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Evaluating the Impacts of Pollinators Decline on Social Welfare at Different Spatial Scales: Economic and Nutritional Aspects

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Dedicated to my mother, Mukagakwaya, and

my father, Mwunguzi.

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Executive summary

Pollinators are threatened in many parts of the world. This alarming phenomenon; for which Human is mainly responsible, raises the following questions: what are the consequences of pollinators decline for society? Should we take actions?

This thesis proposes economic valuation as a decision-making tool. It evaluates the impacts of the decline of pollinators on human well-being through economic and nutritional perspectives. The focus is on marketed and non-marketed benefits for the economic aspects and the quantitative and qualitative dimensions of nutrient intake for the nutritional aspects. The contribution of pollinators to a global food market, territories, and local landscapes in different contexts is examined alternately. More specifically, three case studies were treated each on different spatial scales: the international trade, the Comminges territory, in southwestern France, and the Huye District, in southern Rwanda.

Inspired by welfare economics, our analysis builds on the production function approach, which integrates the dependence ratio of agricultural production on pollinators, the nutrients contained in crops, and the stated preferences approach. The proposed methods combine analytical approaches, field surveys, and simulations.

Chapter 1 reviews the existing economic valuation approaches of the benefits of pollinators, highlights the need to consider various spatial scales of causes and impacts of pollinator decline, and reviews the existing policy responses regarding pollinator degradation. Chapter 2 analyzes global agricultural markets as a whole and shows the implications of pollinators decline in international food trade and their impacts on global social welfare. Chapter 3 analyzes the importance people place on pollinators and their concerns about their decline by assessing the general public's willingness to pay for the marketed and non-marketed benefits of pollinators. Chapter 4 values the contribution of insect pollination on the quantity of production and nutritional quality of consumption in the case of smallholder farm households where subsistence agriculture remains dominant.

The thesis shows that the decline of insect pollinators could have significant consequences on human well-being at local and global scales. Under defined assumptions, results show that an average world price of crops will be 186% higher if pollinators extinct on a global scale. They show that the decline of insect pollinators can induce a decrease in consumer surplus, producer profit, and trade balance value, thus an overall loss of human well-being on a global scale. In particular, these results draw attention to a loss of global nutrient intake, especially in regions where food scarcity is already present. The general public in the Comminges is willing to pay about €516 per household per year to avoid pollinator decline scenarios in order to maintain the diversity of local food, flora, and fauna. In smallholder households in the Huye District, pollinator-dependent crops account for about 20% of the total production value and have a significant share in the self-supply of micronutrients.

This thesis argues that all countries can be impacted by this decline either as exporters or as importers of pollinator-dependent crops even if the impacts of this decline may be heterogeneous across countries due to differences in initial endowments. In fine, the decline of pollinators threatens the diversity and food security of worldwide consumers, the livelihoods of farm households, and local biodiversity. Therefore, arbitration among local decision-makers, national and international governmental bodies, and the general public is necessary to mitigate the decline of pollinators.

In conclusion, this thesis points to the need to combine economic and nutritional aspects in shaping economic valuation literature and public policies and initiatives regarding ecosystem services and pollinators.

Contents

General Introduction

1. Context: Why study the economic and nutritional impacts of pollinators?

Since the São Paulo Declaration on Pollinators (1999)[1], which is among the outcomes of the Third Conference of the Parties (COP3) of the Convention on Biological Diversity (CBD), pollinators have received increasing attention as key components of biodiversity in the global scientific and political arenas (Dias et al., 1999; IPBES, 2016). Pollinators are animals that contribute to plant pollination: they mainly include bee species – both wild bees and honey bees that are managed (Klein et al., 2007) - and other insects (e.g., flies, butterflies, moths, and beetles; Garibaldi et al., 2013). By feeding on nectar, pollinators carry pollen from the male to the female parts of flowers of the same species, which is called pollination. Pollination allows fertilization and reproduction of flowering crops and other plant species. Therefore, pollinators play a crucial role for Nature and humanity. Pollinators benefit the well-being of humans by improving the quantity (Williams, 1994; Klein et al., 2007) and the quality (Klatt et al., 2014) of food products - notably the nutritional quality (Chaplin-Kramer et al., 2014; Sluijs et al., 2016) -, the quality of scenery by maintaining wild flora (Ashman et al., 2004; Ollerton et al., 2011), etc.

Particularly, paying attention to pollinators and their benefits in food production is important as almost 690 million people in the world today still suffer from hunger due to the lack of sufficient and nutritious food (FAO, IFAD, UNICEF, WFP and WHO, 2020). Similarly, the World Health Organization warns that global malnutrition is on the rise with increasing levels of undernourishment and obesity (WHO, 2018). Although malnutrition is a multifactorial problem, many crops that provide important and essential nutrients (e.g., vitamins, antioxidants, and fiber) are pollinated by insects (e.g., fruits and vegetables; Eilers et al., 2011). Several scientific studies in natural sciences (e.g., ecology, biology and agronomy) have reported overlaps between global nutrition and pollinator-dependent micronutrient production (e.g., Eilers et al., 2011; Chaplin-Kramer et al., 2014; Sluijs et al., 2016). However, these overlaps remain little studied and poorly understood in economics.

Hence, our interest in investigating both the economic and nutritional aspects of pollinators benefits. This general introduction provides an insight into this thesis work by highlighting its background and problem statement, objectives, hypotheses, scope of methodology, main results, and its structure.

[1] https://www.cbd.int/doc/ref/agr-pollinator-rpt.pdf

2. Background and problem statement

Threatened by a variety of factors including human economic activities, notably the intensive use of pesticides (Pfiffner and Muller, 2014), agricultural intensification and habitat conversion (Aizen and Feinsinger, 2003), invasive species (Schweiger et al., 2010), introduced pathogens (Cameron et al., 2011), and climate change (Hegland et al., 2009), the abundance and diversity of pollinating insects are declining (Potts et al., 2010). This decline is leading to a "pollination crisis" in agricultural production systems in many parts of the world (see, e.g., Holden, 2006; Goulson et al., 2015). A pollination crisis refers to the notion that a decline in pollinators may threaten the human food supply (Cell Press, 2009), both in terms of quantity and nutritional quality, while the cost of this decline for human society remains poorly understood.

Thus, public policies are often called upon to mitigate the decline of pollinators. To this end, policymakers have shown interest and express the need to understand the costs and benefits that pollinators generate to the people for effective decision-making. This need for the valuation of Nature benefits has already been raised several times by authors such as Daily et al. (1997, 2000) and Costanza et al. (1997), highlighting the role of economic valuations for such a decision-making process. These authors argue that comparing the costs and benefits brought by Nature using an understandable metric can be useful for policymakers and, more broadly, to all stakeholders.

This thesis is therefore part of the ongoing effort to adjust economic valuation tools in order to account for the benefits of pollinators and the costs of their decline for society.

The economic valuation of the benefits of pollinators gained momentum in the economic literature worldwide since some studies alert on the impact of the insect pollination scarcity across the United States of America (USA) in early 2000s (vanEngelsdorp et al., 2009; Porto et al., 2020). Indeed, by improving pollination, pollinators lower the marginal costs of production, thereby boosting agricultural yields at a lower price (Winfree et al., 2011). Most economic studies assess the impact of pollinators decline in countries with a particular focus on the decrease in crop production quantity (Southwick and Southwick, 1992; Morse and Calderone, 2000; Leonhardt et al., 2013; Tibesigwa et al., 2019). In short, the decline of pollinators threatens agricultural production. For instance, Morse and Calderone (2000) estimated the value of crop pollination by honeybees alone in the USA at $14.6 billion per year. The contribution of pollinators to the value of the global agricultural sector has been estimated to be between 153 and 260 billion euros (see Gallai et al., 2009; Lautenbach et al., 2012), which represent about 8 to 10% of the value of global edible crop production (IPBES, 2016). Current economic studies start to extend this assessment to the benefits of pollinators found in landscape features such as floristic scenery (e.g., Breeze et al., 2015; for the UK).

Non-economics literature (e.g., biology, ecology), however, depicts more roles of pollinating insects for humanity including their contribution to the formation of nutrients in crops. For instance, Ellis et al. (2015) find that pollinator-dependent crops contribute up to 40% of the world's supply of nutrients while Eilers et al. (2011) found that around 90% of Vitamin C in crops is produced thanks to insect pollination.

To date, the economic valuation literature on pollinators has not gone far enough to understand the consequences of the link between the decline of pollinators and malnutrition to human society. Thus, the comprehensive benefits of pollinators including crop nutritional quality are still understudied. Hence, the different values of the benefits of pollinators remain still underestimated by public policies. For example, while the nutritional quality of crops is well identified by the market price of crops, the contribution of insect pollination on that quality is not. Yet, the nutritional contribution that the benefits of pollinators offer to humans, which has an impact on health, would be valuable to public policymakers and the general public. To identify such benefits of pollinators, measure them, and thus value them in metrics that are easily understood by all is crucial to raise the general public's awareness about endangered pollinators and the consequences of their decline, which may unlock extended actions.

Economic valuation is powerful in enabling the aggregation of understandable and usable metrics of different value-types into a single metric of economic value, simplifying the analysis for valuation purposes and decision-making. Economic value is especially useful since it allows covering all expressions of values, including the costs of degradation or the benefits of maintaining pollinators. However, such aggregated value considers only the known benefits of pollinators to humans at the moment – while knowledge about all aspects of pollinators is still limited – and therefore results in an underestimation of the value of the overall benefits that pollinators can generate.

Indeed, several studies have contributed to the understanding that a decline in pollinators will increase the cost of agricultural production, or reduce productivity, and consequently increase market prices (see for example Gallai et al., 2009; Garibaldi et al., 2011a). This is especially the case for pollinator-dependent crops, which include many fruit and vegetables (Chaplin-Kramer et al., 2014; Sluijs et al., 2016). As a consequence, the demand and supply of pollinator-dependent crops will alter as people adjust and respond to pollinators decline. People may replace insect pollinator-dependent crops by less nutritive non-insect pollinator dependent crops for consumption. In turn, production and supply will organically match demand.

Considering adjustment to and mitigation of the pollinators decline, Bauer and Wing (2016) point out that specialization may take place across countries and regions. In other words, countries relatively endowed with pollinators may adjust to production technologies by focusing on the supply of pollinator-dependent crops while other countries may adjust to production technologies by focusing on the production of other crops. Thus, through the demand and supply, adjustment processes of economic mechanisms to the decline of pollinators can be regarded as “substitution processes” (i.e., as in Fisher and Pry, 1971; Maguire, 2004).

However, the phenomena resulting from these substitution processes may occur within a country, in the fields, and thus in production systems as well as inside household consumption. Of course, these changes and adjustments may take different forms in different countries, regions, and villages where actors operate according to different norms, knowledge, habits, etc.

Nevertheless, in the era where international trade is more and more involved in the economic life of countries and local communities, it seems necessary to take into account these substitution processes and their impacts. Hence, how can we be sure that countries driven by international trade mechanisms to produce goods that rely on pollinators will protect their pollinators to maintain the global food balance? How can we be sure that these goods will be accessible to all people through trade? And how can we be sure that these countries will protect pollinators to maintain the global biodiversity or other local benefits of pollinators that are not valued by the market?

Also, it is very crucial not to underestimate the similar kind of substitution procceses that can take place on other smaller scales than the international scale such as the national scale or more local ones. In that respect, it is necessary to work towards ensuring that countries will protect their pollinators through strategic solutions involving a plurality of actors using insect pollination under different contexts with diverse social practices and sometimes competing interests.

From the economic point of view, it is straightforward to imagine the interdependencies and complementarities of the various responses to the issues of the pollination decline. As a result, it seems necessary to have international and national as well as local approaches to sustainably safeguard pollinators. The economic valuation should try to encompasss more and better this multiplicity of scales and, ideally, the phenomena due to their simultaneous functionning.

Indeed, on the one hand, the economic valuation of the benefits of pollinators is concentrated at the national scale and only on their quantitative dimensions; whereas their qualitative dimensions (e.g., nutritional quality), notably in household consumption, and the role of pollinators in regulating biodiversity are little studied in economics. On the other hand, this valuation is concentrated in developed countries (Porto et al., 2020), while it remains rare in developing countries where subsistence farming is still more common and so is households’ self-supply and consumption of food. The developing countries have to be considered in their own right since the types of coordination and arbitration may be different from that of developed countries. For instance, the feature of farm households in developing countries has been considered particular due to the fact that they are consumers of crops they produce and, consequently, their production and consumption decisions are often interdependent (Barnum and Squire, 1979; Sadoulet and de Janvry, 1995). Thus, any shock affecting crop production impacts directly the income and food consumption of such farm households; in terms of quantity and quality.

Paying further attention to the economic as well as health benefits of pollinators and, consequently, to the cost of pollinators decline at different scales with a well-suited methodology, is thus an important challenge that this thesis will contribute to address. Specifically, this thesis aims to help understand both the economic and nutrition aspects that can be associated with the decline of pollinators to inspire public policy and increase general public's awareness. In doing so, it seeks to shed some light on the consequences that the adjustments of economic mechanisms to the decline of pollinators may have on the quantity and nutritional quality of food production and consumption.

To meet this aim, the objectives of this thesis are as follows.

3. Thesis objectives

The objectives of this thesis are to raise new issues, suggest further analyses, and extend existing analytical approaches regarding the economic valuation of the benefits of pollinators by focusing on different spatial scales to better depict complementary responses that can mitigate the decline of pollinators.

Specifically, we suggest addressing the following questions: What would be the consequences of pollinators decline not only on the quantity but also on the nutritional quality of worldwide supply and demand of edible crops given international trade mechanisms? What could be the general public's willingness to protect pollinators? More specifically, what could be the impacts of pollinators decline on farm households' food production and thus on these households' nutrient consumption? We distinguish between two contexts, one in a region of a developed country (France) and another one in a region of a developing country (Rwanda).

Following these questions, three assumptions can emerge.

4. Assumptions

Given that the decline of pollinators will have an impact on crop productivity, the first assumption is that substitution processes, understood as adjustments of economic mechanisms to the decline of pollinators, will take place at different scales. These substitution processes could reduce the diversity of food production and consumption. Consequently, pollinators decline would trigger deficiencies in both the supply and intake of essential nutrients. Hence, the economic and nutritional aspects that may be affected by this decline need to be addressed together.

The second assumption is that it is necessary to consider different spatial scales to address the decline of pollinators. This necessity is due to the fact that the perception of the importance of pollinators may depend on the scale of the analysis, the characteristics of the areas studied, and the definition of the "economic agent" as the unit of analysis, but responses to pollinators decline at each scale as well as different scales are complementary. On the one hand, as free pollination that pollinators may offer declines on farms, other means of pollination may increase production costs thus requiring extra resources from producers operating under different agricultural systems. Such an increase in production costs will increase market prices, which, in turn, will harm the consumer surplus. In some countries this production cost increase is due to the introduction of alternative costly pollinating methods such as hiring beehives or mobilizing mechanical means. This impact corresponds to the reduction of the marketed (natural) pollinator benefits as their number declines. However, an insidious mechanism of substitution processes may take place at consumers level as they may replace in their diet pollinated crops by crops not necessitating pollination but containing less nutritive intakes (for example by replacing some of the fruits and vegetables with grains). This replacement can have negative effects on human well-being. This is especially likely for less fortunate societies who may not be able to invest in the costly substitute of pollination means to sustain their production or to cope with increased market prices, hence a potential for increasing inequalities in society. This negative impact is to be added to that on the biodiversity and the scenery (offered by wildflowers, for example) that are not currently considered or exchangeable through the market. They are called “non-marketed benefits”. As such, they can be neglected if substitution processes leading to specialization in certain crops are supported or prevail.

These considerations lead to our third assumption, which is that, the general public's willingness to protect pollinators will depend on public’s awareness of the contribution of pollinators to human welfare. For the benefits of pollinators can be primarily threatened within their vicinity, societies with richer biodiversity and multifunctional landscapes (e.g., crop production, scenic tourism, research and cultural activities, etc.) may be exposed and sensitive to the direct consequences of pollinators decline, and thus their willingness to protect pollinators may be more important than for other societies.

The next part exposes the scope of the methodology that will be used to address the above-mentioned research questions and test these hypotheses.

5. The scope of the methodology: Case studies, Scales and Indicators

Several authors have pointed out that it is crucial to consider the issue of scales in the economic analysis of the benefits that ecosystems provide to humans (MEA, 2003, 2005; TEEB, 2010; UNEP, 2016), including pollination (Hein et al., 2009; IPBES 2016, Ch. 4) to effectively inform decision-makers. It may therefore be necessary to understand the impacts of pollinators decline on the well-being of actors operating in different contexts at different scales to effectively inform decision-makers about the tendencies of social costs as pollinators decline. But, for the time being, there are not enough statistics at various scales and from different contexts (e.g., economic, social, ecological, etc.) (e.g., Porto et al., 2020), nor is there a suitable economic theory (e.g., Gómez-Baggethun et al., 2010) to allow a theoretical analysis of the complexity of this thesis subject. However, through observations of actors who are linked in some way to the benefits of pollinators focusing on specific indicators, it is possible to identify the costs that pollinators decline may generate to them. To do this, we propose to use a variety of case studies.

