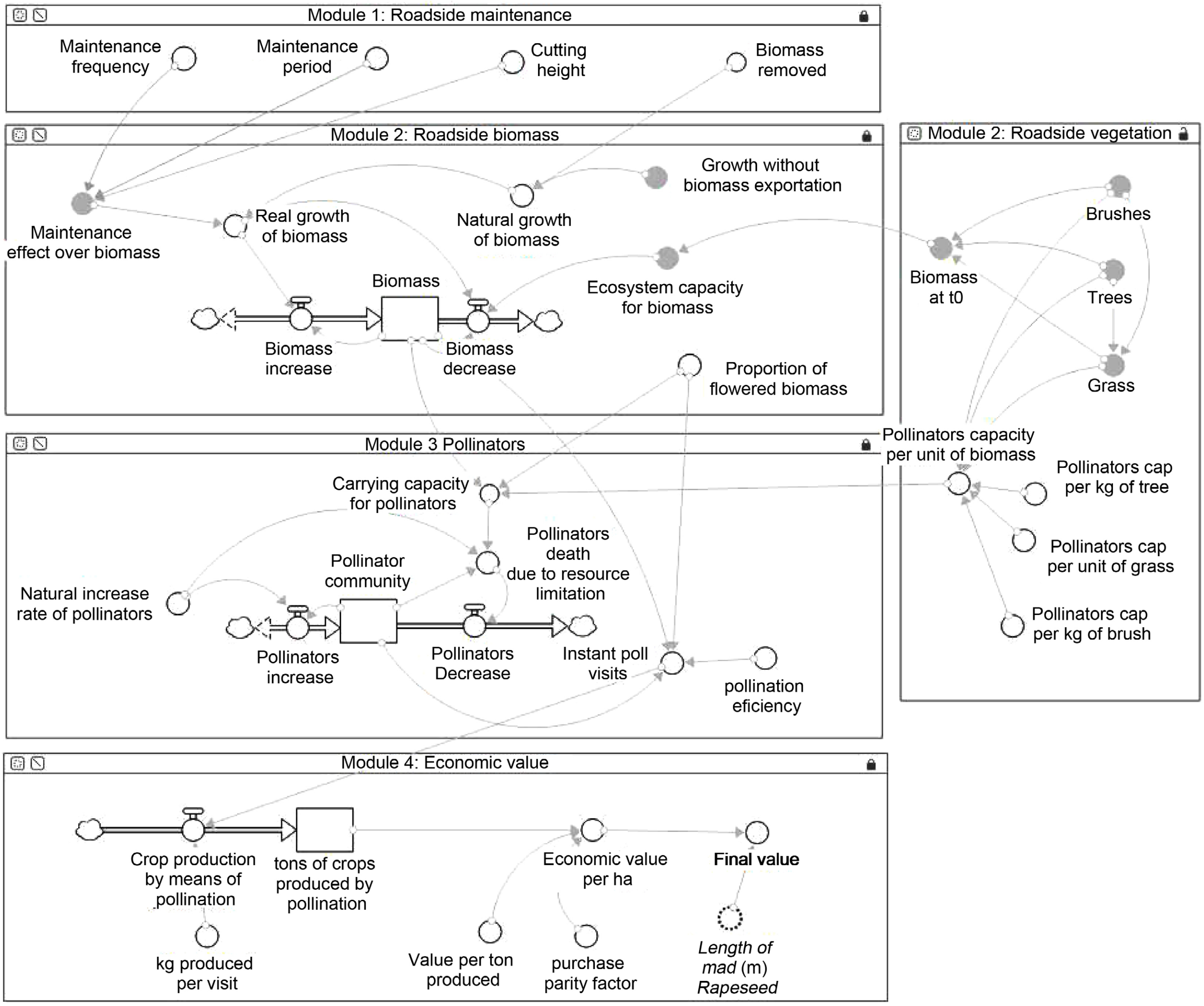

Figure 8. Flow diagram of the model divided into four modules: roadside maintenance, roadside biomass and vegetation, pollinators and economic value.

InVEST model [62], and the GUMBO model [63].

The dependency ratio model [61] has been chosen because it evaluates the price of crop production multiplied by the dependency ratio per crop (EUR/ha) as an indicator of the value of the pollination service (*pollval*). This model was chosen for its ease of use and scale of applications (scales, regions, or countries). However, it neglects other inputs (such as impacts of environmental factors and cultivars on pollinators dynamics) and is sensitive to subjective personal assessments of dependency ratios [9].

Because of the assumptions used and the similarity of the problem studied, this model can be used as a reference for a cross-validity process [64]. For an accurate estimate of management practices, more ecological data should be available, as in production function models. This type of study requires ecological data on the pollination service efficiency of different pollinators and landscape parameters and plant and pollinator community composition [9]. **Appen-**

dix 2 shows the chosen value for all instrumental parameters of the model, along with its justification, except for β and θ. These two parameters are directly linked to the type of ecosystem adjacent to the road verge. Thus, **Appendix 3** presents their values considering different adjacent ecosystems, most of which are crops. The considered crops were those in which the annual production is affected by the pollination service in France. In order to identify this service, crop production data from the AGRESTE[1] reports for 2020, and pollination dependency from [10] [12] were used.