As mentioned earlier, many studies focusing on the economic valuation of pollinators have concentrated their estimations on the contribution of pollinators to the crop sector using market prices at a national scale (e.g., Southwick and Southwick, 1992) and an international scale (e.g., Kevan and Phillips, 2001; Bauer and Wing, 2016). Other economic studies have addressed the issue of pollinators decline focusing on the fluctuations of crop yields at the farm scale (e.g., Nderitu et al., 2008). Also, a few economic studies have focused on the benefits that pollinators generate to human well-being at local and territorial scales mobilizing the stated preferences approach, which is particularly known for assessing the value of the characteristics of goods other than their production quantity (e.g., Breeze et al., 2015; Mwebaze et al., 2018). However, while farmers can directly witness the impacts of pollinators decline on their livelihoods, none of the previous studies have addressed the impacts of this decline on their household welfare. This thesis aligns with these economic studies assessing the benefits of pollinators at different spatial scales.

Thanks to the different opportunities we have had throughout this thesis research work, we investigate the benefits of pollinators through three case studies set in different contexts, focusing on global, territory, and households' scales. To estimate the impacts of the decline of pollinators on human well-being, we focus on standard economic indicators including price, quantity, and quality characteristics. Below, we introduce these i) case studies, ii) scales, and iii) indicators.

i. Case studies

From a data collection standpoint, we conducted a database-based survey primarily from the FAOSTAT database, a questionnaire-based survey in the Comminges territory, in Southwestern France, a developed country, and a questionnaire-based survey in the Huye District in Southern Rwanda, a developing country.

The reason for focusing on the FAOSTAT database was twofold. On the one hand, the engagement in this doctoral research was initiated by a closer collaboration we had with the International Pollinator Initiative Coordinating Team from the Food and Agriculture Organization (FAO) of the United Nations in Rome within the framework of a master's internship. This gave us hands-on experience on this subject and in the FAOSTAT database. On the other hand, FAOSTAT is the main database that provides the most complete data on agriculture worldwide.

For the Comminges case study, the observations were performed under the SEBIOREF project, which aims at promoting Ecosystem Services rendered by BIOdiversity to agriculture: from the production of REFerences, to advices and proposals of incentive tools, in line with the agro-ecological transition in France. The project was funded by the Occitanie Region (France) and the French National Institute of Agricultural Research (INRA) within the framework of the PSDR4 program "Pour et Sur le Développement Régional" (For and About Regional Development), 2016-2020[2]. Specifically, we contributed to the economic valuation chapter of SEBIOREF, where we evaluated the local actors' willingness to pay for the benefits they derive from pollinators.

As for the case of Rwanda, we were not only motivated by lived experiences[3] but also by the fact that, under FAO partnership, this country seeks effective ways of adopting crop intensification practices while at the same time considering environmental patterns. Intensive farming refers to a system dominated by the introduction of monoculture systems, inorganic fertilizers, and high pesticide use (Perfecto et al., 2019), whereas farming activity in this country remains generally dominated by less effective traditional practices aimed at subsistence production (NISR, 2019b). Rwanda is indeed among few FAO project partners that are actively collaborating for a more integrated way of supporting agricultural development by linking the efficient use of high-value inputs with the use of natural resources for sustainable intensive production (FAO, 2017a, b). However, for now, this country has been

[2] https://www.psdr-occitanie.fr/PSDR4-Occitanie/Le-projet-SEBIOREF-Services-Ecosystemiques-rendus-par-la-biodiversite.

[3] I was born and raised in Rwanda in a family and community of small-scale farmers. I also have worked with farmers in this country for five years.

experiencing a loss of biodiversity in its agroecosystems throughout the country, particularly where agricultural intensification is taking place (Wong et al., 2005).

These case studies allow an analysis of the impacts of the decline of pollinators in strictly different economic, social, and ecological contexts. By economic contexts, we mean the contrast between developed and developing countries, and more precisely the difference in their income levels (low-income country and high-income country) as defined by the World Bank. For social contexts, we refer to the different norms, knowledge, habits, cultures, traditions, history, etc. that characterize populations and the relationships of these populations to each other and to their natural ecosystem. As for ecological contexts, we refer to the different climate, soil, and plant genetics that participate in the functioning of an ecosystem.

To effectively inform policymakers as mentioned earlier, it is essential to consider not only different contexts but also different scales to address the different angles of social well-being that pollinators decline can impact and, thereby, convey a multitude of possible responses involving various actors operating at different levels. Therefore, our analysis in this thesis work also takes into account different scales.

ii. Scales

From an analytical standpoint, we suggest focusing on global, territorial, and household scales. Through international trade mechanisms, the global scale analysis focuses on the incidences of pollinators decline on the quantity and the nutritional quality of food supply and demand. Such analysis implies to account for the substitution process effects and the changes in nutrient intake in the food products. But this level of analysis does not allow us to account for locally-bounded non-marketed benefits and cannot provide tailored solutions for diverse social, ecological, and economic contexts. We then extend our analysis to territorial and household scales in order to go beyond such macro-level limits and account for locally-bounded non-marketed benefits like flora and fauna biodiversity, scenery, and non-tradable farm household own food.

Hence, the territorial scale analysis focuses on both marketed and non-marketed pollinator benefits. This analysis allows not only to evaluate the incidences of pollinators decline that are specific to a territorial context but also allows to understand the general public awareness and concerns about the decline of pollinators and the scarcity of insect pollination. Particularly, a territorial scale overlaps with an ecological scale where actors can work together for managing and protecting the pollinators (see TEEB, 2010). This is why it is important to consider the awareness of people at this scale.

The farm household scale analysis focuses on mechanisms of the incidences of pollinators decline on the quantity and the nutritional quality of food available in or accessible for farm household livelihood. Particularly, the incidences of this decline on farm households in a developing country context where these households are both producers and consumers of the crops they produce.

iii. Indicators

Indicators refer to data elements that can be used to represent specific, observable, and measurable characteristics of a subject under study (UNECE, 2000). As noted earlier, this thesis combines economic and nutritional aspects in the evaluation of impacts of the decline of pollinators on human well-being. As such, by focusing on standard economic indicators (e.g., prices, quantity and quality characteristics), we drew on data elements that can be found in markets, landscapes, and those specific to farm households.

For the economic aspects, we focus on both marketed and non-marketed benefits of pollinators. In case the benefits of pollinators are traded on the market (e.g., pollinator-dependent crops), standard supply and demand curves can be constructed based on prices (see Hein, 2009). The other way around, in the case some of such crops are not traded on the market, as is the case for some rural farm households in developing countries (see, Sadoulet and de Janvry, 1995), it was convenient to also consider characteristics of farm households' self-consumption.

In addition, the state of flora and fauna in a landscape, which offer benefits that are not exchanged on a market, is another indicator that we propose to examine. Specifically, this is convenient for assessing the non-marketed benefits of pollinators. In the case of non-marketed benefit valuation, a range of approaches has been developed in economic literature, including revealed and stated preference methods (see, e.g., Pearce and Moran, 1994; Hanley, 2001).

For the nutritional aspects, we consider both quantitative and qualitative dimensions of nutrient intakes. Nutrients represent measurable characteristics of crops including fibre, vitamins, minerals, etc. (WHO, 2021).
Our findings can be summarized as follows.

6. Main findings

The question of scales being important, we propose in each chapter to assess the impacts of the decline of pollinators in the scale at stake and discuss the possible responses to this decline at the level of public policies and collective initiatives across the scales[4]. In general, this thesis shows that the decline in pollinators will have an impact on the economy and the nutritional quality of food in different ways in studied areas. Our work also shows that the decline in pollinators will have an impact on human well-being across countries through international trade mechanisms. Hence, matching concerns from stakeholders to decision-makers influencing the management of pollinators at different scales may depict the scale interdependencies and complementarity of the various responses to pollinator-related issues.

More, specifically, the results of this thesis are framed by three main ideas. First, this thesis shows that as pollinators decline, the levels of both agricultural production and consumption of nutrients may decrease if pollinator-dependent crops are not relatively replaced by other crops. As a result, there will be an overall loss of human welfare on a global scale. Unfortunately, some countries are already undernourished. This decline can thus aggravate malnutrition in countries already affected, but not exclusively. Our findings highlight the fact that pollinators decline can impact countries not only through their production of pollinator-dependent crops but also through their demand for agricultural products. In other words, pollinators decline is a global concern because it will increase the marginal costs of pollinator-dependent crops, which can create uncertainty on the income of exporting countries, while importing countries will consume less of these products if prices rise, which can create uncertainty on their nutrient consumption. These results imply that measures to protect pollinators must be taken at the local, national and global spatial scale.

Second, this thesis also shows that in the Comminges territory of southwestern France, respondents consider highly important the benefits they get from insect pollinators and, consequently, they are strongly willing to pay to avoid scenarios where pollinators decline. Significantly, individual preferences and choices favor safeguarding endangered pollinator species, varieties of local fruits and vegetables, wildflowers and the quality of local fruit and vegetable. In this rural area, actors often buy food from local markets, especially local fresh fruits and vegetables they consume at home, and visit quite often floristic landscapes that surround them. They express concern about the issue of pollinators decline, especially in their territory. In other words, these results show that, in this area, people highly value flora and fauna biodiversity through pollinators. Indeed, they value pollinators not only because they benefit from them but also, they value pollinators as full-fledged animals in their world. These results underline the fact that the public concerns for the decline of pollinators can differ depending on local economic, social, and ecological contexts. Therefore, an empirical economic policy to conserve

[4] This is also considered for chapter 2 through international cooperation.

endangered insect pollinator species is assumed to be specific to the characteristics of the area under consideration.

Third, this thesis finally shows that in the Huye District in southern Rwanda, insect pollination makes a non-negligible contribution to the agricultural production, consumption, and revenues of farm households. Especially, insect pollination contributes to the nutritional quality of food produced by and for farm households, allowing thus these households to self-supplying essential nutrients contained in pollinator-dependent crops such as fruits, vegetables, and oilseeds. It shows that if the insect pollinators are totally extinct, more than half of the nutrients contained in the consumed fruits by these small farm households will be lost. In short, farm households in developing countries can be affected by the loss of local pollinators, notably in terms of income and nutrient consumption because the food consumption of these households depends, to a certain extent, on the self-supply for crops rich in micronutrients. Consequently, these households are particularly exposed and sensitive to the decline of pollinators.

Finally, in what follows, we present the organization of this thesis.

7. Thesis structure

This thesis consists of four chapters summarized in table 0.1 below.

Chapter 1 provides a state of the art of this thesis. In doing so, it reviews the existing economic valuation approaches of the benefits of pollinators, highlights the need to consider various spatial scales of causes and impacts of pollinators decline, and discusses the existing policy responses regarding the degradation ofpollinators. More specifically, it matches concerns from stakeholders to decision-makers influencing the management of pollinators at different scales. Second, it depicts the interdependencies of the ecological and economic phenomena and the complementarity of the various responses to pollinator-related issues.

These insights are put into practice in the following three independent chapters[5].

Chapter 2 assesses the economic and nutritional impacts of pollinators decline on worldwide consumers and producers, raises new questions about global food scarcity, and extends existing analysis approaches. Using world databases (the FAOSTAT; World Bank) and literature reviews (Klein et al., 2007; Chaplin-Kramer et al., 2014), we mobilize the market partial equilibrium simulation method (reminded in Chapter 1). This method implies measuring the relative variations in crop market prices,

[5]These three chapters are currently being edited for publication and each have been accepted for presentation at international conferences, including ESEE2017 in Budapest/Hungary, Tropentag2018 in Ghent, ESEE2019 in Turku/Finland, and Globelics2021 in Heredia/Costa Rica.

demand and supply quantities that may result from marginal changes in insect pollination services (e.g., Gallai et al., 2009). Specifically, we use the production function approach, which integrates the crop production dependence ratio on pollinators (i.e., Bauer and Wing, 2016), and consider nutrient ratios in crops (see Chaplin-Kramer et al., 2014). On this basis, we then estimate the relative variation in nutrient intake due to the new crop market equilibrium for different scenarios of a decline in pollinators, which is an original aspect of this research work. This chapter argues that the pollination crisis should be addressed as a collective concern between exporting and importing countries of pollinator-dependent crops.

Chapter 3 examines the general public's willingness to protect the benefits of pollinators and conserve threatened pollinating insect species at a territorial scale in the Comminges territory of southwestern France. We extend few existing analyses on Willingness to Pay (WTP) to protect pollinators by including more benefits of pollinators (e.g., nutritional quality, pollinating insects' existence) in our assessment than in those considered in previous works, as they focus only on crop produce and wild flowers (e.g. Breeze et al., 2015). Using a choice experiment survey, we identify local benefits of pollinators as pollinators attributes: quality and varieties of local fruits and vegetables, wildflowers diversity, and the "existence value" of insect pollinators. The latter represents the satisfaction that individuals can derive from simply knowing that pollinating insects exist (i.e., Davidson, 2013). Then, different levels of these attributes are defined, and hypothetical market scenarios are designed. Willingness to pay was estimated using mixed logit model based on random utility theory. The study discusses the implications of these findings on agricultural practices and public policies related to pollination and other related ecosystem services.

Chapter 4 raises new questions about risks that small-scale farming can be confronted with in the case of pollinators decline and suggests an analysis approach quantifying the effects of this decline on crop production and nutritious consumption for farm households. Specifically, we conducted a survey at farm households' scale in the Huye district of southern Rwanda. This consists of a household perspective in a particular context where production and consumption are often interlinked. From an analytical and theoretical standpoint, we were inspired by the farm household theory first developed in economic models analyzing interdependence between utility and profit maximization decisions of farm households (e.g., Kuroda and Yotopoulos, 1978; Barnum and Squire, 1979; Dillon and Barrett, 2017; Chenoune et al., 2017). This theory postulates that the welfare of farm households in developing economies depends on jointed production and consumption decisions, given that the utility of these households is subject to farm production and cash flow constraints (on and off-farm income). Due to these jointed production-consumption decisions, the decline of pollinators would impact simultaneously the farm household income and nutrition consumption. Analytically, our analysis relies on the production function approach (reminded in Chapter 1) referring to Gallai et al. (2009) model that mobilizes the crop-pollinators dependence ratio method (defined in Chapter 1). For nutrition aspects, our analysis on nutrient ratios was based on Chaplin-Kramer et al. (2014) (i.e. as in Chapter 2). From the data collection standpoint, to identify the impacts of pollination services decline on smallholder farm households, a closer look at their food production, supply, and consumption is done using a questionnaire-based survey. We argue that, in developing countries, public policies should promote agriculture transformation policies by taking into consideration characteristics of smallholdings, which might be beneficial to pollinators (see Garibaldi et al., 2016; Smith et al., 2017) and living conditions of farm households with low-income.

Table 0. 1. Thesis structure

Chapters	Objectives	Methods	Results	Implications
1. Using economic valuation for the protection of pollinators benefits focusing on various spatial scales: An Overview	- Providing a state of the art of this thesis. - Emphasize the importance of considering different spatial scales.	- Review the economic valuation approaches of pollinators benefits, including the crop-pollinators dependence ratio, market partial equilibrium simulation, etc. - Review spatial-scales of causes and impacts of pollinators decline - Review of policy responses to pollinators decline issue.	- Description of both the economic values and scale interdependencies of the benefits of pollinators. - Analysis of complementary responses to pollinator-related issues across scales.	- Matching concerns from the stakeholders to decision-makers influencing the management of pollinators at different scales. - Depicting scale interdependencies and complementarity of the various responses to pollinator-related issues.
2. Incidences of pollinators decline on the international trade: social welfare and food security analysis.	- Assessing the economic and nutritional impacts of pollinators decline on consumers and producers at a global scale. - Raising new questions and extending existing analysis approaches.	Using databases and production function approach: - Simulate the changes in international market prices, supply, and demand for edible crops for different scenarios of pollinators decline based on the international trade theory. Due to the new crop market equilibrium: - Estimate variations in nutrients consumption.	- The average global crop price will increase by about 187% if pollinators are totally extinct worldwide. - As pollinators decline, there will be an exponential decrease in consumer surplus and producer profit. - There will be a loss in global nutrient consumption, especially in areas where food shortages already exist.	- Allows us to argue that the consequences of pollinators decline on well-being of countries is not only a function of the crop production but also a function of the demand of nutrients contained in these products as their global supply decline, which is new compared to previous analyses.

3. Economic valuation of the maintenance of pollinators marketed and non-marketed benefits: The Case of the Comminges Territory in Southwestern France.	- Extending existing analysis approaches. - Estimating general public's awareness about the decline of pollinators and their ecosystem services.	Using the Choice Experiment survey: - Local pollination attributes were identified including quality and varieties of local fruits and vegetables, wildflowers diversity, and the "existence value" of insect pollinators. - Levels of these attributes are defined. - Hypothetical market scenarios are designed. WTP was estimated using mixed logit model based on random utility theory.	- Respondents are strongly willing to pay to avoid scenarios where pollinators decline. - Significantly, individual preferences and choices favor safeguarding endangered pollinator species first, then local varieties of fruits and vegetables, then wildflowers, and finally the quality of local fruit and vegetable.	-Allows us to highlight that the general public's concerns about pollinators decline can differ given characteristics of the area under consideration and local actors' awareness, so the responses to this decline should be tailored to different scales.
4. Vulnerability analysis of food production and nutrient consumption on pollinators decline: The Case of Smallholder Farm Households in Huye district in Southern Rwanda.	- Quantifying the effects of pollinators decline from a household perspective in a particular context where production and consumption are interlinked.	- By conducting a questionnaire-based survey on food production, supply, and total food consumption in farm households including quantity purchased and own produce consumption. - The effects of pollinators decline on farm households were estimated using welfare economic model (i.e., Gallai and Salles, 2016) based on the farm household theory.	- Pollinating insects contribute to the agricultural revenues and participate especially to the nutritional quality of food produced by and for farm households, allowing thus these households to self-supplying essential nutrients contained in pollinator-dependent crops such as fruits, vegetables, and oilseeds. -If the insect pollinators are completely extinct, more than half of the nutrients contained in the consumed fruits by these farm households will be lost.	Enable us to argue that public policies should: - Promote the transformation towards sustainable intensification systems by focusing on characteristics of smallholdings. - Complement external inputs use which might be mutually beneficial to pollinators and the ecosystem service they provide to food supply.

Chapter 1 – Using Economic Valuation for the Protection of Pollinators Benefits Focusing on Various Spatial Scales: An Overview

1.1. Introduction

To provide a state of the art of this thesis, in this chapter we review the existing literature on pollinators and pollination with the objective to address the following questions:

1) What is the relevance of assessing the impacts of the decline of pollinators on human well-being?
2) How is the economic value of the overall benefits generated by pollinators measured at different scales?
3) What are the possible responses to the decline of pollinators at each scale and at different spatial scales?

Indeed, for nearly three decades now, the decline of wild and managed insect pollinators has been reported in most parts of the world (Levin, 1984; Willmer, 2011). This decline of insect pollinators is primarily induced by the changes in the biophysical structure of the natural ecosystem or in the various processes within the ecosystem. Specifically, causes of pollinator decline include invasive species, habitat loss, and climate change, which may also be resulting from social-economic mechanisms such as agricultural intensification practices that spur pesticides use, pollinator habitat degradation, etc., thereby altering insect pollination (IPBES, 2016).

The consequences of this decline of insect pollinators on human well-being are manifold. As noted in the general introduction, this decline can decrease the supply of crops, such as many fruits and vegetables, that depend on insect pollinators for their reproduction (Klein et al., 2007), increase market prices (Gallai et al., 2009) and thus threaten consumers' access to quality and balanced food (i.e., Chaplin-Kramer et al., 2014). Also, pollinators decline threatens biodiversity (Dias et al., 1999), scenic landscapes with diverse wildflowers (Ollerton et al., 2011), traditions or customs that may depend on insect pollination services, etc.

Therefore, private and public decision-makers must provide solutions to the decline of pollinators given that it can raise concerns about the availability and accessibility of the benefits that these pollinating insects may provide to each actor in society. Solutions to this decline will need to consider the trade-offs between social-economic activities and actions safeguarding ecological processes in ecosystems to ensure an appropriate balance between Nature and social interactions, which is challenging (see, for example, Delgado-Serrano, 2017). It is challenging because activities to manage and restore pollinators can constrain the development of some socio-economic activities on a territory - e.g., agricultural intensification. Such intensification can affect, among other things, habitat and food composition of pollinators, threatening thus their density and population in an area if pollinator benefits are not taken into consideration in production process. Overlooking the role of pollinators in production is particularly likely when their benefits are not well understood. But for producers, even if they may understand this role, it is not always clear how to integrate pollinators into their production processes and then convey their efforts to consumers who might be willing to value such efforts. As a result, producers who are not constrained to integrate pollinators into their decision-making process, when pollinators are not yet part of their production costs, may not perceived the benefits of these insects. Consequently, decision-making support is needed to provide both private and public decision-makers with complete knowledge and viable solutions to this decline, emphasizing the relevance of assessing the impacts of pollinators decline on human well-being.

With this in mind, this thesis suggests to use economic valuation as a decision-making tool for protecting pollinators and their benefits. Economic valuation is powerful in depicting the importance people place on benefits and the satisfaction they get from natural ecosystems by focusing on things that society uses (use-value) and those that are of non-use value but remain still important to the society (non-use value) (as i.e. in TEEB, 2010). Indeed, as stated by Daily (1997), attaching an economic value to Nature benefits, such as pollination, can support decision-making given that the way decisions are made today is based almost exclusively on the importance that society attribute to things, which is often expressed through a monetary value (Pigou, 1920). As such, economic valuation can inform the value of private or social benefits from insect pollination services through the marginal utility that these benefits provide to the private agents or to the society that can be interested by such services (see Chapter 3). Also, such value can be measured as the costs of degradation of pollinators or the benefits of maintaining pollinators, thus their economic values.

Besides, economic valuation of the Nature benefits, like pollination, should take into account issues of scale (spatial and temporal) (MEA, 2003; Hein et al., 2009; IPBES, 2016, Ch.4). The Millennium Ecosystem Assessment reports (2003, 2005) highlight that the consideration of different spatial scales is highly relevant for the analysis of the interactions between society and ecosystems because most of the social costs of the degradation of natural ecosystems are borderless; which makes socio-economic phenomena interdependent across the world. Also, Gomez-Baggethun et al. (2013) show that even though Nature benefits are supplied at the local scale, their preservation decisions depend on institutions operating at various levels including local, national, and global scales.

Considering different spatial scales is even more important in analyzing pollination because even if it takes place in a given area it contributes to the availability of both quantity and nutritional quality food to the world population, which is currently facing an increase in malnutrition (i.e., WHO, 2018). As

Hein et al. (2009) argue, considering the spatial scale dimension would assist in understanding and predicting pollinator decline processes and thereby provide important contributions to improving decision-making for the management of pollinators. It is true for example that if local actors may have a role to play on a local scale, the actors that can intervene at the national, regional (e.g., European, African, etc.) or international levels are of different Nature such as governments or international cooperation organisms. These actors also need to dispose measurements and evaluations to support their decision-making process.

Hence, in this thesis, we focus on the measurement of the economic values of the benefits that pollinators generate to people by assessing the impacts of the degradation of pollinators at different spatial scales. However, scholars across disciplines have acknowledged that equity considerations are crucial for effective public policy-making, in particular for the aggregation of the values of such Nature benefits or costs over scales (space and time) and over a range of actors (TEEB, 2010). While it is not the intent of this thesis to address equity considerations, a brief overview may offer perspectives particularly relevant to the pollinators benefits valuation exercise. Indeed, various studies show that there can be discrepancies and imbalances among a range of actors operating at different scales, which can give rise to conflicts concerning the questions of social relations, power relations, and influence associated with the protection of Nature in decision-making (see, e.g., TEEB, 2008; Martín-López et al., 2019). From an economic standpoint, risk of such imbalances or conflicts between users of different benefits that pollinators generate implies that the state interventions via public policies are even essential. Thus, public policies should be structured not only to address the practices that induce pollinators decline but also to deal with the possible imbalances and discrepancies that this decline can generate in society, which emphasizes the need for economic valuation over a large range of actors operating at different scales.

As such, economic valuation can inform policy-makers on the implications of this decline on social costs to enable well-targeted state interventions, which can play by internalizing the social costs resulting from the decline of pollinators, in at least two ways. On the one hand, state interventions can be structured into market mechanisms through, for example, classical policy instruments by integrating insect pollination services into market instruments such as food standards, insecticide standards, taxes, subsidies, etc. On the other hand, it can intervene through various forms of coordination by proposing public policies and initiatives, or by supporting collective organizations, aiming at changing consumers' and producers' habits through, e.g., education. Collective organizations count especially since the state's range of actions is limited by territorial boundaries and by national laws whereas, the ecological consequences of environmental problems, as is the case of pollination, can impact actors spatially separated from the origin of their causes, and thus out of national public policy reach (UNEP, 2016). In other words, the effects of national choices can be heterogeneously felt among stakeholders at different spatial scales – e.g., negative impacts of pollinators decline in Ivory Coast (the first world producer of cocoa, a crop for which yield depend around 90% on pollinators; Klein et al., 2007) can increase prices of cocoa products worldwide (such a result is detailed in Chapter 2).

Following these considerations, addressing potential imbalances and discrepancies among actors as well as scale interdependencies matters – and economic valuation of the benefits that pollinators generate at different spatial scales is central – for decisions aimed at reducing pollinators decline and boosting shared prosperity. Particularly, effective decision-making regarding pollinator-related issues may depend on information about the use of the benefits of pollinators, which may depend on their users' perceptions, the value they place on such benefits, and the scale of that use, which may depend on the types of actors involved. Thus, beyond economic valuation, these considerations make it difficult to completely bypass another area of economics that analyzes an organization of cohabitation of actors, which is that of property rights concerning the different users of pollinators and their benefits.

In what follows, we thoroughly review the existing literature on both the economic values and scale interdependencies of Nature benefits, particularly pollination. Then, we discuss the complementarity of the various responses to pollinator-related issues.

Specifically, the second section reviews the theoretical and methodological framework concentrated on the economic valuation of Nature features focusing on the benefits of pollinators. The third section stresses on the importance of considering different scales when assessing the effects of pollinators decline on human well-being in efforts to provide effective responses to this decline. The fourth section focuses on responses to pollinators decline including public policies and initiatives from the individual, national, and international levels, which can be provided by the general public, national governments, and international organizations. Finally, the fifth section concludes and highlights the common thread of the case studies explored in this thesis.

1.2. The economic valuation approaches of pollinators benefits

This section reviews the theoretical and methodological framework that focus on the economic valuation of the impacts of the degradation of pollinating insects on human well-being. In doing so, it first introduces the link between pollinators in the ecosystem and human well-being. Second, it reviews the value of Nature in economic theories. Third, it describes the total economic value of the overall benefits that can be generated by pollinators to humans. And finally, it reviews and categorizes existing economic valuation approaches focusing on the benefits of pollinators studied in economic literature.

1.2.1. The link between pollinators and human well-being

Using the TEEB's (2010) illustration of the link between ecological functions and social benefits, in figure 1.1 below, we draw attention to the nexus of pollinators and human well-being. Ecological function represents a set of interactions that occur in Nature for its well performance, which is beneficial to all beings (and non-beings); the potential of an ecosystem to deliver a service that is itself dependent on ecological processes and structures (de Groot et al., 2010).

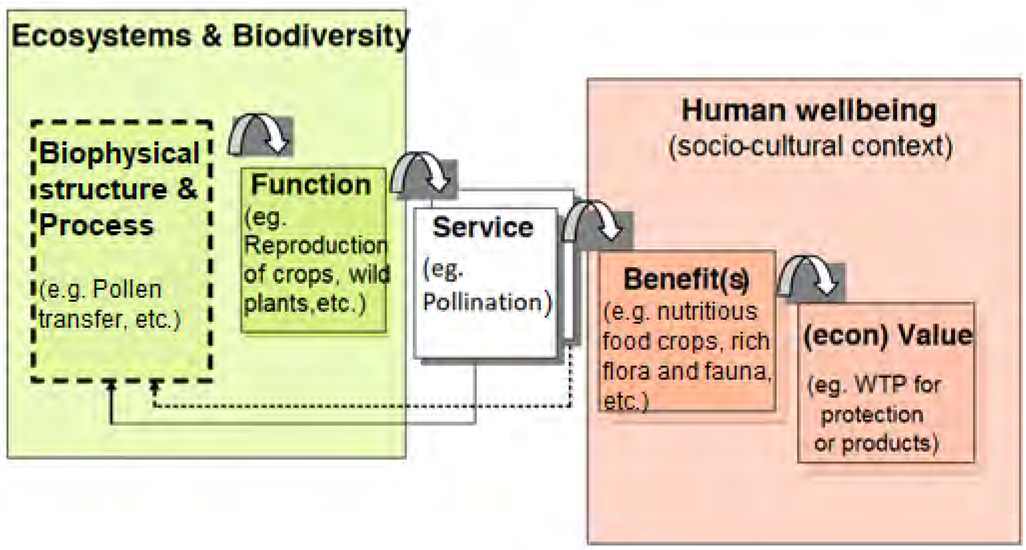

Figure 1. 1. The pathway from pollen transfer by pollinators in the ecosystem to human well-being

Source: Adapted from TEEB (2010)

As figure 1.1 shows, ecosystems and biodiversity are the fundamental parts of the system on which the biophysical structure, various processes, and ecological functions are based (see Figure 1.1, left box; TEEB, 2010). When these generated functions or interactions contribute in some way to human well-being (see Figure 1.1, right box), they can subsequently be perceived as services. Initially introduced in the fields of conservation biology and landscape development, the direct and indirect benefits of natural ecosystems to human well-being have been referred to as ecosystem services (MEA, 2005, Gomez-Baggethun et al., 2010; Kurt et al., 2013). Ecosystem services support the human population within and beyond their local boundaries through provision services (e.g., food provision), regulation services (e.g., pollination, climate regulation), and cultural services (e.g., tourism; MAE, 2005). Such services are said to contribute to human well-being when an individual or a society perceives their benefits or derives some satisfaction from them (i.e., MEA, 2005) to the extent of willing to pay for its benefits or participate for its protection. Pollen transfer by pollinators is an example amongst various processes that connect Nature to human well-being.

Pollen transfer is a process that characterizes an ecological function playing a role in the interaction between Nature and human society because it is involved in the production of both crops and wild plants (Klein et al., 2007). This phenomenon is referred to as the pollination service, indicating the direct and indirect benefits from pollination to human well-being (IPBES, 2016). This pollen transfer process serves society in a sophisticated manner as it gets involved in human well-being through ecological, social, and economic mechanisms. For instance, through ecological mechanisms, pollinators contribute to the production of nutritious food which is distributed from farms to consumers worldwide by farmers and stakeholders operating at local, national, and international markets through social-economic mechanisms. Also, insect pollination services play a central role in plant genetics and biodiversity (Winfree, 2011), which benefits in different ways current and future users of Nature including indigenous, scientific, tourist, artist, aesthete communities, etc. (i.e., Martin-Lopez et al., 2019).

But how are these benefits of Nature, especially those provided by pollinators and their pollination, perceived by their users and society, and subsequently valued?

1.2.2. The value of Nature in economic theory

Before diving into the heart of the economic valuation of benefits generated by pollinators, it is noteworthy to have a look at a chronological understanding of the value of Nature in economic theory. Giving value to things has always been one of the notions central in economic sciences (see Gómez-Baggethun et al., 2010). As this study shows, in the different traditional schools of economic thought, positions on the theory of value have been largely related to the economists' perception of production factors, primarily capital, labor, and land, in the creation of wealth. As a factor of production, capital referred to the assets (e.g., machines, buildings, etc.) that people use to produce goods and services, measured primarily in monetary metrics. Labor has been considered as the efforts (e.g. physical efforts, mental efforts, etc.) applied to produce goods or services, measured primarily in terms of time. Land, as an element of Nature, was the first to be used in production. And then the other elements of Nature have been introduced progressively, such as other natural resources etc. It is only in recent decades that the understanding of the value of Nature has been extended from the creation of wealth to the provision of welfare at large including thus environmental aspects and ecological functions.

Indeed, until the beginning of the 19th century, the economic theory of value was closely linked to wealth creation. For economists of the 17th and early 18th centuries, land played a central role in wealth creation, so that the land factor was of significant value to them – see, for example, William Petty, 1623-1687. Adam Smith (1776), David Ricardo (1817), and Karl Marx (1867), who had differing views on many subjects, agreed on the fact that wealth is created primarily through human labor. In classical economic perception, the value of Nature implied their use-value as wealth production factors (Gómez-Baggethun et al., 2010).

In the late 19th century and beginning of the 20th century, the economic theory of value took another dimension. Jean-Baptiste Say (1829) and the neoclassical economists (1870) argued that everything has value from the moment it has a utility and undergoes a scarcity constraint. Following these authors, the utility concept refers to the satisfaction that an individual gets from the consumption (or utilization) of a good or service and scarcity refers to the shortage of supply of such goods or services in relation to consumers' (users) demand. The value was by then perceived in terms of marginal utility. Marginal utility refers to the variation in the satisfaction a good or service procures from a unit change in consumption (or utilization) of such a good or service. Therefore, one can deduce that the neoclassical theory of value suggests that any component of Nature can have a value from the moment that society perceives that it is a useful and exhaustible resource (i.e., as defined in Hotelling, 1931) under threat of extinction or degradation. In the neoclassical economic stance, the value of Nature can be directly or indirectly revealed in various ways. For instance, the value of an ecosystem good or service can be revealed by comparing it to other objects, which may provide the same level of utility, susceptible to replace it on the market; its exchange-value (Gómez-Baggethun et al., 2010). Since then, numerous economists have sought to broaden the understanding of value by mobilizing the theory of welfare economics emphasized by Pigou (1920), following Alfred Marshall (1842-1924). For Pigou (1920), both "economic" satisfaction, which relates to the valuation of the benefits of material goods and services (e.g. food, scenic amenity, traveling, etc.), and "non-economic" satisfaction, which relates to the non-material goods and services (e.g., spiritual, traditions, culture, et.), contribute to total welfare. As such, this author defines economic welfare as a part of total welfare which can be brought directly or indirectly into relation with a value of a good or service measured in a monetary term.