In **Appendix 3**, the order of crops is given by the largest total amount of tons produced annually by pollination in France. The values per ton produced (θ) are extracted from AGRESTE reports and reused in the data column *Product of Producer Price* of **Appendix 4**. The number of tons produced per visit (β) is obtained by dividing the total amount of tons produced monthly by pollination per hectare by an approximation of 90 million pollination visits in one month (calculated over the values taken by the product $\alpha P\gamma M$).

Reference [61] propose a dependence ratio model which allow calculating the Producer Price of Crop multiplied by the dependence ratio per crop. According to [9], this model measures the "*market price of additional plant production resulting from pollination services*" using theoretical parameters to estimate the contribution of pollinators based on pollinator dependency ratios of crops. Note that in the absence of pollinators, this dependent crop ratio will be completely lost. The required data are crop yield per hectare, crop market price per unit, and insect pollination ratio measure [9]. The proposal by [61] includes a method for estimating the overall value of pollination:

$$pollval(t) = inf(t) \cdot \sum_{j=0}^{m} p_{pp\,j}(t) \cdot \sum_{i=0}^{n} dr_i \cdot pp_{i,j}(t) \cdot pq_{i,j}(t) \tag{8}$$

where p_{pp} is the purchasing parity factor, $inf(t)$ the inflation correction factor, dr the crop's pollination dependence ratio, pp the product of the producer price (US $/ton) and pq the quantity produced (ton).

The studies of [10] [12] were used for the pollination dependency ratio data and the AGRESTE reports [65] for the other data (production quantity and producer product price reported by product category and corrected by the relative importance of each crop based on tons produced). The approach used to identify the pollination values of crops in France is shown in **Figure 9**.

The data used are for the year 2020 as this is the latest information available, published in November 2021. The purchasing parity factor (p_{pp}) for France in 2020 was 0.705 [66] and $inf(t)$ was taken as equal to 1, because the study period was 1 year. Only crops with a dependency ratio greater than 0 are presented in **Appendix 4**, which summarizes the value of pollination in euros/ha for French crops.

The Column *Pollination Value* (*euros for total production*, *in tons*, of **Appendix 4**), was used to validate the results of the model. The values were multiplied by a factor of 0.12 to account for the fact that, in Europe, linear green

[1]Department of statistics, evaluation and prospective of the minister of agriculture and food supply.

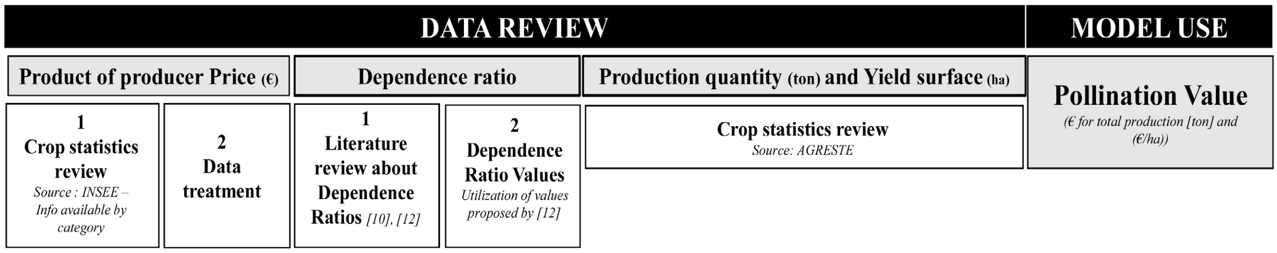

Figure 9. Identification of pollination value of crops in France.

elements are responsible for 12% of the pollination for dependent crops [8].

3.5. Simulations

Table 1 summarizes the scenarios proposed to evaluate the impact of the maintenance of road verges on pollination. Each simulation was run for 12 months.

The scenarios 2 to 4 assess how a single change in the maintenance strategy can affect the final value of the ecosystem service. The "no maintenance" scenario is proposed to evaluate the actual impact of maintenance by studying how the value of pollination would change in the absence of maintenance.

Finally, the last two scenarios are proposed based on the strategies recommended by *Plantlife* in their best practices guide for managing grassland road verges [54]. The autumn strategy consists in cutting most of the verge (90%) between mid-July and September to mimic the pattern of hay meadow management and then cutting the entire area (100%) again from October to December to remove late-season growth. In terms of the model, this can be translated as doing 0.9 cuts plus one full cut, for a total of 1.9 cuts per year. The late winter strategy consists in cutting during February or March, before the plants flower, and then cutting again in October or September.

3.5.1. Current Roadside Scenario

The simulation of the current management scenario performed by the model presented surpasses that carried out with the dependency ratio model by 0.055% (considering the average over all crops). The error for each crop is detailed in Appendix 5.

Both models estimate that the value of pollination by road verges is around 318.8 million euros (318 945 831.03 by the one presented in this article and 318 770 538.14 by the dependency ratio model). Figure 10 illustrates how this value is distributed among the different types of crops considered in the study. The left-hand figure shows the number of euros contributed by each crop. In the right-hand figure, the radius of each circular sector represents the area occupied by each crop in France adjacent to the road verges, and the length represents the value in euros per hectare.

We can see that even though some crops contribute in similar amounts to the total value of pollination, the reasons behind these contributions (total area and value per unit of area) vary drastically among them.

Table 1. Value of the parameters defining the maintenance strategy in each scenario proposed.