Following Pigou (1920), economists seek to account for "marketed" and "non-marketed" benefits and satisfactions people derive from goods and services generated by Nature in the economic theory of value. With the term "marketed benefits" of, for example, pollinators, we refer to goods or services whose supply are supported by pollinators and are currently considered or exchangeable through markets (e.g., some fruits and vegetables) (i.e., as noted in the general introduction). As opposed to marketed benefits, non-marketed benefits refer to non-market-based goods and services; i.e. things people value that are not exchanged in market systems (Turner et al., 2003) (e.g., free pollination, wildflowers, biodiversity, etc.). These goods and services are considered as the attributes that enable the materialization of Nature services (see, for example, Hanley et al., 2001) such as pollination services (e.g., Breeze et al., 2015). Indeed, the non-market-based Nature services, which contribute to the marginal utility as externalities (e.g., free pollination services), can still be omitted if not cautiously valued among the wealth or welfare creation factors. In economics, the externality concept refers to a benefit or a cost that affects the production or utility of a party who did not choose to incur that benefit or cost and does not get or pay compensation for it (Varian, 1995). When it comes to benefit, we will speak of positive externalities; when it comes to costs or detriments, we will speak of negative externalities. For example, a positive externality may be bee pollination when, as a by-product of honey production, contributes to crop production. A negative externality could be the loss of crop production resulting from declining insect pollinators or the use of pesticide that would kill honeybees and reduce the quantity and quality of honey production. Also, the appearance of the decline in nutritional quality food due to the disappearance of pollinators constitutes a negative externality.

Currently, economic science is widely adapted to investigate the value of Nature through welfare economics. Welfare economics postulates that the utility perceived by individuals in society is associated with a choice made over a particular good or service. Put another way, utility is seen as a matter of individual choice rather than pleasure received. As such, individuals seek to maximize their utility not only through their consumption choices but also through their actions (for example, satisfaction one can get from anthropocentric and altruistic actions; Andreoni, 1990; Brown et al., 2019). In this context, the interactions of consumers and producers through the supply and demand in different markets can reveal their utility or satisfaction, which, in economics, is represented by indicators of consumer surplus and producer surplus. The consumer surplus is the difference between the consumer's willingness to pay and the market price. The producer surplus is the difference between the producer's marginal cost of production and the market price. Thus, in economics, social welfare is represented as the sum of consumer surplus and producer surplus, which derive traditionally from the market price of goods or services.

With this insight, a variety of economists (e.g., Krutilla, 1967; Kareiva and Marvier, 2011, etc.) have been advocating ecological economics to account for non-marketed benefits of Nature in the theory of value. These economists depict Nature as a bedrock in providing not only wealth but also welfare, notably beyond the utilitarian dimension. Since the founding article of Krutilla (1967), there has been a body of work that, both conceptually and methodologically, has sought to provide answers to the question of the economic value of non-marketed services linked to Nature. One of the first assessment of the contribution of ecosystems to social welfare at the global scale is that of Costanza et al. (1997) which, although the methodology used was largely controversial (Toman, 1998), led to questions about the importance of the contribution of ecosystems to economic activities. Furthermore, Kareiva and Marvier (2011) show that an individual or a society values Nature not only 1) for the own satisfaction (economic and non-economic) this individual or society can derive from Nature use, which are use-value; but also 2) for the satisfaction this individual or society derives from preserving Nature for other living beings and future generations, which are non-use values.

However, the economic valuation of Nature struggles to find both real scientific legitimacy and social acceptance.

On the one hand, the economic valuation of Nature struggles to find social acceptance because of a lack of awareness of the Nature degradation problem and thus the consequences for society. But also, due to the lack of understanding of the usefulness of Nature valuation since Nature should be an end-in-itself (e.g. Piccolo, 2017) when actors are seen as ethical agents with motivations that are different from mere pleasure-seeking (Vatn, 2005). Unfortunately, actors have different priorities, different social practices, different levels of information, sensitivity, etc. Indeed, how can we be sure that individuals, countries, regions, and villages operating according to different norms, knowledge, habits, needs, etc. will protect global biodiversity, or other local natural elements important for overall ecological interactions? If we cannot be sure, it is much more relevant to work on decision-making tools by specifying, inter alia, the benefits of Nature for everyone, to provide effective responses to the degradation of Nature that is happening as exemplified by the decline of pollinators.

On the other hand, the economic valuation of Nature still struggles to find scientific legitimacy because of the limitations of the theoretical support and limited methods used in empirical economic valuation analyses (Spash, 2012). Indeed, from a theoretical perspective, various studies (e.g., Pearce and Turner, 1990; Hanley and Spash, 1993; Munasinghe and Schwab, 1993; MAE 2005; and TEEB, 2010) have sought to provide several types of benefits and values of natural ecosystem services to humans. For example, TEEB (2010) makes a distinction between ecological, social, and economic benefits and their values by linking ecosystems and human well-being, which can be measured using different indicators, as summarized in figure 1.2 below. Natural scientists define ecological values through the roles that Nature plays in sustaining life on earth, which includes the contribution of one species to the survival of other species or the resilience of the entire ecosystem (Farber et al., 2002). According to TEEB (2010), social and socio-cultural values refer to the contribution of Nature to non-material human well-being, which can be identified through their influence on mental health and their historical, national, ethical, religious, spiritual aspects, etc. And economic values refer to the importance people place on goods and services that Nature generates (IPBES, 2016).

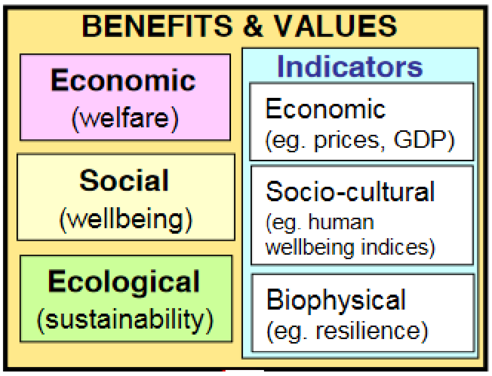

Figure 1. 2. Benefits and values of Nature for human well-being

Source: TEEB (2010)

Let figure 1.2 reminds us of the fundamental question we address in this section: how are all those values of Nature, which may convey heterogeneous driving forces motivating human actions in different ways, determined? Such values are measured in a variety of metrics including monetary (e.g., Costanza, 1997), quantitative (Klein et al., 2007), nutritional (e.g., Chaplin-Kramer et al., 2014), or the Human Well-being Index (TEEB, 2010). However, given that the values have to be additive to inform in an efficient way on the decision-making processes (Pearce and Turner, 1990), the monetary unit is the most used in economic valuation because of its ability to allow the aggregation of different types of values into a total economic value. In that respect, Gómez-Baggethun et al. (2010) depict **the total economic value (TEV)** of Nature as a concept representing a sum of Nature marginal utility.

Various studies have developed a TEV conceptual framework articulating the links between ecological and economic aspects (e.g., Pascual et al., 2010; Davidson, 2013). However, although this conceptual framework of TEV aims to cover a wide range of values, the values that this Nature's TEV framework can include or represent remain controversial across schools of economic thought. We can look at these controversies in two ways. On the one hand, some economists support the fact that TEV of natural ecosystem components can include both their benefits to humans and those to Nature through welfare creation factors; which includes both use and non-use values (e.g., Davidson, 2013). On the other hand, other economists argue that this TEV may not consider in an efficient way all environmental values (economic, ecological, and social) (e.g., Aldred, 1997; Spash, 2009; Chan, 2012; Spash and Aslaksen, 2015). For Aldred (1997), it may not be relevant to consider non-use values of Nature's benefits as a factor in creating human welfare. For Spash (2009), TEV cannot include all environmental values, especially if they imply commensurability with traditional economic value as measured in terms of marginal utility. Also, for Spash and Aslaksen (2015), there is a risk of the commodification of Nature in economic valuation; which may be based on a narrow idea of value. While for Chan (2012), only the utilitarian dimension of ecosystem services would be considered, to the detriment of other values that are hard to quantify, such as socio-cultural and relational values. In this regards, another TEV framework suggests that it is necessary to distinguish between instrumental values and intrinsic values that people place on ecosystems. Arias-Arévalo et al. (2017) defines instrumental value as "the value of an entity as merely a means to an end" and intrinsic value as "the value of Nature, ecosystems, or life as ends in themselves, irrespective of their utility to humans". As such, intrinsic value implies that Nature should be valued and protected for its own sake (Piccolo, 2017). Hence, intrinsic values may represent ethical and moral judgments about pollinators for their own sake without reference to its market values, whereas instrumental values depends on the relation of the Nature to other goods and services (Attfield, 1998). In other words, the instrumental values stand for the values that Nature may have for the sake of ecosystem interactions for human well-being, be it now or in the future.

Yet, the distinction between such types of Nature values, or the distinction between human-centered and nature-centered benefits, is somewhat blurred (see, e.g., Rea et al., 2017). It is difficult to draw a specific line between Nature values or to define when adjustments shift from one value to another or from a nature-centered benefit to a human-centered benefit of Nature (e.g., the existence value of species). Thus, as TEEB (2010) points out, it can be argued that not all values of Nature (ecological, social, and economic) can be fully captured by economic valuation techniques and thus need to be supplemented (e.g., by methods used in other scientific fields such as natural and political sciences) to inform decision-making. Nevertheless, as explained in the general introduction, economic valuation increases the awareness and the understanding of policymakers, users, and the general public about the value of Nature and its degradation consequences, which may unlock extended actions.

Despite this impetus to assess the value of Nature, the methods used in empirical economic valuation analyses remain limited. Thus, approaches based on productivity effects and thus wealth creation, i.e. which rely on the valuation of impacts of Nature degradation to the production of direct marketable goods, are more widely used because they appear to be more robust (Chavas, 2008).

In sum, welfare provision factors, as well as wealth creation factors, of Nature are still not well established in the economic theory of value. However, as this review of the literature has pointed out, several types of values of Nature, which combine both use-values and non-use values have been studied, notably via the total economic value framework.

Following the above discussion, in the next section, we suggest reviewing the total economic value that people may place on the benefits they can get from pollinators and their ecosystem services.

1.2.3. The total economic value of pollinators benefits: A welfare analysis

The economic valuation of insect pollination services focusing on the marginal utility of marketed goods, like for example; food in terms of monetary units has been extensively developed in economic literature (Gallai et al. 2009; FAO, 2008; Bauer and Wing, 2016). However, economic valuation focusing on the contribution of pollinators and their pollination services to human welfare through non-marketed benefits by, for example, maintaining biodiversity richness in ecosystems (Winfree, 2013), in terms of nutritional quality (Chaplin-Kramer et al., 2014), or floristic landscapes (Breeze et al., 2015) are still scarce. Nevertheless, IPBES (2016) reports on the marketed and non-marketed goods and services to which pollinators contribute, as well as the benefits that can be derived from pollinators per se.

As a theoretical illustration of the TEV of the benefits of pollinators, let us consider the proposal recently presented by IPBES (2016) that we summarized in table 1.1 below.

Table 1. 1. Total Economic Value (TEV) of the benefits of pollinators

Use-values	Direct use	Hive products and crop production	Marketed benefits
		Spiritual, leisure and aesthetic, nutritional quality	Non-marketed benefits
	Indirect use	Faunistic and floristic biodiversity	Non-marketed benefits
	Option and insurance values	Value given to pollinators for possible future use	Non-marketed benefits
Non-use values	Bequest value	Willingness to preserve pollinators for future generations	Non-marketed benefits
	Existence value	The existence of pollinator species	Non-marketed benefits

Source: Adapted from IPBES report, 2016.

This TEV covers a wide range of pollinators benefits since, as noted in the introduction, the economic valuation is sought to depict the importance people place on things that society uses (i.e., use-values) and those that are of non-use value but remain still important for society. More precisely, using table 1.1, we specify the 1) use-values of both marketed and non-marketed benefits of pollinators and 2) non-use values of non-marketed benefits of pollinators. However, it should be noted that some benefits of pollinators are identified as non-marketed because they are not considered in the current market system, while they can evolve into marketed benefits if, for example, they are standardized by public policy through nutrition norms (e.g., crop nutritional quality). To avoid the possible underestimation of the overall values of pollinators and their ecosystem services (i.e., Sagoff, 2011), it is necessary to mention that table 1.1 may represent only a fragment of the overall value (ecological, social, and economic) of pollinators and their ecosystem services as it can only be based on the results of existing studies. Yet, the currently existing knowledge or understanding regarding Nature feature interactions remains still a good subject of research. Thus, this TEV of the benefits of pollinators can be further explored.

1) Use-values: marketed and non-marketed benefits

The use-values of pollinators can be related to the direct and indirect benefits of pollinators and their pollination services that an individual in society can enjoy, such as the production or consumption component of goods or services. Such direct use-values can be represented through marketed benefits and non-marketed benefits of pollinators. Marketed benefits can include hive products (such as honey) and crop production quantity; which are the only products whose production is supported by pollinators that are currently exchanged on the market in monetary units. As such, the marketed benefits of pollinators can be expressed in monetary terms through the different methods of evaluation that we display afterwards, notably production function (Section 1.2.4). Non-marketed benefits can include leisure and aesthetic benefits that pollinators and pollination services provide directly to humans as well as nutritional quality embedded in well-pollinated crops. The indirect use-value of pollination services can include genetic diversity and procurement, as well as the reproduction of wild flora contributing to biodiversity. Also, the non-marketed benefits (direct or indirect use) of pollinators can be expressed in monetary terms through adequate methods (which we review in the following Section).

In addition, pollination services have option value and insurance value (Diaz et al., 2015; Pascual et al., 2010). The insurance value of pollinators is their capacity to reduce the risks associated with the use of pollination services (Baumgärtner and Strunz, 2014). The option value is the value allocated to the preservation of pollinators because people want to keep all their benefits in their choice in the future (Diaz et al., 2015).

2) Non-use value: non-marketed benefits

Non-use value can be related to the anthropocentric and altruistic benefits linked to pollinators as such and their ecosystem services. For instance, following Kolstad (2000), the non-use value of pollination services with an impact on ones' welfare can include bequest value and existence value. According to this author, bequest value comes from the preservation of pollination services for one's descendants. Existence value is the satisfaction that one can derive from knowing that pollinators and pollination services continue to exist (Davidson, 2013). The different categories of non-use value, however, are often difficult to conceptually or empirically separate from other values such as option and insurance values (Weikard, 2002).

Finally, understanding the plurality of values of pollinator benefits is crucial to assessing them and thus protecting them effectively. Therefore, in this thesis, by pollinators benefits, we refer to not only goods and services that are attributes of insect pollination benefits (in Chapter 2 & 4), but also pollinators in their own right, given the importance that people may place on their existence, bequest, option, and insurance value (in Chapter 3).

But, with all that plurality entails, how are these values assessed and quantified in economics, with what analytical and conceptual framework?

We review the economic literature on approaches and methods used to measure these different economic values of the benefits of pollinators in the next section.

1.2.4. The economic valuation approaches addressing pollinators benefits in the literature

In general, various economic studies show that estimates of the values of ecosystem services can be obtained indirectly through a revealed relationship between these services and marketed goods or services or directly through stated preferences (e.g., Pearce and Howarth, 2000; Hanley et al., 2001). Clearly, in economics, such values are assessed and quantified based on physical characteristics of a good or a service; or behavioral characteristics of an economic agent willing to compensate for the absence of a service or to obtain a service.

In that respect, the methods used in the economic literature focusing on pollination are essentially oriented towards both the supply perspective, based on the effects of insect pollination on productivity, and the demand perspective, based specifically on the stated preferences regarding the benefits of pollinators in ad hoc procedures[6]. From a supply perspective, production functions and production costs are mobilized to analyze the effects of insect pollination on productivity or yields of crops[7]. When the benefits of pollinating insects (e.g., pollinator-dependent crops such as some fruits, vegetable, etc.) under consideration are marketed, market prices of these benefits serve as a valuation method and price is expressed in monetary terms. Therefore, the productivity effects-based approaches make it possible to deal with the supply-demand balances via a price and appear in this respect more appropriate for considering the effects of degradation of an ecosystem service on the entire economy. An economy is characterized by a set of interrelations between sectors where an ecological shock will generate positive or negative impacts, direct in some markets, indirect in other markets, and thus in total welfare (see Bauer and Wing, 2016). In the case of crops produced for one's own consumption, which can be a loss in case of pollinators decline, the effects of insect pollination on productivity and consumption of such crops for a producing agent can be valued using various production function approaches[8]. However, focusing solely on the supply perspective cannot be relevant to the overall benefits of pollinators. Indeed, for some non-marketed benefits of pollinators, such as fauna and flora biodiversity, bequest values, etc., or any other non-use value of pollinators, the demand perspective based on preferences for such benefits has been the most used in the economic literature (e.g., Mwebaze et al., 2010; Diffendorfer et al., 2014; Breeze et al., 2015). Figure 1.3 below synthesizes the economic methods mobilized in various economic studies to estimate the value of the benefits of pollinators in three approaches.

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[6] Although, from a demand side perspective, the revealed preferences method, like the stated preferences method, is generally used in the field of environmental valuation to assess non-use, indirect, non-market, and option values of ecosystem services (TEEB, 2010), no study in the literature concerning pollinators and pollination services has used it to our knowledge.

[7] While the supply-side perspective may be of interest in assessing the value of hive products, such as honey production, this aspect does not fall within the scope of pollinators and pollination, which this thesis proposes to evaluate.

[8] We consider more thoroughly this case in Chapter 4.

In this section, we review the economic valuation approaches existing in the literature addressing the benefits of pollinators from: a) the cost-based approach, b) the production function approach, and c) stated preferences approach. The first two a) and b) adopt the producer perspective while the third c) adopts the consumer perspective.

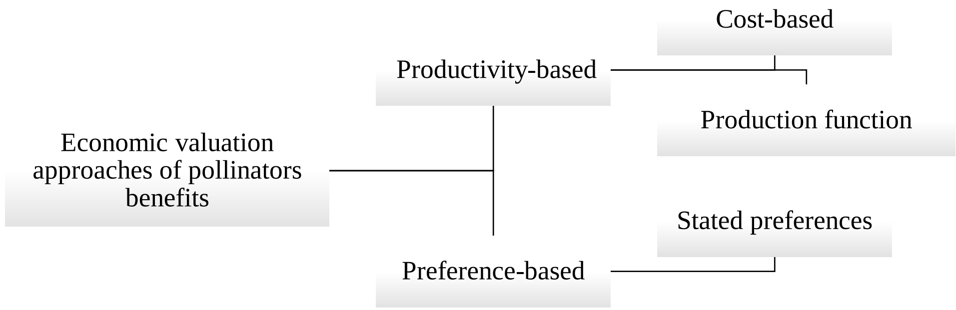


Figure 1. 3. Categories of existing economic valuation approaches of pollinators benefits

a) Cost-based valuation approach

This approach can refer to all methods that base their valuation on the costs generated by the decline of pollinators or by preserving them on farms and/or on a landscape. A method used in this respect consists, for example, of the costs of pollinators substitute or replacement cost approach.

Replacement cost method is relative to the costs of investing in labor or in other inputs to replace pollinators. Technological or mechanical techniques and other investments in pollinator management practices can allow assessing costs of pollination where non-animal pollination alternatives are considered viable substitutes (see Allsopp et al., 2008). Alternatives to insect pollination can involve labor (hand pollination) or capital (mechanized pollen dusting) that would be needed to maintain the level of crop production at that specific level provided by pollinators. Also, the investment cost of pollinator management practices to enhance pollinator abundance on the farm (or landscape) can inform decision-makers of the value of these pollination services. This approach assumes the willingness and ability of economic agents (farmers, community, national state, etc.) whose production may necessitate pollinators to pay for these replacement costs.

b) Production function valuation approach

In microeconomics, a production function expresses the relationships between the factors of production and the quantity produced (Freeman, 1993). It is in that respect that the production function approach integrates pollination service in the same manner as other production factors. And, like any other production input, the economic value of pollinators can be equated with its impact on the productivity of the marketed output. As a result, the welfare effect of a change in the quantity in which pollination services are provided is measured following market equilibrium simulation (as we will see in Chapters 2 and 4).

As such, the production function approach can consist of all practices of determining the value of pollinators based on their effects on production or their consequences on consumer and producer surpluses, or both. In this approach, the value of benefits generated by pollinators can be deduced from direct or indirect observation of market transactions. Various methods were used in this regard, including (1) the yield analysis, (2) the pollinator dependency ratio, (3) production function models, (4) the crop market price, (5) the pollination services market, (6) partial equilibrium models, and (7) general equilibrium models, which we describe below:

1) **The yield analysis method:** The yield analysis method allows comparisons between outputs of pollinated crops and crops without or with partial access to insect pollination services based on field experiments (see Garratt et al., 2014; Klatt et al., 2014). This method allows capturing direct benefits of insect pollination services on the field scale, to estimate more precise variations in benefits between cultivars, and to seize marginal benefits of these services. However, this method is appropriate for very local scales. It requires capturing data on the benefits and deficits of insect pollination, but it does not directly account for the relative effects of other inputs or ecosystem services that are important in crop production. But it can provide the level of vulnerability or sensibility of crop production on pollinators (IPBES, 2016).

2) **The pollinator dependence ratio method:** The pollinator dependence ratios are metrics of the proportions of yield specific to insect visits to a variety of crops by dint of the ecological experiments (see Klein et al., 2007). These ratios allow depicting the value of total annual crop production directly attributable to insect pollination services in different areas by focusing on the same cultivars farmed across places (see Brading et al., 2009; Lautenbach et al., 2012; Leonhardt et al., 2013). A pollinator dependence ratio expresses the vulnerability level (i.e. the general introduction) of crop varieties to insect pollination services; however, it may overgeneralize between cultivars (i.e. as a metric of the proportion of yield lost without insect pollination ecosystem services). This method permits to estimate the dependence of crop production on insect pollination ecosystem services. However, it assumes that insect pollination services are currently at maximum levels in the area, and from this assumption, it models different scenarios of pollinators decline, although the levels of pollinators decline are not straightforward to determine. Moreover, this method does not account for the effects of other production inputs (e.g., water, fertilizers, pesticides, etc.) used or ecosystem services interactions within the agroecosystem (e.g., interactions between crops, hedgerows, strips, etc. on production).

3) **Production function models**: This method can be used to determine the optimal combination of inputs that maximizes production relative to cost. As such, evaluating pollination services based on production function models allows measuring the production that results from marginal changes in pollination services relative to other production factors (e.g. land, pesticides, labor, etc.) that influence crop production (Bateman et al., 2011; Hanley et al., 2015). The amount or costs of each input, including

the threshold of pollinators or pollination services, involved in the production process are captured, allowing more accurate economic estimation of the value of pollination services. That is to say, this method can put in evidence the effects of insect pollination services relative to other inputs (e.g. land, pesticides, labor, etc.) and ecosystem services (e.g., water, soil, etc.; Ricketts and Lonsdorf, 2013). Thus, this method can accurately assess the value of pollinating insects in an area, models the effects of the decline of insect pollination services and extrapolates the experimental results from one area to other locations. However, the production function model method requires extensive ecological data. It implies more complex models in economics. Indeed, only Ricketts and Lonsdorf (2013) have developed such a complex economic model integrating economic and environmental aspects into the production function to link the crop production with the pollination services provided by the local pollinators in a landscape. Also, production function models can allow estimating the value of insect pollination based only on producer surplus.

4) **The crop market price method:** In this method, the benefits of pollination services are valued based on the prices of insect-pollinated crops (as in Matheson and Schrader, 1987; Costanza et al., 1997). As such, it provides a simple way to grasp the value of insect pollination services as only data on crop prices are required. However, it does not reflect the real value of the insect pollination services as a market price considers all the production inputs used in production of crops.

5) **The pollination services market method:** In this method, the value of pollination services is measured based on pollination services exchanged through markets where these services are provided by, for example, a rented or purchased bee colony (Burgett et al., 2004). Burgett et al. (2004) shows that in case of a rented or purchased bee colony the price of these services is a direct per-unit of bee colony measure which indicates the value of bee pollination services. In this way, the economic value of purchased or rented managed pollinators for pollination services reflects their pollination benefits in a manner comparable to other inputs. This means that this market (supply and demand) reveals the value without calculation of this demand through the above crop market price methods. However, the pollination services market approach has limitations (IPBES, 2016). Indeed, bee colonies or hives renting market prices are influenced by market forces more than that of their pollination benefits (e.g. from the honey market). Furthermore, this method does not consider the role of wild pollinators in crop pollination. Yet, as Kleftodimos et al. (2021) have argued, substitution of wild pollinators with managed bees may be inefficient, as the cost of production may be higher and efficiency lower, which is especially likely during extended periods of harsh weather (Britain et al., 2013; Ellis et al., 2017). This substitution may be inefficient, in particular for flowers that honeybees have difficulty foraging, such as red clover, alfalfa, or tomatoes, which are chiefly pollinated by specialized wild bee species (Westrich, 1990). In addition, many countries still rely solely on wild pollinators for pollination services.

6) **Partial equilibrium models:** In the economic valuation of insect pollination services (see, for example, Gordon and Davis, 2003; Gallai et al., 2009; Winfree et al., 2011), the partial equilibrium method used estimates the welfare value of price changes on available income to producers and consumers on the crop market. This method has many strengths but also weaknesses. Of those strengths, it allows assessing the impacts of pollinators decline on consumer surplus (e.g., Gallai et al., 2009) and producer benefits (e.g., Winfree et al., 2011). It captures marginal benefits and it can measure impacts of pollination service loss at a large scale. However, partial equilibrium models are very complex to estimate. To date, the partial equilibrium approach used does not account for the possibility of consumers switching from pollinator-dependent crops to their other preferred crops (e.g., coffee to tea, or locally grown apples to imported apples). Similarly, it does not account for the possibility of producers to substitute between different crop categories in their production decisions or to substitute crop production inputs when pollination services decline (IPBES, 2016).

7) **General equilibrium models:** In the economic valuation of pollination services, the general equilibrium models used estimates the welfare value of price changes on producers and consumers both within the crop market and across other linked markets (e.g., labor and non-agriculture markets) (e.g., Bauer and Wing, 2016). This method captures effects of insect pollination services across and within markets; and as such this general equilibrium method generates many substitution effects. As a consequence, this method cannot allow identifying the effects of pollination decline alone (IPBES, 2016).

Finally, it is worth noting that pollination thresholds or levels of pollinators decline in production systems are not simple to determine using economic valuation techniques. As a result, most valuation approaches from the producer's perspective have been, to some extent, inspired and supported by other fields (e.g. ecology, agronomy, biology, etc.). As described above, for example, ecological studies (e.g., Klein et al., 2007) have allowed for economic valuation using pollinator dependence ratios (e.g., in Gallai et al., 2009). Similarly, the landscape approach (e.g., Ricketts et al., 2004) has also enabled economic valuation using the level of pollination services that exist in a given landscape (e.g., through the InVEST pollination model[9]; Lonsdorf et al., 2009).

Thereafter, we review the economic valuation approach addressing the benefits of pollinators from the consumer's perspective.

c) Stated preferences valuation approach

Stated preferences approach has been the only used approach in assessing non-marketed benefits of pollinators from the consumer's perspective, which is based on respondents' preferences survey

[9] InVEST model incorporates a complex production function which calculates the level of pollination services provided in a landscape in relation with the dynamics of population of pollinators, pollen resources and existing natural habitats.

(Diffendorfer et al., 2014; Breeze et al., 2015; Mwebaze et al., 2018). This approach consists of assessing the willingness to pay (accept) of individuals or a group of individuals towards a set of attributes (benefits) of pollinators. Thus, respondent's preferences survey depicts the value respondents' associate with the benefits they get from pollinators and their pollination services. Indeed, the stated preferences method is the only valuation method that can be used to quantify the non-use values of non-marketed benefits generated by ecosystem services in monetary terms, in addition to their use-values.

However, appropriate survey design and valuation methods are essential when using such an approach since researchers and respondents should both have a common understanding about the attributes at stake in the valuation exercise. For researchers, it thus requires more effort to develop appropriate survey design in a manner easily understood by respondents (e.g. Carson, 2012), especially if they are unfamiliar with the ecosystem service under consideration like pollination. For respondent, it requires a lot of motivation and cognitive effort to express a value one place on environmental goods or services (Lienhoop et al., 2007). This method is expensive to test and implement. Moreover, the aggregation of different values (social, ecological, cultural, and economic, etc.) into one metric (e.g., monetary value) is not always conceivable by respondent (e.g., Breeze et al., 2015).

To conclude, in table 1.2 below, we summarize the description of economic valuation approaches of pollinators and their ecosystem services and we provide examples of methods found in economic literature.

Table 1. 2. A summary of economic valuation approaches in the assessment of the pollinators benefits

Approach	Description	Method Used	Example
a) Cost-based approach	• This approach can refer to methods that base their valuation on the costs generated by pollinators decline or by preserving pollinators on farms.	• Replacement cost method: Pollinator substitute costs (hand pollination, mechanized pollen dusting, etc.)	• Allsopp et al., 2008; Winfree et al., 2011
b) Production function approach	• This approach can consist of practices of determining the value of pollinators based on their effects on production or their consequences on consumer and producer surpluses, or both. • In this approach, the value of pollinators and pollination services can be deducted from direct or indirect observation of market transactions.	• Yield analysis method • Pollinator dependence ratio method • Production function model method • Market prices method • Market equilibrium simulation method	• Garratt et al., 2014; Klatt et al., 2014 • Brading et al., 2009 ; Lautenbach et al., 2012 ; Leonhardt et al., 2013 • Gallai et al., 2009, Bauer and Wing, 2016

c)	Stated preferences approach	• For the benefits of pollinators, stated preferences valuation consists of assessing the willingness to pay (accept) of individuals or a group of individuals towards a set of goods and services that are attributes (benefits) of pollinators. • These approaches are especially useful for non-marketed goods and services.	• Respondents' preferences survey	• Breeze et al., 2015; Diffendorfer et al., 2014; Mwebaze et al., 2010, 2018

Of those economic valuation approaches, an approach and a specific method to mobilize in assessments of the benefits of pollinators may depend on the types of economic values and the ecological, social, and economic context under consideration (Hein, 2009). The economic value that individuals or societies may associate with pollinators and insect pollination services will be largely related to a variety of phenomena that they perceive from goods and services for which provisioning is supported by pollinators. Thus, insect pollination values may differ according to the context and the mechanism at play in a studied area. For example, in the case of the decline of pollinators, which may increase marginal production costs and then market prices, countries' production specialization may take different directions. Depending on the level of increase in marginal production costs, some countries may tend to specialize in the production of goods that are relatively less dependent on insect pollination. Conversely, depending on the level of increase in market prices, some countries may tend to specialize in the production of goods that are more dependent on insect pollination. It is, therefore, necessary to apprehend concerns regarding pollinators decline in different angles.

With this in mind, we review in the next section the importance of adopting different scale perspectives in analyzing ecosystem services, such as insect pollination.

1.3. Different scales perspective for the analysis of pollinators decline

In this section, we first define the scale and review the importance of adopting different scale perspectives for analyzing ecosystem services, such as insect pollination. Then, we introduce the interdependence of ecological and socioeconomic phenomena towards the benefits of pollinators across scales and review the causes and economic impacts of pollinators decline in the economic literature. Finally, we describe discrepancies between levels of dependence on insect pollination services and levels of decision affecting the management of pollinators.

1.3.1. Scale and different scales reasoning

First of all, it is necessary to define the term "scale" to which this chapter refers and to distinguish it from the term "level" with which it can be confused. The term "scale" refers to the measurable dimensions of phenomena or observations expressed in physical units, such as size or years (MEA, 2005). The scale is like a window of perception through which an analysis, observation, knowledge, and information can be considered and/or defined. The main components of scale analysis are spatial and temporal. On the other hand, the term level refers to a unit of a scale, characterization of the perceived influence, not a physical measure, is what people accept it to be (MEA, 2003). For example, the term level can indicate levels of management, organization (Buizer et al., 2011), influence, coordination, etc. To clarify, let's use figure 1.4 below to illustrate the spatial scales and management levels of, for example, natural ecosystem costs and benefits.

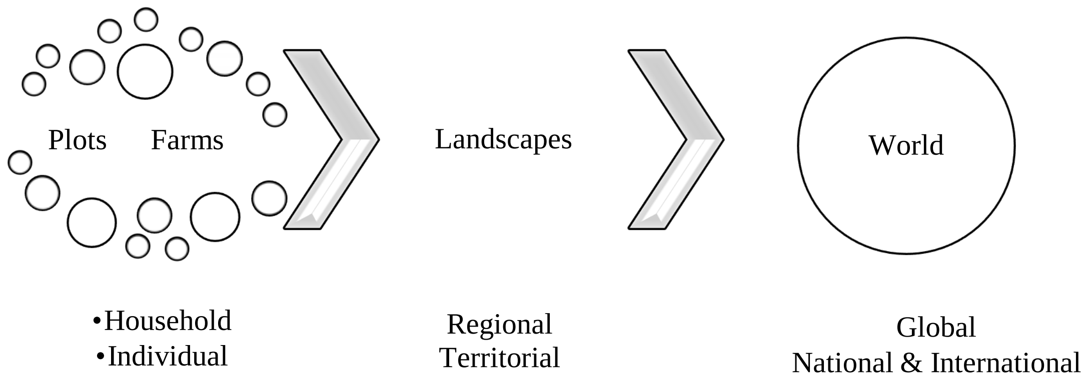


Figure 1. 4. Spatial scales and levels of management with respect to the costs and benefits of Nature

As noted (in Section 1.2.1), this figure can depict how ecological phenomena are linked across scales (e.g., from the plots up to the world spatial scale) and how the resulting socio-economic phenomena are interdependent across scales (e.g., from individuals up to a global spatial scale). Such interdependencies imply that the management of all these phenomena may involve actors operating at different levels. In general, natural ecosystems impact different scales at several levels (Leemans, 2006). But space or time intervals between an action and a consequence generated by a change in natural ecosystems due to that action can be small (short) or large (long): from individual plants to an entire plot, from agro-ecosystems to landscape aesthetics, from individuals to households, and from nations to the world. These processes can determine the linkages and interactions of different users (beneficiaries) of benefits to which pollinators contribute at different levels of spatial and temporal scales. Following some principles of the ecological economics approach, emphasis on the time-scale aspect reflects, among others, the question of the irreversibility of natural processes and all the dynamics of phenomena during time. The space-scale aspect reflects the question of the coordination of Nature users (e.g., Passet, 1979; Faucheux and Noël, 1995). Such complexity should be considered in the economic analysis of insect pollination since one can rarely describe the complex behavior of actor adaptation to the decline of these services at a single spatial or temporal scale. For simplicity, in this chapter we will limit our analysis to the spatial scale.