Scenario	Maintenance frequency (F, times per year)	Maintenance period (P, month of the first operation)	Cutting height (C_H, cm)	Percentage of biomass removed (E)
1) Current	3	5	8	0%
2) Biomass removal	3	5	8	100%
3) One more cut	4	5	8	0%
4) 2 cm lower cut	3	5	6	0%
5) No maintenance	0	-	-	-
6) Plantlife Autumn	1.9	7	8	0%
7) Plantlife late winter	2	2	8	0%

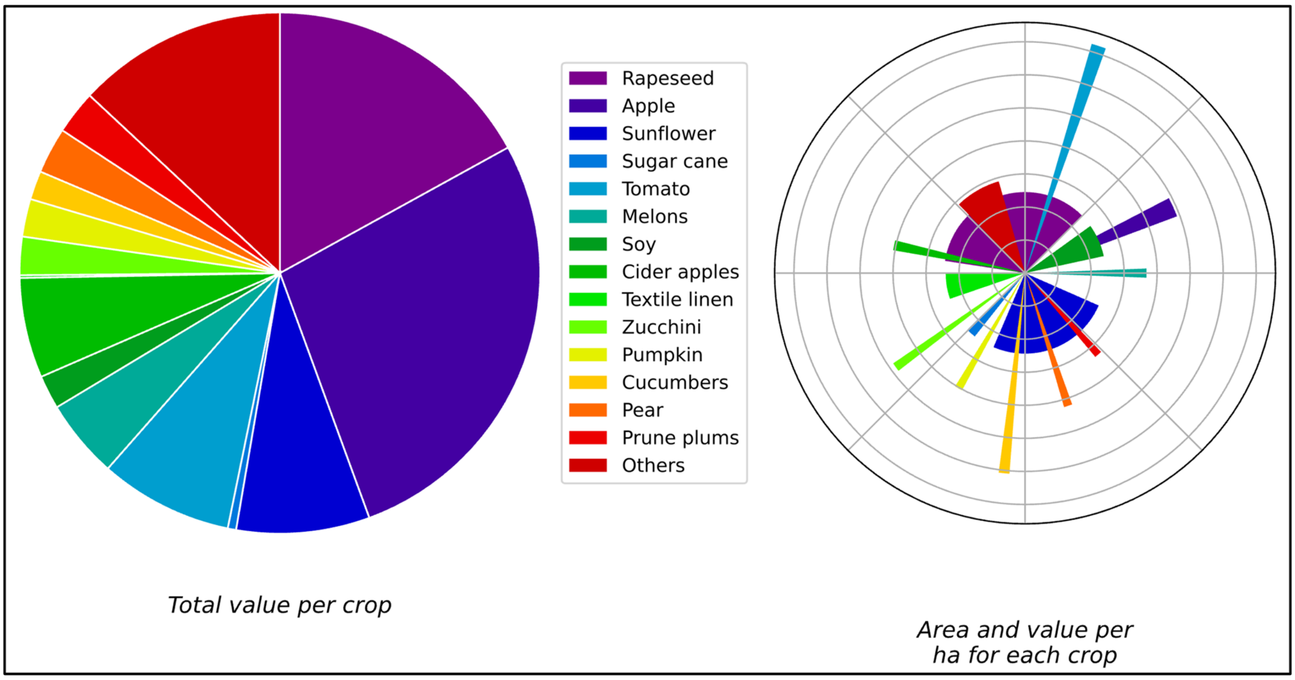

Figure 10. Contribution of the top 15 French crops to the total value of pollination.

3.5.2. Influence of Maintenance on the Ecosystem Service of Pollination

According to our model, the value of pollination in the current scenario amounts to 318.94 million euros in the first year. The removal of 100% of the biomass (Scenario 2) leads to a 2.09% decrease in pollination value (−6.66 million euros in the first year). Augmenting the number of cuts from 3 to 4had a negative impact of 5.04% on pollination value (−16.7 million euros), while reducing the cutting height from 8 to 6 centimeters represented a loss of 11.75% (−37.46 million euros).

These relative losses were preserved across each type of crop, which means that the absolute loss changes drastically among them. For example, an 11.75% loss in apple croplands means −10.27 million euros, while the same percentual loss in a crop of the category *other industrial crops* means −6.74 euros. The model predicted that, if the maintenance is not carried out, the value of pollination increases by 36.14% (+115.27 million euros). However, this result emerges from a limitation of the model that will be discussed in Section 4. It should also be underlined that this is a hypothetical scenario not feasible for road security reasons.

Plantlife's autumn strategy consists in cutting most of the verge between mid-July and September and then cutting the entire area again from October to December. This strategy performed 16% (+51.04 million euros) better than the current strategy, while the late winter strategy, which consists in cutting during February or March, before the plants flower, and then cutting again in October or September, performed 2.32% (+7.41 million euros) better than the current strategy.

Figures 11-14 illustrate the dynamic behavior of the pollination population in these scenarios. To conclude, Figure 15 shows the final value for pollination estimated for each scenario from our model.