In the field of geography, a spatial scale is a geographical space in which events occurring at the same timeframe overlap (Delvaux et al., 2002). A variety of events (e.g., climate change, ecosystem services degradation, and pollution) that include components of Nature, economic activities, political and social phenomena can take place at the same time. The interaction of these components is complex in the way that if one of them is modified others can be altered. As stated by Delvaux et al. (2002), everything functions as a dynamic space system that is constantly evolving and interdependent with larger geographical areas in which it is integrated and/or smaller geographical areas in which it integrates. The patterns identified in the assessment of the farm household level differ from those appearing in assessing the individual and global levels in the same timeframe but they are interlinked. Analysis at different spatial scales permits the construction of an explanation referring to processes occurring at different geographical scale (local, territorial, national, global).

Different spatial scales perspective, widely elaborated in the fields of geography as a determining factor behind many environmental issues, is becoming a prerequisite consideration in environmental analysis (Buizer et al., 2011). Analysis at each scale reveals only certain phenomena determining some facets of the issue to be addressed within the spatial scale in which it is, or can be, integrated (Lacoste, 1976). All the facets cannot be taken into consideration in the same order of magnitude, either because they are too large to observe their configuration, or because they are too small. They then fall under different levels of analysis. It is, therefore, necessary to articulate different levels of spatial scale analysis to study the same phenomenon, and to grasp the various facets of an ecosystem service like pollination. But the reasoning goes further. Lacoste (1976) argues that each geographic level makes it possible to study part of a phenomenon, but also that there are interactions between scales. Thus, according to this author, what happens at a local scale interacts with what happens at the global scale. For instance, if a country like Ivory Coast can succeed in asserting its cacao production in international trade, it can be thanks to its local farmers that are favorable to this economic activity and then to the national development. As Lacoste states:

> ”*This approach* [different spatial scales perspective] *leads to take into account the different types of interactions (formal/informal), the distribution of resources between the different actors (material, legal, institutional, expertise, symbolic, legitimacy, mobilization resources, etc.), interdependencies (that is, how resources are exchanged within the network), power relationships, and existing alliances within the studied configuration*.”
>
> Lacoste (1976, p. 170)

Various studies on the analysis of ecosystem services, which take into account spatial scales, point in the same direction and argue that ecological phenomena are interconnected in such a way that a disturbance in one scale can induce ecological changes elsewhere (see Clark, 1985; Kremen et al., 2000; Allen and Holling, 2002; Rotmans and Rothman, 2003, Hein et al., 2006, Martín-López et al., 2019).

The importance of considering different spatial scales highlighted in these studies can be threefold. First, economic valuation at a specific spatial scale focuses on impacts most relevant to the issues of local actors in a defined context, which allows a better problem definition concerning the actors' relation to the local ecosystem and ecosystem services. Then, the values reflected in the different economic valuations of a specific ecosystem problem, such as the decline of pollinators, may be complementary even though these values may depend on the loss of benefits or increase in costs perceived by stakeholders operating in different contexts (e.g., ecological, social, economic, etc.). Third, each scale of analysis may ultimately offer a different perspective for addressing current and future challenges of global ecosystem services degradation.

Hence, the different spatial scales perspective allows combining the wealth of information coming from the scale of the farm to the scale of the territory, nation, and the world. It is a step towards explaining the multiplicity of actors benefiting from pollinators and actors involved in their management at each level and scale. As such, the different spatial scales perspective can allow determining the dominant actors who hold the influence over the preservation and management of pollinators across the scales.

Finally, the consideration of different spatial scales highlights that the interactions and feedback across scales determine, strongly, the global system dynamics (Schellnhuber, 1998). Thus, the different spatial scales perspective indicates the possible pathways that actors' adaptation strategies may follow in the global tendency of pollinators decline and the levels through which the private and public policies about protection and management of pollinators must be structured.

1.3.2. Ecological and socioeconomic phenomena interdependence towards pollinators benefits across scales

Pollinators improve the pollination of crops, wildflowers, and other plants when foraging for food in individual plots, farms, or even the entire landscape. Indeed, while farms dominate the rural landscape, this landscape also includes non-agricultural plants such as hedgerows, which are home to many of the pollinators at the territorial scale. The landscape assures connectivity between different ecological areas through plants network or functional corridors. In the nature conservation domain, corridors are "avenues along which wide-ranging animals can travel, plants can propagate, genetic interchange can occur, populations can move in response to environmental changes and natural disasters, and threatened species can be replenished from other areas" (Walker and Craighead, 1997). Thus, the conditions of agricultural systems and their surrounding non-agricultural areas contribute to the quality of pollination of crops and wild plants with flowers. Specifically, the protection of the population and the density of pollinators in a given area is based on a combination of three main pillars: improving pollinators foraging, improving the nests of pollinators, and reducing the use of chemicals that harm these insects.

However, regardless of the spatial scale on which the population and the density of pollinators are located, the benefits of pollinators can be scaled up from the plant level to the global scale through social, ecological, and economic activities (e.g., supply of agricultural commodities, biodiversity regulation, research activities, ecotourism activities, use of floristic scenery, etc.). For instance, through socioeconomic phenomena, the supply of agricultural commodities flows from individual farmers to household levels, then territorial levels, to national and international levels (e.g., as a means of donation, payment for services rendered, marketed goods, etc.).

Furthermore, while the benefits of pollinators are potentially unbounded, the causes of their decline are not bounded either. The acknowledgment of the interdependencies of scales for the benefits of pollinators by actors at different scales can result in the best appropriation by these actors of issues concerning pollinators decline (causes and impacts). Such appropriation may allow for better consultation and cooperation in decision-making towards the protection of these ecosystem services. Indeed, the causes of the decline of pollination services range from individual plots of land to farms, across the landscape, to global environmental, economic and political phenomena. For example, the factors affecting pollinator ecosystems can come from agricultural practices within a territory, but also global, regional, and national factors (e.g. climate change, the introduction of invasive species, international trade, agricultural policies, and land-use governance).

Also, the decline of insect pollination services can have both global and local impacts. On a global scale, this decline may, for example, decrease the production of pollinator-dependent crops and increase market prices (see Chapter 2). At the local level, the decline in insect pollination can change local diets, food traditions, and cultures (see Chapter 3), and it can decrease the income and well-being of farming households (see Chapter 4).

Therefore, regardless of the causes of pollinators decline in one area, this decline can have impacts on different actors across other spatial scales. Figure 1.5 below illustrates the interdependent socioeconomic phenomena connected to the benefits of pollinators.

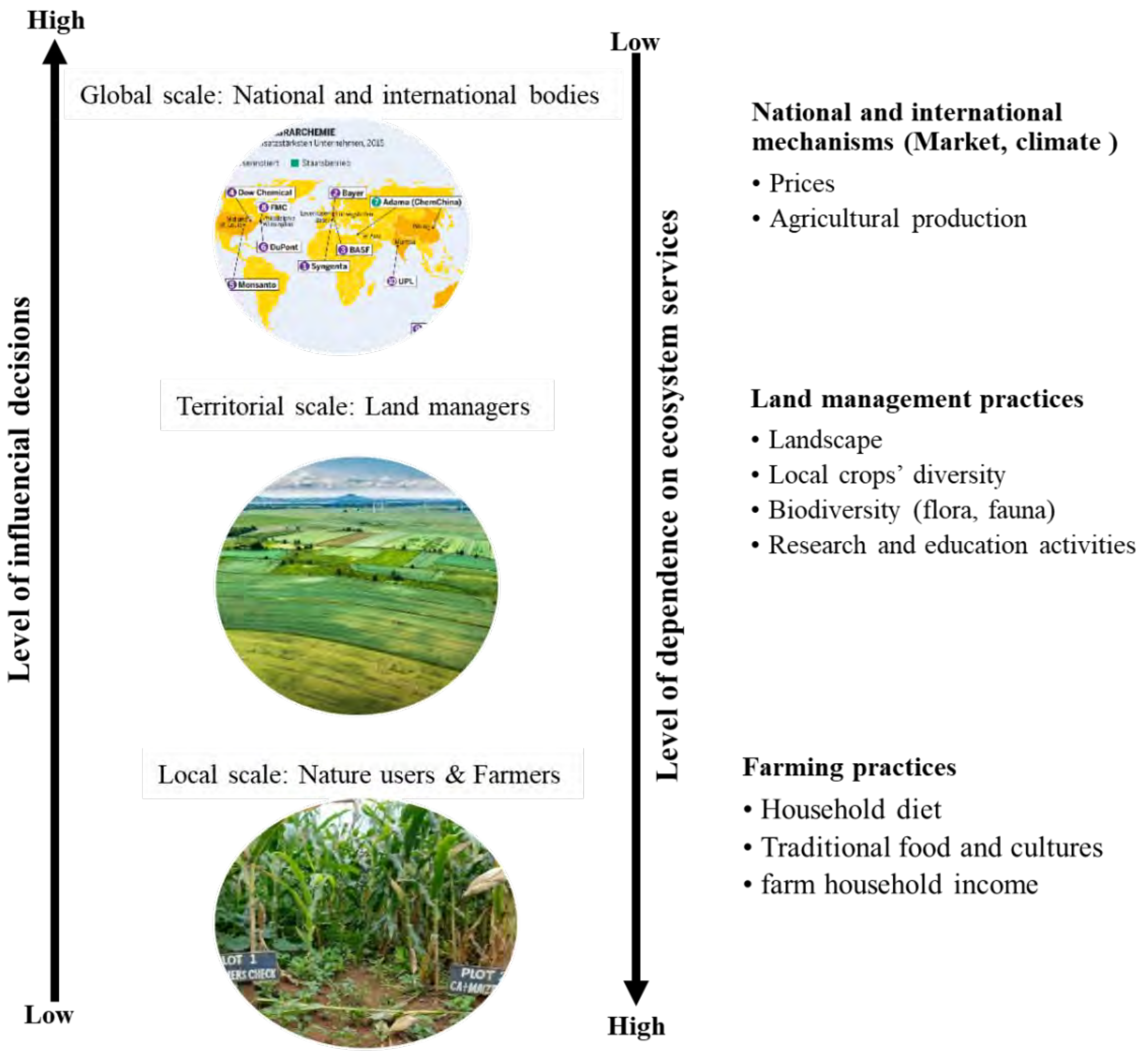


Figure 1. 5. Mapping spatial scales of causes and impacts of pollinators decline, actors most concerned, and the mismatches between dependence and influence levels

Source: Adapted from Martín-López et al. 2019

Figure 1.5 draws for each scale the causes of pollinators decline, the impacts of this decline on the benefits of pollinators, the actors involved, the levels of dependence among actors, and the levels of influence of pollinator-management decisions. Arrows indicate the disparities between actors who are highly dependent on the benefits of pollinators and actors whose decisions significantly influence pollinator protection measures.

Following these considerations, the collective management scheme can propel interventions at different scales to facilitate, to a large extent, preventing the causes of pollinators decline. Various research studies (e.g., Dick et al., 2016; IPBES, 2016) have recommended different measures that can reverse the current trend of the decline of pollinators, which are relevant to: 1) plots or farms at the local scale, 2) landscapes at the territorial scale, and on 3) a global scale in the management decisions of the different stakeholders.

1) Plots and farms at the local scale: Farming practices

The protection of pollinators at the local plots and farms scale should focus on crop management practices, which are specific to farmers. Farming practices have direct impacts on the food and habitat of pollinators in agroecosystems and thus on their abundance in agricultural landscapes.

On the one hand, some practices, such as crop intensification, are prejudicial to the population of pollinators. Intensive crop systems, specifically detrimental to habitats of pollinators, have been mobilized all over the globe as an economically viable way to feed the growing population. Thus, adjusting these systems into environmentally efficient systems is a challenge for current farmers and decision-makers. Intensive agriculture is characterized by monoculture systems that consist in increasing farm sizes, which in combination with an intensive application of herbicides and pesticides reduce the diversity and spatial and temporal availability of foraging resources and nesting sites for bees (Potts et al., 2010; Willmer, 2011; González-Varó et al., 2013). Indeed, some pesticides can result in direct mortality of insects, while others can cause abnormal communication dances, inability to fly, and displacement of pollinators, especially queens of honeybees (Johansen et al., 1983; Kearns et al., 1998; Potts et al., 2010; Willmer, 2011). Consequently, in the longer term, farming practices prejudicial to pollinators result in the decline of pollination services, which in turn can offset the expected benefits from agricultural intensification (Deguines et al., 2014). It is particularly true that such practices result in decreased agricultural productivity for crops that depend on insect pollination.

On the other hand, there are crop management practices, such as intercropping techniques and crop rotation techniques, beneficial to the populations of pollinators. These crop management techniques, when standardized in an area, characterize an efficient landscape at the territorial spatial scale, which reinforces the connectivity between the different ecological areas through the plants network or corridors.

2) Territorial landscape scale: Land management practices

Expanding the scale of the single plot or farm to the territorial landscape scale is not just about adding up the plots and farms in the territory. This scope enables to take into account the diversity of existing landscapes such as urban, forest, grassland and other landscapes. This means considering the impact of pollinators on all these landscapes, as well as the users associated with them, which can allow thinking about a variety of responses to causes of pollinators decline.

Indeed, the impact of landscape alteration on pollinator habitat is one of the causes to which the decline of pollinators has been attributed (González-Varó et al. 2013; Goulson et al., 2015). In practice, therefore, in order, to improve landscape quality for pollinators, much needs to be done at the territorial scale, notably land-use management level. Land managers can promote management practices among networks of citizens, professionals, and environmental associations for pollinating insects in agricultural and non-agricultural areas. Also, they can promote diversity of cropping systems, delineation of plots and farms with strips of grass, tree edges, strips of grass on the edges of residents' land, agroforestry, rational management of pastures, etc.

Effective land-use practices and land management lie as much at the level of collective participation as at the level of individual approach. Hence, strategies to strengthen pollinator management practices should aim to target collective actions (production and consumption) (see IPBES, 2016).

3) Global scale: National and international mechanisms

National and international mechanisms (e.g. climate change, invasive species, market pressures, etc.) that deregulate the functioning of ecosystems can harm pollinator populations. For example, climate change affects the strength of signals that attract pollinators and the number of pollinator generations per year (IPBES, 2016). This IPBES (2016) report asserts that climate change causes the dispersal of weakened pollinator species to less fragile habitats and, thus, fosters a decline in insect pollination services. On the other hand, market pressures play a major role in decisions regarding the fragmentation of pollinator habitats (or insecticide use). For example, large parts of oil palm plantations in Southeast Asia, currently the world's largest oil palm exporting region, were created from biodiversity-rich forests in 1989 (Vijay et al., 2016). The fragmentation of the habitats of these pollinators reduces associated pollination services, which may, in turn, reduce the productivity of pollinator-dependent crops. As a result, crop prices on national and international markets may increase.

At the global scale, the decline of pollinators and their benefits requires thus the attention not only of local actors but also of national and international actors, including governmental and intergovernmental bodies.

1.3.3. Discrepancies between actors' levels of dependency on pollinators benefits and levels of decision affecting pollinator management

The governance of the distribution of ecosystem service benefits among potential beneficiaries involves considering a variety of social-ecological trade-offs (Lehmanm et al., 2018) given that causes of ecosystem services degradation can be spatially (or temporarily) separated from their consequences. Besides, various studies examining the beneficiaries of ecosystem services and the levels of their management indicate the discrepancies and imbalances between a range of actors operating at different scales (e.g., TEEB, 2008; Martín-López et al., 2019). TEEB (2008) indicates that the dependence of the poor or certain communities on ecosystem services for their livelihoods is higher than others (e.g., many of subsistence agricultural-based economies, native communities, etc.). Dependence on Nature is likely to increase as a result of the lack of substitution, such as a less ability to replace local consumption, activities, etc. (e.g., Vallet et al., 2019). Yet, Martín-López et al. (2019) warn about existing mismatches between the levels of dependence on ecosystem services in relation to the level of influential decisions addressing their protection. In this study, Martín-López et al. (2019) show that those who are not primarily affected by the consequences of the degradation of ecosystem services are mainly those with power and, thus, make influential decisions. In the same vein, Vatn (2005) argues that the criteria of efficiency that institutions tend to support often reflect the interests of those in dominant positions.

As such, economic valuation focusing at various scales can inform the distribution of the benefits of pollinators or their degradation costs and thereby support suitable decision-making. In that respect, pollinator-protection decisions may require complex analysis that takes into account social-ecological trade-offs, at least in two ways.

On the one hand, such analysis should consider the discrepancies between actors' levels of dependency on pollinators benefits, which can imply understanding trade-offs between production patterns (using natural or chemical inputs) and resulting impacts on consumption patterns of actors at different spatial scales.

From the producers' side, as Cely-Santos and Lu (2019) show, the causes of pollinators decline may be rooted in production practices mobilized by actors less likely to be affected by the effects of that decline. For example, the coexistence of large, intensified (industrialized) farms and small, traditional, diversified (non-industrialized) farms with different farming practices. Intensified agriculture may mobilize high-yield external inputs, including chemicals (pesticides), to a large extent, while traditional agriculture and smallholders may rely primarily on ecosystem services. As factors of production, chemical inputs and natural ecosystem services are expected to improve productivity. However, intensification practices can affect, among other things, the ecosystem services of an area if the benefits of the latter are not taken into account in the production process. The impact of such coexistence on producers is that inefficient practices of intensive farming systems, such as misuse of pesticides, can have negative consequences on neighboring non-intensive farming systems, and so forth.