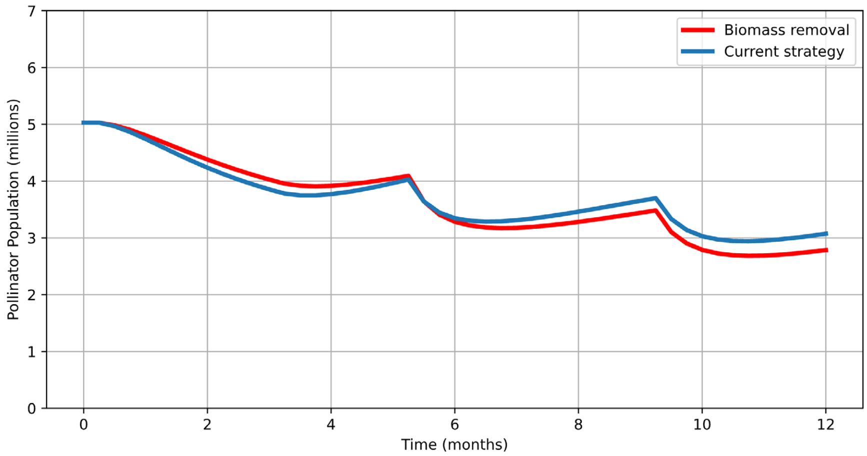

Figure 11. Influence of biomass removal on pollinator population per hectare over time.

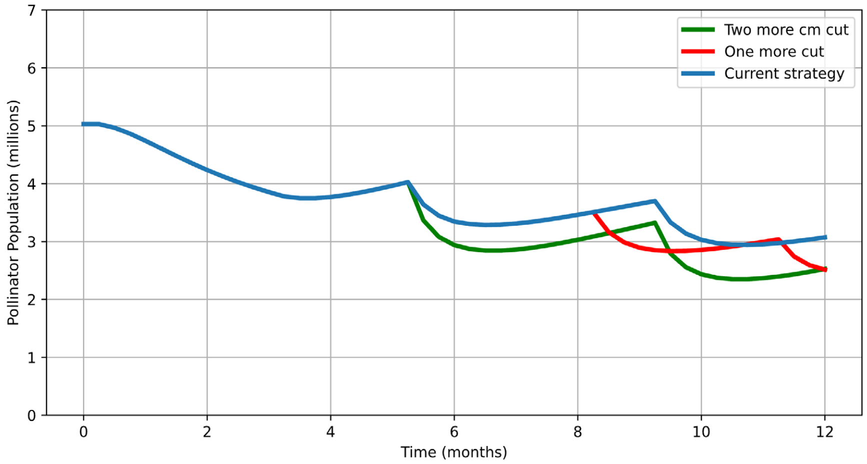

Figure 12. Influence of changing the cutting frequency or height on pollinator population per hectare over time.

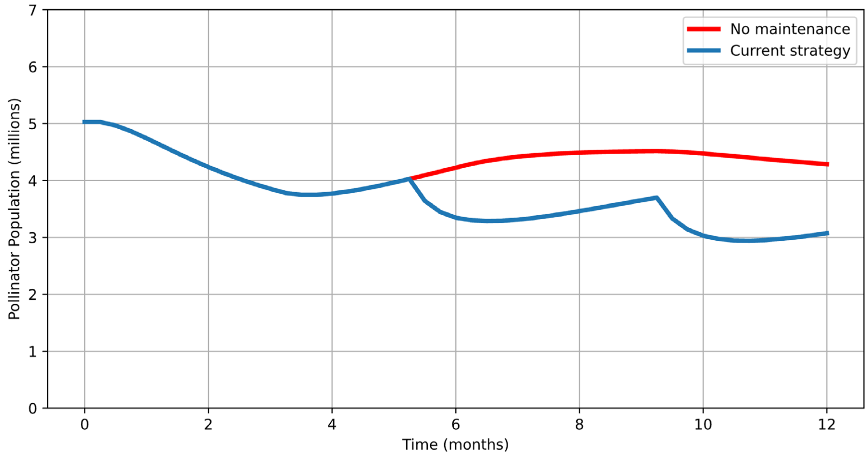

Figure 13. Evolution of pollinator population through time in the scenarios "Current strategy" and "No maintenance" per hectare.

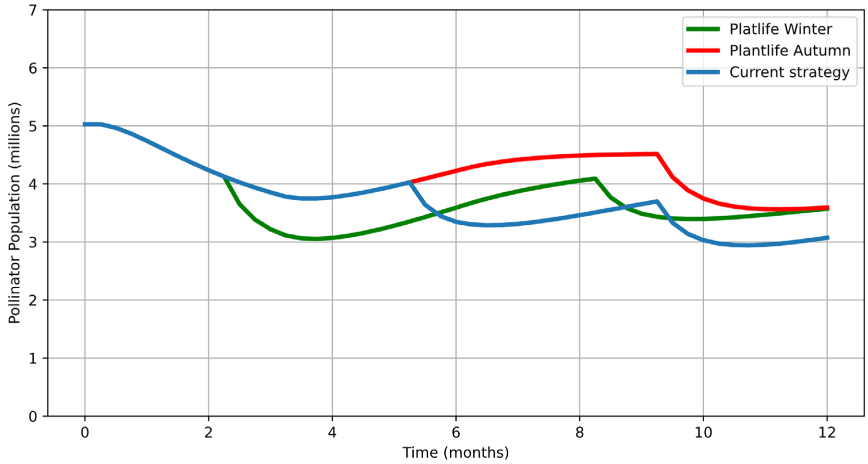

Figure 14. Evolution of pollinator population through time in the scenarios "Current strategy", "Plantlife late-winter" and "Plantlife autumn" per hectare.

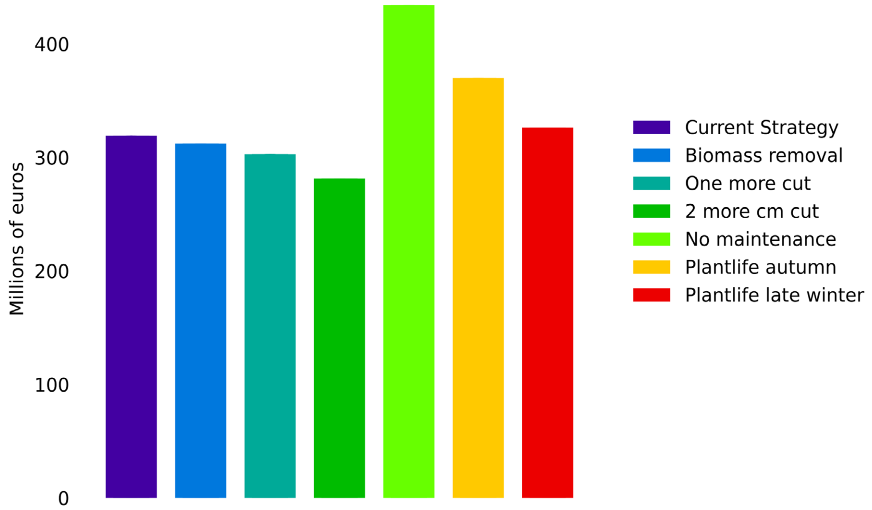

Figure 15. Comparison between the pollination value in euros estimated for each scenario.

4. Discussion

The model estimates an economic value for roadside pollination over a year of approximately 318.8 million euros, which corresponds to 0.0123% of France's GDP in 2020. This value varies significantly according to maintenance strategy, depicting the risk of careless management but also the potential environmental contributions of thoughtful management.

The results show that even though some crops contribute in similar amounts to the total value of pollination in France, the reasons behind these contributions (such astotal area and euros generated per each hectare per year) vary drastically among them. Considering that the relative losses due to maintenance were the same for each type of crop, this means that the absolute losses changed drastically. Thus, the results support the claim that a roadside management strategy that pays differential attention to adjacent crops contributes to providing sustainable roadside maintenance, enhancing its positive impact on pollination services. However, the proposed model presents some limitations that are detailed below.

4.1. Adequacy of Data and Hypotheses

The lack of experimental measurements of the biophysical variables involved in the model is an important limitation of the study that could affect the accuracy of the estimations for each scenario. This is also a limitation faced by other studies involving models of pollination like the dependency ratio model [61], where the authors point out the inconsistent quality of available global data about pollination dependency ratios.

In general, the lack of data on the road verge hinders the parameter estimation process. Some first measurements of the impact of road verge management on pollinator population can be found in [67], but an approach that aims to measure the total values of the variables in the system is still missing for the purposes of this research.

Furthermore, it may seem unusual to simply compare the final values of the variables with published data in the literature to validate a system dynamics model. As suggested by SD experts, it is important to check simulated time series data of stock variables with historical data or time models based on literature or accepted knowledge. Validated system behaviours ensure a sound SD model structure, which can then be used for scenario analyses. However, we did not find any reference models in the literature that would allow us to compare this first proposal.

Aligned to the above-mentioned, in the presence of more data, the process of model validation could be expanded by incorporating external validity (comparing model results to real-world results), and predictive validity (comparing model results to prospectively observed events), as a complement of cross validity, acknowledging that the former two are the strongest form of validation [64].

4.2. Potential Impact of Changing the Maintenance Regime

Simulating a change in cutting frequency or height resulted in a decrease in pollination value. The model shows that in the first year, reducing the cutting height from 8 to 6 centimeters had a greater negative impact than augmenting the number of cuts from 3 to 4. Overall, the model was able to represent the fact that an over-intense regime has a negative impact on pollination value.

For its part, *Plantlife*'s strategies performed better than the current one, suggesting an opportunity to improve the maintenance regime. Therefore, it could be useful to study the viability of these strategies in France and other countries, as well as their long-term performance, in order to implement them.

4.3. Biomass Removal

The study was able to represent the impact of biomass removal over pollination value by formalizing the known relations between biomass removal and the variables that characterize the road verge, such as biomass growth rate. The progress made in this matter can be an important first step to modeling the relation between those ecosystem services.

On the other hand, the results do not seem to confirm the claim that biomass removal is beneficial for pollination and the preservation of verges. Nevertheless, as stated by *Plantlife*'s guidelines [54] and a technical study conducted in France in 2021 by the Center for Studies and Expertise on Risks, Environment, Mobility, and Development [23], the removal of biomass residues at the time of mowing leads to the removal of a source of nutrients, which reduces soil fertility and promotes flowering plants and thus pollination.

A possible explanation for this contradiction is that our model does not consider the benefits of biomass removal (namely, the enrichment of flowered biomass in terms of abundance and diversity), but only its drawbacks (namely, the idea that as the general growth rate of biomass is lower, there are fewer resources for pollinators); nor does it consider the other ecosystem services affected positively by biomass removal (for example, regulation of invasive plant species) and how they impact pollination.

Additionally, reducing gramineous plants and augmenting flowered biomass enables fewer cuttings per year (as the former need more control than the latter), reducing operational impacts. Thus, it would be fairer to decrease the number of cuttings in the biomass removal scenario for comparison.