From the consumers' side, the impacts of these practices can, for example, be observed in the consumption patterns of rural populations to those of urban populations, which are very different across countries. In the case of pollinators decline, the urban-dwelling population that buys food on national or international markets can have access to pollinator-dependent crops even though insect pollination no longer occurs at the local scale. But those who rely heavily on their food production and/or locally produced food for their livelihoods would be highly impacted by the local decline of pollination services. If pollinators decline, the later populations will have difficulty in obtaining pollinator-dependent crops (e.g., fruits and vegetables) to supplement their food consumption, while such crops provide nutrients (e.g., vitamins, antioxidants, and fiber) (Eilers et al. 2011) that are essential for human body maintenance and growth (WHO, 2021). Yet, as noted in the general introduction, the World Health Organization warns that global malnutrition is on the rise as the level of undernourishment and obesity increases (WHO, 2018). Consequently, pollinators decline may curtail the consumption of locally produced nutritious foods in rural areas, thereby exacerbating the problem of malnutrition that is currently on the rise.

On the other hand, such analysis should consider different levels of influential decisions affecting the management of pollinators such as conflicting mandates that may exist among various organizational levels. Concerning conflicting mandates, public policies designed to enhance the sustainability of ecosystem services versus those focusing on improving productivity may have conflicting land-use agendas and understanding. For example, it happens very frequently that national trade policies or food security measures in some countries aim to support highly productive agricultural systems (e.g., using intensification), while the same public authorities tend to support conservation management practices. In this respect, economic valuation can inform cross-cutting mandates at different levels and thus support pollinator protection decisions effectively.

Finally, the articulation of the causes and impacts of pollinators decline and pointing the mismatches between dependence on ecosystem services and their influential decision levels comfort the need for economic valuation of the benefits of pollinators (e.g., pollination services) at different scales. This is especially necessary to inform decision-makers addressing efficiently pollinators decline as it can raise the question of what decisions could be individual, local, national, and international and which actors should better deal with the decline of pollinators at their scales and across scales?

In the next section, based on the economic literature, we discuss possible public and private responses to the decline of pollinators and ways to ensure that the social, cultural, environmental, productive or other values of pollinators and their ecosystem services are maintained.

1.4. Possible responses to pollinators decline: public policies and initiatives

As far as the degradation of Nature features is concerned, the possible responses may theoretically relate to how society perceives their importance as well as the rights to use these features (IPBES, 2016). Nature often provides complex goods and services (i.e. as in Mitchell and Singh, 1996) to diverse types of actors, including marketed and non-marketed benefits, as is the case of pollinators. For instance, insect pollination services are particularly subject to collective use and accessible to common use, while managed pollinators like honeybees as well as pollinators benefits like food crops can be privately owned. As such, the contribution of pollinators to human well-being can be perceived in different ways (see Section 1.2.2). Therefore, it is not straightforward to understand either rationales driving individual or collective decisions regarding pollinators decline. Yet, while privately owned benefits can be maintained by their users, collective (or social) benefits will be maintained if the government takes them in charge or if collective action inside groups undertakes to manage them through conscious common action (e.g., Wynne-Jones, 2013).

Hence, the sustainable use of the benefits of pollinators for human welfare and even more generally for economic development requires both government interventions through public policies and stakeholders coordinated actions through collective initiatives at different scales.

Public policies provide a framework for consistent decision-making and actions, which is necessary for better use of the information about the benefits of pollinators and the costs of their degradation for society across scales. The need for public policies can be based on many reasons. One of those reasons can be the fact that the market failed to perform adequately in conveying price signals resulting in suboptimal use of Nature services for achieving maximum aggregate income (Pigou, 1920). As pointed out by various studies (e.g. Stiglitz, 1989; Laffont, 2008), the market does not take into account factors such as public goods, externalities, imperfect competition, imperfect distribution of information, etc. Thus, information about pollinators as public goods and their pollination services as positive externalities to production, and the consequences of their decline, is needed to guide stakeholders who use or give guidance on the use of Nature at all levels (Braat and de Groot, 2012).

However, as stated by Aoki (2006), the expected policy outputs cannot always be achieved if there is not an implication of the general public. Indeed, public policies focused on individual actions (e.g., incentive-based instruments) are limited. For example, incentive public policies to reduce the agricultural inputs introduced in OECD countries have only partially been used to meet their objectives (OECD, 2008). Also, alternative fertilization or pesticide techniques offered to farmers by the public authorities have not been met with the expected success (Del Corso and Kephaliacos, 2011). As Del Corso and Kephaliacos (2011) argue, the reason for action necessarily includes other ingredients such as knowledge and skills. Moreover, as noted in the introduction, a country’s public policy is only applicable on the national scale, which emphasizes the need for coordinated initiatives at the global scale between sovereign nations.

Following the above considerations, the possible responses to these challenges should link information on insect pollination ecosystem services regarding the knowledge of the ecological systems that provide these services, the economic sectors and even systems that benefit from them, and public awareness (Braat and de Groot, 2012) at different scales. At the individual and territorial scales, there can be a certain number of organizations that protect natural resources, different types of coordination of individuals who take ownership of pollinators as well as pollination services, and therefore the different types of public policies can be based on different economic and social activities in place, such as education, local communities or associations, etc. At the national and global scales, the protection of pollinators can be supported by more scalable initiatives. Hence, government responses to pollinators decline should be tailored not only to the public policies addressing pollinator management practices, but also to the global coordination initiatives and the driving forces of the general public. In this light, the economic valuation we consider in this thesis contributes to the application of suitable measures at these spatial scales.

Subsequently, based on the existing economic literature on ecosystem services, including pollination, we discuss possible responses to pollinators decline through: 1) the public policies addressing pollinators management practices, 2) the global coordination initiatives, and 3) the driving forces of the general public.

1.4.1. Public policies addressing pollinators management practices

The implementation of public policies focused on the management of pollinators and their services is complex because they have multiple uses and are at different scales of use, and concern the different actors. Policymakers can therefore be challenged by questions such as: are pollinators and their services likely to be owned? Who owns pollinators or who does not have access to them while needing their pollination services? Or who wants or can appropriate them and thus can manage them sustainably?

These questions can enable decision-makers to identify the direct beneficiaries of these services, and thus anticipate and support different modes of coordination involving local public authorities and local communities who can effectively discuss how to implement and control the practices within their reach. In order to organize the coexistence of actors who use pollinators and their pollination services in different ways, it is necessary to associate the interests of stakeholders with the right they have to use such feartures of Nature. Hence, a complementary consideration implying property rights is necessary for our analysis. Moreover, because the costs of pollinator degradation or the benefits of pollinator maintenance involve both individual (private) and collective (public) costs and benefits, they can be managed according to several circumstances and the institutional contexts (i.e. Cheung, 1973). In this sense, public policies supporting pollinator management practices may need to understand the costs (and/or benefits) that the market can account for, thereby targeting individual behavior, and those that the market cannot account for, thereby targeting collective actions.

Identifying economic status or modes of appropriation of pollinators and pollination services by individuals or collective organizations whose activities benefit privately from them (e.g., beekeepers, farmers, tour agencies, etc.), can inform policy-makers about the level of utility these users derive from using these services and thus their willingness to protect pollinators at the forefront. Depending on how users perceive the contributions of pollinators in serving individual or collective interests, their management may, potentially, be as that of public goods, common pool resources, club goods or private goods (IPBES, 2016). In economics, a public good is a good that is both non-excludable and non-rivalrous (e.g., fresh air, knowledge). In contrast, a private good is a good that is both rivalrous and excludable (e.g., food, clothes). And a common pool resource is defined in economics as a good that is rivalrous and non-excludable (e.g., pasture land, wild berry piking, etc.). Conversely, a club good is a good that is both excludable and non-rivalrous (e.g., recreational area, private park, etc.). Pollinators as goods can refer to the flow variable of pollinating insects within ecosystem, while insect pollination as a good can relate to the flow variable of pollinator visits to plants in a given area.

Insect pollination can serve as public goods because controlling or delineating pollinator visits to plants in a given area might be almost impossible as pollination is offered in an omnidirectional manner by a fixed ecosystem. This is especially the case for wild pollinators that provide pollination service benefits to an extended group of individuals. Moreover, the pollination service is hardly exclusive as no user can exclude others from using it. However, pollination services, that are mainly provided by managed pollinators, become private goods on the market when there is an organized hive rental market (e.g., in the US, France, China) (i.e., Fisher et al., 2009; Rucker et al., 2012). Also, managed pollinators, or patches of pollinator habitat, can be privately owned (e.g., Stern et al., 2001). Besides, rivalry in pollination services may take place when one or more actors damage ecosystem of pollinators by using insecticides or by destroying the natural habitat of insects. These damaging practices result in a depletion of pollinators both in terms of abundance and diversity, which creates rivalry among insect pollination services necessary for crops and wild plants depending on the insect pollination services. Hence, the quality of pollinators and pollination services depends on the uses of diverse practices by multiple actors and sometimes with competing interests , thus their management may, potentially, be as that of common pool resources (see, i.e., Fisher et al., 2009). Also, pollinators can be club goods between beekeepers and farmers (Stern et al., 2001), if a group of farmers and beekeepers work together to look after the bees and to watch pesticides use practices.

In short, this identification can be a useful tool of who benefits from pollinators in the first place and is thereby willing to manage them, and who is not interested in managing pollinators in an area, which may have implications for their long-term management. In that sense, the protection and preservation of pollinators and pollination services as private or club goods can be expected through market mechanisms and collective organization, particularly for managed honeybees. However, it is not enough from all the points of view regarding all the types of values at stake as discussed in the previous section (see Table 1.1). Thus, the role of public authorities to ensure the proper allocation of the benefits derived from pollinators as a complement to the market is crucial, since the market is of little use especially when it comes to the collective and public uses of the benefits of pollinators. Also, the public authorities should watch over the overall use of these services, when users can tend to value immediate benefits more than future benefits given their preference for present over future use (see Pigou, 1920). In that respect, government interventions can support actions to protect current and future pollinators and pollination services by mobilizing public-policy measures addressing pollinators decline and pollinator management practices tailored to a variety of actors from different perspectives (e.g., farmers, pesticides producers, etc.).

Current public policy measures concerning the protection of pollinators are still limited and are barely adopted in agricultural policies, particularly in developed countries[10]. For instance, some countries in Europe already mobilize European Agri-environmental Schemes that incentivize environmentally friendly farming systems (e.g., biological farming) as prescribed in the Common Agricultural Policy (CAP) (see, for example, Mosnier et al., 2009), which can be beneficial to pollinators. Recently, many Agri-Environmental Measures/Schemes (AEM/S) were improved, to specifically encounter for the protection of pollinators where farmers are encouraged to implement them voluntarily (Batáry et al., 2015). Furthermore, the maintenance of pollinators is supported by the E.U. Pesticides Directive 2009/128/E.C., which member States are encouraged to implement as it is the cornerstone of E.U. policy to reduce the negative environmental impacts of pesticides (European Parliament, 2016). Specifically, after various studies have described three neonicotinoids to be harmful to bee pollinators, i.e., managed (Apis mellifera) and wild bees (Osmia bicornis) (see, Laycock et al., 2012; Whitehorn et al., 2012; Sandrock et al., 2014; Henry et al., 2012; Rundlöf et al., 2015), the member countries of the European Union (E.U.) has voted for their ban. These three neonicotinoids are imidacloprid (i.e., the most used insecticide worldwide), clothianidin, and thiamethoxam (European Food Safety Authority 2018a, b, c). Yet, even though those regulations exist in E.U. prescriptions, they are not sufficiently applied in E.U. member countries (see, e.g., Lefebvre et al., 2015; Kleftodimos et al., 2021).

However, as described earlier, the expected public policy outputs cannot always be achieved if there isn't the implication of the general public. And also, causes, as well as impacts, of pollinators decline go beyond national and regional boundaries, and, as such, public policy has its limits. For that reason, national and international entities need to work together and pool their resources to coordinate actions of this magnitude.

Thereafter, we discuss the global coordination initiatives and the general public driving forces for the protection of pollinators and pollination services.

1.4.2. Global coordination initiatives for pollinators and pollination services

The pollination crisis is acknowledged at the international level (Kluser and Peduzzi, 2007) and has raised concerns among international decision-makers (Dias et al., 1999; Kremen et al., 2002; MEA, 2005; FAO, 2008; Byrne and Fitzpatrick, 2009; Potts et al., 2010; Goulson et al., 2015; IPBES, 2016). Some international entities (e.g., FAO) are pushing for decisions to initiate supporting systems for the preservation of pollinators and pollination services in the face of concerns regarding the decline of pollinators. These entities launched a variety of global initiatives that support ecosystems and ecosystem services — e.g., Millennium Ecosystem Assessment, The Economics of Ecosystems and Biodiversity,

[10]Further details on public policy can be found in Kleftodimos' thesis entitled "Economic valuation of bees' pollination services on arable crop farms: the role of Public Policy regulations towards the provision of pollination services" (Kleftodimos' doctoral Thesis, 2019, Ch. 4).

and The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Specifically, the São Paulo Declaration on Pollinators (Dias et al., 1999) made pollinator concerns explicit globally and fostered the establishment of the International Pollinator Initiative.

Officially, the International Pollinator Initiative (IPI) was established in 2000 at the 5th Conference of the Parties of the Convention on Biological Diversity (Byrne and Fitzpatrick, 2009; Willmer, 2011). This initiative's plan of action offers guidelines for the improvement and/or development of policies and practices that enhance the conservation of pollinators and that restore their habitats, which can be summarized in four elements: assessment of bees and bee pollination services; adaptive management; building capacity; and getting bees into decision-making.

The globally coordinated implementation of such guidelines aims at reaching four fundamental objectives. The first objective is about monitoring pollinators decline, their causes, and impacts on pollination services. The second objective focuses on addressing the lack of taxonomic information on pollinators. The third objective focuses on assessing the economic value of pollination and the economic impacts of pollinators decline. Indeed, this thesis was initiated in collaboration with IPI coordinating team of FAO as an effort to contribute to this objective. The last objective is about promoting conservation, restoration, and sustainable use of pollinator diversity in agriculture and related ecosystems (Byrne and Fitzpatrick, 2009; CBD, 2017).

Since the formation of the IPI, several other initiatives have joined its goal at different spatial scales and organizational levels. On a global scale, there are the African Pollinator Initiative, the North American Pollinator Protection Campaign, and the Oceania Pollinator Initiative; and at the national scale, there are the French, Brazilian, Colombian, and the UK Pollinators Initiative, etc. (see CBD, 2017). To name a few at the organizational level, there is the Xerces Society[11], the STEP (Status and Trends in European Pollinators Project), and the COLOSS (Prevention of honey bee Colony LOSSes).

Even though efforts are still needed to deepen, for example, the analysis of the impacts of the impoverishment or disappearance of pollinators on social well-being to highlight the importance of preserving bees and other pollinators, these initiatives are increasing awareness. They are increasing awareness of both policy-makers and the general public about the role of pollinators in agriculture and social welfare in particular. Global initiatives underpin the complementarity of knowledge-based evidence and actions to serving social welfare by, among other grounds, stressing on how the economic valuation of Nature can be an asset for decision-making at different scales. Subsequently, we discuss the driving forces of the general public to protect pollinators.

[11] The Xerces Society aims at protecting the natural world through the conservation of invertebrates and their habitats and produced the "Bring Back the Pollinators" as the 2017 annual report. https://xerces.org/publications/annual-reports/bring-back-pollinators-2017-annual-report

1.4.3. General public’s driving forces to protect pollinators

Awareness of the general public about the relationship between pollinators and society cannot only facilitate the adoption of pollinator-friendly policies and management practices in general but also influence consumption behaviors towards the benefits of pollinators. As stated above, this implies effective learning, since the reason for action necessarily incorporates knowledge and skills. Socioeconomic factors, like knowledge, landscape characteristics, preferences, and attitudes (e.g., moral or ethical) of actors, can further their sensibility, awareness towards pollinators, and thus willingness to participate in actions preserving pollinators (i.e., Wilson and Hart, 2000; Wynn et al., 2001; Sattler and Nagel, 2010). Likewise, various studies consider that it is necessary to enrich the pollination assessment information that takes into account a variety of value domains (economic, ecological, sociocultural, etc.) and different levels of the definition of these values (individual and collective) for effective pollinators protection (Arias-Arévalo et al., 2018). Understanding how actors perceive the value they derive from elements of Nature, such as pollinators, can highlight their driving forces in engaging in pollinator-friendly policies and management practices. In short, figure 1.6 below formulates the components underlying relations between pollinators and society as follows:

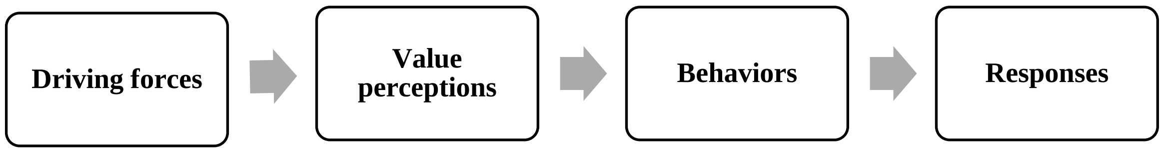


Figure 1. 6. The components underlying individual actors’ concern about the decline of pollinators

As figure 1.6 depicts one can expect that the forces that drive the general public influence value perception, which in turn may dictate actors’ behavior towards pollinators and their services, and thus serve as the basis for effective responses to the issues of pollinators decline. Thus, considering the presence or absence of forces that might motivate the general public to act to preserve pollinators is noteworthy.