4.4. Impact of the Absence of Maintenance

The arguments presented in Subsection 4.3 could also explain why the model suggests that doing no maintenance at all is the best strategy for the ecosystem service of pollination, disregarding the benefits of maintenance. Therefore, a possible continuation of this research could focus on improving the model so that these benefits become visible, while keeping track of their impact on the results.

We claim that the results of this scenario happen because the model does not consider the impact of maintenance on other ecosystem services and processes that affect pollination. Specifically, we hypothesize that studying how biomass abundance and flower presence change though time, as well as the impact of maintenance on this process of ecological succession, is key to estimating more exactly the impact of road verge management on the environment. As stated by [68], any managing problem that involves plant populations also involves ecological succession.

Furthermore, the literature indicates that the positive effects of maintenance and biomass removal on the pollination service are more evident over a number of years [54], implying that increasing the time scale of the simulations may be needed as a complement to the previous proposals. Taking this into consideration, the use of a system dynamic as a modeling strategy could also prove to be a good choice in future studies.

5. Conclusions

Our research provides a representation of the behavior of the maintained roadside and pollination considering the biophysical components and dynamics of the ecosystem, the economic elements involved in the valuation of the service, and the changing factors related to management. The choice of system dynamics as a modeling strategy proved to be suitable to portray the interaction between anthropogenic and biophysical factors; specifically, it outlined how the pollinator population is affected by the maintenance of road verges and how this effect changes in different scenarios. Overall, the study contributes to the current scientific literature by providing a first simplified model of the effects of the maintenance of road verges on the pollination service.

Regarding the limitations of the study, it is important to note that the absence of experimental data on road verges led us to calibrate the parameters based on studies undertaken in other contexts (see **Appendix 2**). This may affect the final estimations but not the general behavior of the variables. Thus, the exactness of the values in euros assigned to each strategy depends on the accuracy of those estimations that should be further studied. In addition, this article presents a modeling, excluding some exogeneous factors that can have a strong influence on the pollination service.

When comparing the results with the literature, we conclude that modeling the impact of the maintenance of road verges on a single ecosystem service in a period of one year could lead to underestimations of certain managing strategies; for example, the ones involving biomass removal. This highlights the importance of a more integrated approach to ecosystem service modeling and valuation that considers multiple ecosystem services, their relations, their processes, and the long-term effect of maintenance.

Another possible perspective of this study could be to add an experimental perspective to the validation process, by comparing the model's predictions with measurements of its variables taken at the roadside. This could not only be useful for this research but also address the lack of empirical data on the topic of ecosystem services and their economic values in landscape planning, management, and decision-making indicated by [21]. All things considered, this first estimation of the value of pollination shows the potential of the dynamic system dynamics method as a modeling strategy for the impact of the management of road verges on ecosystem services. To go further in the development of a potential tool dedicated to decision-makers, this type of model could be linked with GIS tool in order to have accurate information on the territory, road network [69] and the pollination service.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Appendix

Appendix 1. Parameters involved in the equations that describe the dynamics of pollinators and biomass.

Parameter	Description	Interpretation	Unit
bp	Birth rate of pollinators	Number of new pollinators per each existing one per unit of time.	months^{-1}
K_p	Ecosystem's carrying capacity for pollinators	Maximum number of pollinators that can be reached without perturbation in the ecosystem.	animals
b_m	Increase rate of biomass	Amount of new kg of biomass per each existing one per unit of time	months^{-1}
K_m	Ecosystem's carrying capacity for biomass	Maximum amount of biomass that can be reached without perturbation in the ecosystem.	kg
h	Impact of maintenance over biomass	Biomass extracted per unit of biomass per month.	months^{-1}
κ	Carrying capacity per unit of biomass	Number of pollinators carried per kg of grass.	animals kg^{-1}
γ	Proportion of biomass corresponding to flowers	Kilograms of flowers in the hectare per kilogram of biomass.	none
υ	Weight parameter of the impact of human activity if the maintenance is done without interfering with plants life cycle	Biomass extracted per unit of biomass per month per centimeter cut assuming no intervention with plant life cycle.	$\text{kg}\cdot\text{cm}^{-1}$
ω	Weight parameter of the impact of human activity if the maintenance is done interfering with plants life cycle	Biomass extracted per unit of biomass per month per centimeter cut assuming intervention with plant life cycle.	$\text{months}^{-1}\cdot\text{cm}^{-1}$
α	Pollinators visit ratio	Expected number of pollinating visits per pollinator per kg of biomass per month.	visits animals months^{-1}
β	Pollination efficiency	Kilograms of biomass produced in each pollinator visit (see Appendix 3)	kg visit^{-1}
θ	Economic value of crop unit	Price received by farmers for kg of their produce at the farm gate (see Appendix 3)	Euros kg^{-1}
p_{pp}	Purchasing power parity	Ratio between prices in France and in the global economy.	none

Appendix 2. Values of the parameters involved in the equations that describe the dynamics of pollinators and biomass.

Parameter	Description	Value	Justification
bp	Birth rate of pollinators	0.9375	625 new bees per day throughout the year in a colony of 20,000 bees, which means 18,750 bees per month, or approximately 18,750/20,000 = 0.9375 bees per month [57] [70].
$b_{m,0}$	Biomass growth rate assuming no removing	0.3	Assumed.
$b_{m,1}$	Difference between bm,0, and the growth rate if all biomass is removed	0.07	Data directly extracted from [71].
K_m	Ecosystem's carrying capacity for biomass	13,140 in winter, 24,090 in spring, 19,026 in summer, 16,912 in autumn	Assumed in such a way that it matches the seasonal tendencies presented in [57].
G	Percentage of the road verge covered by grass	74.1	Assumed.
B	Percentage of the road verge covered by brushes	20.9	Assumed.
T	Percentage of the road verge covered by trees	5	Assumed.
d_G	Biomass on a hectare totally filled by grass	8400	Data directly extracted from [60].
d_B	Biomass on a hectare totally filled by brushes	9500	Assumed in such a way that the value is higher than the one of grassland, but less than culture's [60].
d_T	Biomass on a hectare totally filled by trees	72 800	Based on the assumption that a road tree is ten times lighter than a forest protect tree and using data from [60].
K_G	Number of pollinators carried per kg of grass	1100	Data extracted from [72], converted to hectares and divided by grass weight.
K_B	Number of pollinators carried per kg of brushes	1244	Calculated assuming that dG/dG = dB/KB.
K_T	Number of pollinators carried per kg of trees	9533	Calculated assuming that dG/dG = dT/KT.
γ	Proportion of biomass corresponding to flowers	0.08	370,000 flowers per hectare [72] with an average weight of 3 g per flower [73]: 1110 kg as the weight of flowerson a hectare. 12,500 kg of biomass in a road verge [74], so the ratio is 1110/12.500 = 0.08.

Continued

υ	Weight parameter of the impact of human activity if the maintenance is done without interfering with plants life cycle	0.05	Assumed.
ω	Weight parameter of the impact of human activity if the maintenance is done interfering with plants life cycle	0.0575	Assumed.
α	Pollinators visit ratio	0.019	0.4 visits per flower per hour, *i.e.* 292 visits per flower per month and 97,333 visits per kg of flower biomass per month or 0.019 visits per pollinator per kg of flower biomass per month, assuming that we have approximately 5 million pollinators [75].
p_{pp}	Purchasing power parity	0.727	OCED public data (For France, 2020).

Appendix 3. Values of the parameters related to the economic value of pollination [65].

Crop	mg produced per visit ($\beta \cdot 10^6$)	Value per ton produced ($\theta \cdot 10^3$)
Rapeseed	1,37	388,56
Apple	21,3	1202,91
Sunflower	0,955	388,56
Sugar cane	148	33,98
Tomato	67,53	728,31
Melon	17,88	728,31
Soy	1,008	388,56
Cider apples	14,08	1202,91
Textile linen	1,221	33,98
Zucchini	34,16	728,31
Pumpkins	22,78	728,31
Cucumbers	51,59	728,31
Pear	15,43	1202,91
Prune plums	7,715	1202,91
Broad bean	0,8976	388,56
Peaches	11,92	1202,91
Apricots	4,237	1202,91
Nectarines	10,45	1202,91
Kiwi	11,59	1202,91
Turnips	15,06	728,31
Cherry	2,966	1202,91

Continued

Other plums	13,33	1202,91
Beans	0,4802	728,31
Watermelon	15,33	728,31
Linseed	0,428 9	388,56
Strawberry	3,85	728,31
Reine-Claudes	8,534	1202,91
Mirabelle plums	6,019	1202,91
Another oilseed	0,7347	388,56
Eggplant	8,266	728,31
Blueberries	2,327	1202,91
Raspberries	4,745	1202,91
Pavies	14,66	1202,91
Mango	2,938	1202,91
Mandarins	0,992	1202,91
Passion fruit	8,557	1202,91
Chestnuts	0,2371	1202,91
Oranges	1,934	1202,91
Morello cherry	2,476	1202,91
Plums	5,641	1202,91
Peppers and chillies	1,368	728,31
Guava	3,861	1202,91
Avocats	5,168	1202,91
Figs	1,761	1202,91
Soursop	3,796	1202,91
Pickles	5,143	728,31
Coconut	0,549	1202,91
Currants	1,61	1202,91
Lemon	0,3976	1202,91
Grapefruits	1,065	1202,91
Lychee	0,2988	1202,91
Okra	0,6384	728,31
Vanilla	0,0491	33,98

Appendix 4. Pollination value of crops in France (euros/ha) [65].

Crop	Crop Pollination Dependency Ratio	Product of Producer Price	Production quantity (ton)	Yield surface (ha)	Pollination Value (euros for total production [ton])	Pollination Value (euros/ha)
Rapeseed	0,5	388,56	3 297 725	1 113 935	451 681 130,3	405,5
Apple	0,65	1202,91	1 321 781	37 344	728 611 140,8	19 510,8
Sunflower	0,5	388,56	1 607 078	778 401	220 117 446,9	282,8
Sugar cane	0,25	33,98	2 297 852	37 770	13 761 816,1	364,4
Tomato	0,65	728,31	659 271	5 875	220 029 195,4	37 451,8
Melon	0,95	728,31	266 559	13 111	130 022 926,7	9 917,1
Soy	0,5	388,56	406 665	186 718	55 699 886,1	298,3
Cider apples	0,65	1202,91	298 095	12 804	164 320 214,9	12 833,5
Textile linen	0,25	33,98	745 568	141 346	4 465 200,4	31,6
Zucchini	0,95	728,31	129 423	3 332	63 130 328,5	18 946,7
Pumpkins	0,95	728,31	127 506	4 923	62 195 248,7	12 633,6
Cucumbers	0,65	728,31	142 057	1 657	47 410 984,9	28 612,5
Pear	0,65	1202,91	137 927	5 379	76 030 105,4	14 134,6
Prune plums	0,65	1202,91	130 627	10 190	72 006 094,4	7 066,3
Broad bean	0,5	388,56	148 407	76 539	20 326 934,9	265,6
Peaches	0,65	1202,91	94 108	4 749	51 875 565,8	10 923,5
Apricots	0,65	1202,91	85 830	12 190	47 312 447,5	3 881,3
Nectarines	0,65	1202,91	80 272	4 621	44 248 686,8	9 575,6
Kiwi	0,95	1202,91	49 768	3 777	40 095 602,1	10 615,7
Turnips	0,65	728,31	57 777	2 308	19 282 854,6	8 354,8
Cherry	0,65	1202,91	35 742	7 252	19 702 219,5	2 716,8
Other plums	0,65	1202,91	35 209	1 589	19 408 411,6	12 214,2
Beans	0,05	728,31	419 178	40 407	10 761 466,7	266,3
Watermelon	0,95	728,31	17 508	1 004	8 540 103,3	8 506,1
Linseed	0,25	388,56	59 428	32 070	4 069 852,1	126,9
Strawberry	0,25	728,31	55 548	3 339	7 130 359,3	2 135,5
Reine-Claudes	0,65	1202,91	16 222	1 144	8 942 124,2	7 816,5
Mirabelle plums	0,65	1202,91	16 012	1 601	8 826 365,0	5 513,0

Continued

Another oilseed	0,5	388,56	15 836	9 978	2 169 017,2	217,4
Eggplant	0,25	728,31	27 461	769	3 525 001,8	4 583,9
Blueberries	0,65	1202,91	9 400	2 431	5 181 603,2	2 131,5
Raspberries	0,65	1202,91	5 393	684	2 972 807,1	4 346,2
Pavies	0,65	1202,91	4 606	189	2 538 985,6	13 433,8
Mango	0,65	1202,91	4 570	936	2 519 141,2	2 691,4
Mandarins	0,05	1202,91	46 575	2 172	1 974 903,2	909,3
Passion fruit	0,95	1202,91	2 364	243	1 904 557,2	7 837,7
Chestnuts	0,25	1202,91	8 857	8 644	1 877 801,1	217,2
Oranges	0,25	1202,91	8 156	976	1 729 179,9	1 771,7
Morello cherry	0,65	1202,91	2 926	711	1 612 911,8	2 268,5
Plums	0,65	1202,91	2 906	310	1 601 887,1	5 167,4
Peppers and chillies	0,05	728,31	29 175	987	749 003,5	758,9
Guava	0,65	1202,91	2 207	344	1 216 574,3	3 536,6
Avocats	0,65	1202,91	2 044	238	1 126 723,1	4 734,1
Figs	0,25	1202,91	3 340	439	708 124,2	1 613,0
Soursop	0,65	1202,91	1 047	166	577 142,4	3 476,8
Pickles	0,65	728,31	923	108	308 047,7	2 852,3
Coconut	0,25	1202,91	2 386	1 005	505 863,6	503,3
Currants	0,25	1202,91	1 997	287	423 390,4	1 475,2
Lemon	0,05	1202,91	9 981	1 162	423 220,8	364,2
Grapefruits	0,05	1202,91	8 423	366	357 157,5	975,8
Lychee	0,05	1202,91	8 185	1 268	347 065,7	273,7
Okra	0,25	728,31	513	186	65 850,7	354,0
Vanilla	1	33,98	21	376	503,1	1,3

Appendix 5. Percentual difference between the estimation of current pollination value per crop done by the model presented and the dependency ratio model.

Crop	Percentual difference
Rapeseed	0.008%
Apple	0.039%
Sunflower	−0.037%
Sugar cane	0.029%
Tomato	0.039%
Melon	0.030%
Soy	0.019%
Cider apples	0.536%
Textile linen	0.049%
Zucchini	0.030%
Pumpkins	0.040%
Cucumbers	0.036%
Pear	0.033%
Prune plums	0.047%
Broad bean	0.042%
Peaches	−0.005%
Apricots	0.035%
Nectarines	0.004%
Kiwi	0.045%
Turnips	0.008%
Cherry	0.041%
Other plums	0.006%
Beans	0.035%
Watermelon	−0.009%
Linseed	0.038 %
Strawberry	0.026 %
Reine-Claudes	0.046 %
Mirabelle plums	0.045%
Other oilseed	0.041%
Eggplant	0.048%
Blueberries	0.042%
Raspberries	0.044%
Pavies	0.000%
Mango	0.032%
Mandarins	−0.026%
Passion fruit	0.045%
Chestnuts	0.014%
Oranges	0.030%
Morello cherry	0.017%
Plums	0.034%
Peppers and chilies	0.015%

Continued

Guava	0.042%
Avocats	0.034%
Figs	0.041%
Soursop	0.049%
Pickles	0.039%
Coconut	−0.053%
Currants	0.007%
Lemon	0.034%
Grapefruits	0.008%
Lychee	0.035%
Okra	0.044%
Vanilla	−0.008%