In light of the above-mentioned considerations, we subsequently argue that the general public’s driving forces can be based on different values that actors assign to pollinators, including, for instance, 1) ethical (or moral) value, 2) economic value, and 3) collective (or social) value (see Table 1.3 below).

First, some actors may value pollinators, on an ethical (or moral) basis, just for the sake of their existence. For some farmers, the information about, for example, the efficient agronomic and ecological practices for the management of pollinators may seem to be sufficient to adopt pollinator preservation behavior since one can expect a high willingness to adopt preservation behavior towards pollinators by them.

Second, other actors may value pollinators due to the benefits they get from pollinators – e.g., pollination services. For these actors, the information about the economic value of pollination services can influence their behavior towards some actions protecting pollinators as farmers or consumers. Yet, it implies selective actions concentrated only on what these actors consider as useful, which may lead to the extinction of a vast number of species still essential for the ecosystem. Concerning the pollination services and the related ecological function, for example, many recent studies in ecology (Ellis et al., 2017) have pointed out the potential synergy between wild and domestic bees. Similarly, Kleftodimos et al. (2021) show reasons why farmers should be interested in this synergy, as wild and honey bees working together can reduce their operating costs. Such actors need mainly actionable information about the complex links between the ecological systems that provide these services and the economic systems that benefit from them.

Third, there are also collectivity-driven individuals. As stated by Wynne-Jones (2013), actors do not only prioritize economic profits they may get from Nature as individuals, but they also value their community welfare. Therefore, public policy interventions should target to improve some level of cultural understanding (see Del Corso and Képhaliacos, 2017). These individuals are likely to engage in actions to preserve pollinators, not only for the benefits they may get individually from pollinators, but rather in the sense of ethical values.

For the precaution, however, the absence of driving forces should also be anticipated in case some actors are indifferent to pollinator decline issues. In the case of indifferent actors, rising awareness about pollinator benefits may not be enough to bring about changes in such agents' behavior towards pollinating insects. Indeed, some individuals can be indifferent to pollinators and their services even if they may have preferences for the benefits to which pollinators contribute like food provision. These individuals may not be willing to do any action to conserve pollinators by themselves. In case public characteristics of a good or a service comfort "indifference" type behavior, a result that is particularly possible when it comes to the production of public environmental goods, specific effort on behalf of public authorities might be needed to trigger reasons for acting. For example, in France, the implementation of the neonicotinoid ban is not welcomed by all farmers, and thus meets the difficulties as well as the lack of voluntary and strong public policy to implement the banning of these neonicotinoids (see, for example, Kleftodimos et al., 2021). Yet, France aimed at reducing pesticides in French arable crop farms by 50% until 2025 (Ministère de l'Agriculture et de l'Alimentation, 2015). Indeed, the expected outputs from such public policies could be promoted further by consumer demand.

With this information, the consideration of the different relationships that individuals in a society may have with pollinators and their benefits highlight the necessity and efficiency of state intervention in preserving pollinators for the interest of all. Also, it comforts the necessity of tailored interventions in the protection of pollinators. However, as long as those whose choices or behaviors influence the dynamics of pollinators are not affected by either market prices or policy instruments or consciously willing to choose to take actions preserving pollinators, pollinator-unfriendly practices can prevail (IPBES, 2016).

Table 1. 3. Driving forces of the general public to pollinator protection

Actor driving forces	Actor probable behavior	Possible responses
Ethical or moral drivers (just for the sake of pollinator existence)	A high willingness to adopt preservation behavior towards pollinators can be expected.	Avail needed information about pollinator management (e.g. agronomic and ecological practices, goods & services in line with their conservation).
Economic drivers	Willingness to protect pollinator benefits for their well-being.	Provide information about the complex links between the ecological systems that provide these services and the economic systems that benefit from them.
Collectivity drivers	Individuals are likely to engage in actions to preserve pollinators, not for the benefits they may get individually from pollinators but rather in the sense of social values.	Address some level of cultural understanding (see Del Corso et al., 2017).
No drivers (indifferent actors)	"Indifference" type of behavior: individuals that may not be willing or able to take any action to conserve pollinators by themselves.	Specific efforts on behalf of public authorities might be needed (e.g., command and control measures).

Finally, in this section 4, we argued that in order to have efficient responses to the decline of pollinators at each scale and at the different scales, it is necessary to combine conservation management practices with both the status of the direct users of the benefits of pollinators in an area and socio-economic drivers of actors involved in implementation. Public decision-makers and international bodies need a clear understanding of the value society attributes to pollinators to make informed decisions. Among the values, which public policies should aim to sustain, include a set of economic values of pollinating insects including their marketed and non-marketed benefits as we depicted earlier in the pollinators TEV (see Section 1.2.). Economic valuation remains, however, a tool that may not be able to highlight all the values that pollinators may offer, which can still be among the driving forces to act for people. Thus, public policy must take an interest in all uses integrating marketed and non-marketed benefits (as discussed above in Section 1.2.2) and the variety of actors involved in efficient pollinator management practices.

Similarly, policy makers and international entities need to work together for the protection of the benefits generated by pollinators and their pollination services (see Section 1.3), as different types of actors are involved in their use. Thus, the problem of pollinators decline can be addressed differently at different scales through, for example, coordination at the international trade, territorial, or household levels.

At the international level, in the absence of a central "international" authority that would enforce common regulations on all nations, a large part of the relations between countries is organized by the rules of the international market (e.g., the rules of the WTO). It is thus worth looking at trade mechanisms to analyze its incidences on the decline of pollinators and then the consequences of this decline on human welfare worldwide (See Chapter 2).

As regards to territorial level, there is a certain amount of individual and collective coordination specific to local actors who share the same landscape, history, tastes, traditions, know each other, and have particular habits concerning the environment when educated about it, etc. (see Chapter 3). As such, this scale is interesting to look at because local actors may facilitate the different coordination (e.g., via local authorities or collective initiatives) concerning insect pollination management practices at local scale.

Besides, there are very different contexts if one scales down to the local and territorial levels depending on the economic contexts, ecological contexts, above mentioned social contexts, etc. For example, what is naturally encountered in developing economies differs from what is encountered in developed economies since the specialization of tasks and lifestyles may be different. Nevertheless, in both cases, billions of people live in rural areas and benefit to a greater extent from pollinators because they are close to Nature. As such, some local structures, habits, history, etc., may cause people to make trade-offs or arbitrage among themselves regarding the use of the benefits of pollinators as pollinators decline in their production systems. That arbitration can be done through households that are consumers and producers (see Chapter 4). And so, this context has to be considered in its own right not only because it is important but also since the types of coordination may be different, consequently the types of public policies should be different in this context. Thus, public policy-makers have to look at things more broadly through, let's say, the different uses but also the different centers of interests or conflict of interests towards the use of pollinators benefits.

Hence, public policy addressing the pollinator-related issues is important but ultimately depending on: the problem definition, the actors concerned, the scales and context under consideration, and all that goes together. Certain public policies are possible in a context and others are not applicable in the same context. Also, depending on the scale, certain policies are possible because there is a legitimate authority and others do not have administrative authority with coercion. And there are other places where it is not effective to have supported coercive public policies because they would be very expensive.

As a reminder, Section 2 on economic valuation and Section 3 on the scales perspective for the analysis of pollinators decline were useful to analyze multiplicity of actors involved in the management of pollinators, and thereby underlining the importance of a wide range of responses.

1.5. A synthesis of Chapter 1 and influence on the thesis hypotheses

This chapter aimed to provide a state of the art of this thesis by highlighting the importance of the economic valuation of the benefits of pollinators at different spatial scales to address their decline. By doing so, it highlighted the fact that this thesis subject is a multi-factorial and multidimensional problem involving a range of actors operating from different spatial scales and therefore must be studied in several contexts. The reasoning at different scales, a variety of interventions, and actors that have been put forward in this chapter inspired the economic valuation of pollinators benefits covered at each spatial scale in three case studies analyzed this thesis. Even if the economic valuation tools we use lead us to consider that each actor, which we take into account at each scale analyzed, acts as if pollinators decline had an impact at only one scale, the public policies and initiatives that emerge consider the need for complementary responses at different scales. To conclude, we first offer a synthesis of this chapter and then highlight its influence on the hypotheses of this thesis.

1.5.1. Key ideas covered in Chapter 1

Figure 1.7 below summarizes the main ideas we discussed in this chapter. Specifically, this figure illustrates the role of decision-making at different spatial scales in supporting pollinators and human society relationships. It explains that the pollinators and pollination services support ecosystems and agroecosystems in providing marketed and non-marketed benefits that are of ecological, socio-cultural, and economic values (such as food, scenery, medicines, traditions, etc.); which improve human welfare.

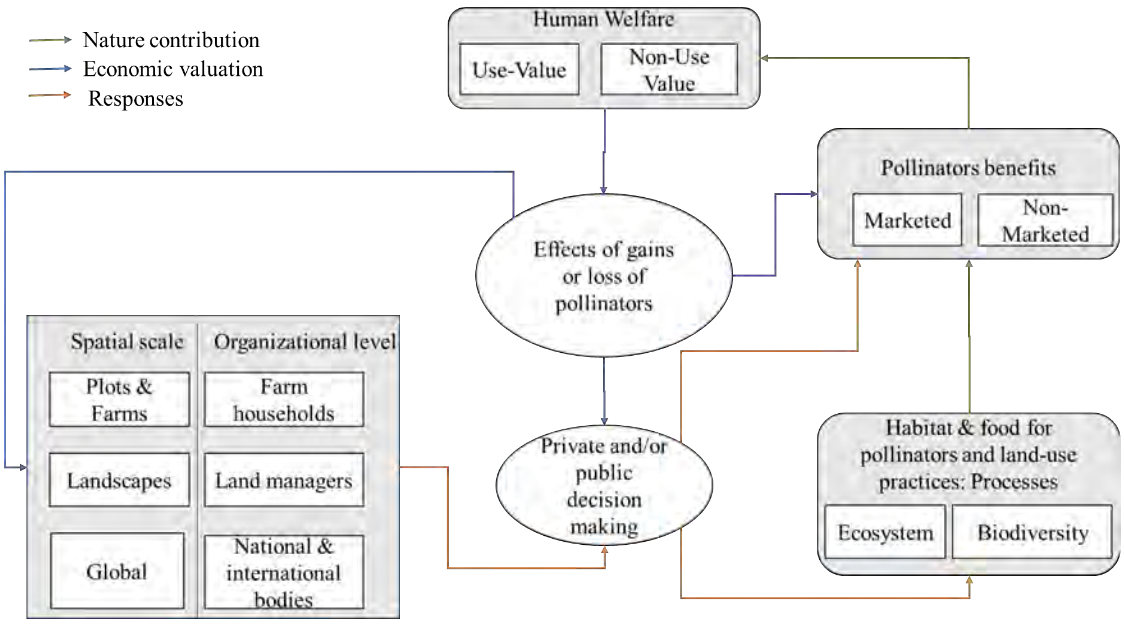


Figure 1. 7. A synthesis of Chapter 1

Note: Illustration of the role of decision-making at different spatial scales in supporting pollinators and society relationships adapted from IPBES, 2016. Alongside the organizational levels, we added the corresponding spatial scales as discussed in this chapter.

Indeed, in Section 1.2, we focused on the economic valuation of pollinators benefits. It showed that the pollinators, through their pollination services, support the agro-ecosystems and landscapes worldwide; which provide many goods and services to human society that are of use and non-use values (TEEB, 2010). As such, this analysis sets the stage for the following chapters on economic valuations of the impacts of pollinators decline on human well-being.

In Section 1.3, we underlined the importance of considering different spatial scales in the analysis of the benefits of pollinators. On this basis, we argued that matching the information of the economic value from these ecosystem services to the stakeholders, affected by the decline of pollinators, and decision-makers, whose decisions influence to a great extent the management of pollinators at different scales, is important. Considering the specific questions relative to pollinators decline at each scale may provide complementary information about the value of pollinators, which might lead to an efficient way to manage ecosystems of pollinators for human welfare. Indeed, as noted above (Section 1.3.1), Hein et al. (2006) argue that perspectives gained from other scales would contribute to a fuller understanding of the pollinator issues and a better problem definition of a scale under consideration. Given that national, regional, and international findings may not adequately reflect all facets of an issue due to the use of macro-analytical methods that tend to neglect local heterogeneity and sub-regional differences, considering different scales results in increased attention.

And finally, in Section 1.4, we focused on the possible responses addressing pollinators decline. It discussed that the efficient responses and policy-prescriptive mechanisms for coping with pollinators preservation may depend on the coordination of actors from various scales. Section 1.4 highlighted the interdependencies and complementarity of the various responses to pollinator-related issues. These responses necessitate the involvement of global, regional, national, and individual actions to mitigate pollinators decline. To put forward management practices to conserve pollinators and pollination services, responses can be crafted into public policies and local actors' collective initiatives. The actors whose decisions are at the forefront in pollinator management are national and international entities, local land managers, collective organizations, and individual landowners. The different spatial scales perspective increases awareness of these stakeholders' needs, improves analysis of scale-dependent processes, and thus more reliable and accurate outcomes.

1.5.2. The common thread of the case studies explored

To recall the scope of this thesis, the rest of this thesis brings together the economic valuation of the benefits of pollinators at global, territorial, and farm household scales on which the management of pollinators may depend. Figure 1.8 summarizes the following chapters consisting of these three distinct case studies and emphasizes the consistency between them in terms of the potential responses to mitigate the degradation of pollinators, which can be defined at different spatial scales.

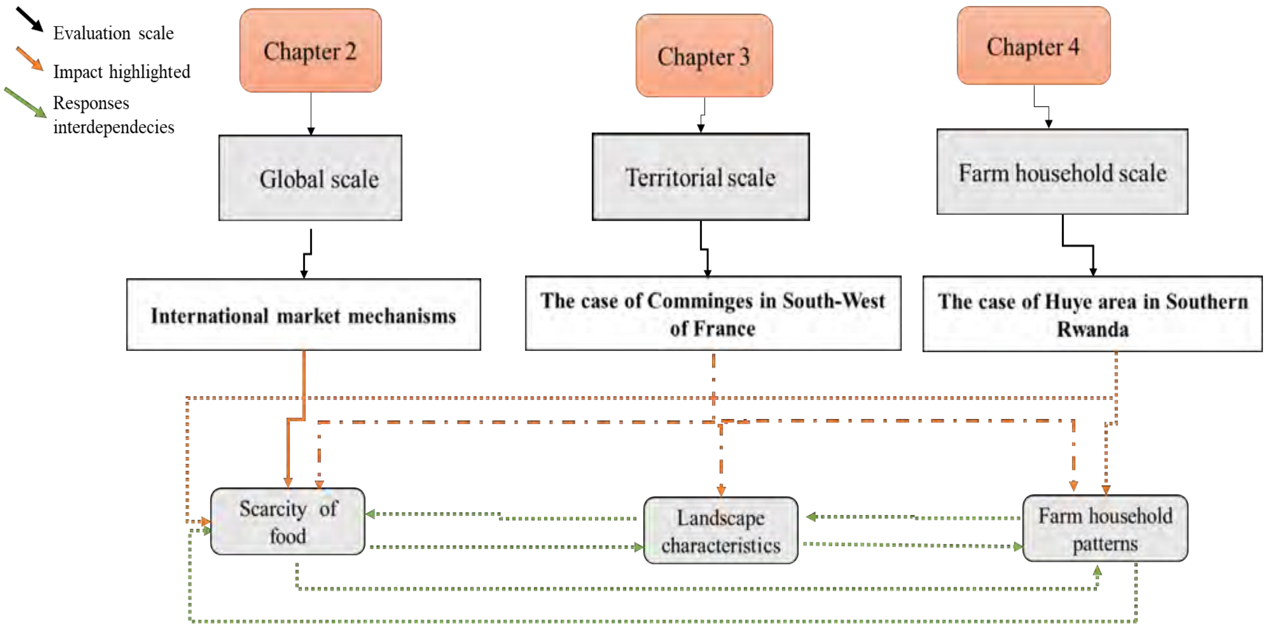


Figure 1. 8. Thesis case study framework

In all these three case studies, the spotlight is on the consequences of the decline of pollinators on human well-being. In so doing, this thesis highlights the interests of combining globally and locally focused analyses in the economic valuation of the benefits of pollinators for the efficient protection of endangered pollinators.

In the following chapters, economic valuation at each of these scales will focus on distinct concerns and will consider welfare economics to assessing the economic and nutritional impacts of the decline of pollinators on social welfare. Specifically, these impacts have been geared towards classical economic indicators including the variations in market prices that may induce food scarcity, landscape flora and fauna characteristics, and farm household production and consumption characteristics. These indicators are interdependent in sophisticated ways. For example, an increase in the international market price of certain crops may have incidences on the crop production of countries as they adapt to the market changes. The consequence of that shift will be seen in farms and then farm household production and consumption patterns as farmers will try to adapt to pollinators decline in their production costs as well as changes in market prices of their products. Also, market changes on farms may be seen through landscape changes at the territorial scale, where connectivity between different ecological areas through plants' network or functional corridors may be disturbed. Table 1.4 below summarizes the impacts highlighted, methods mobilized, and pollinators benefits considered in this thesis.

Table 1. 4. An overview of the roadmap for our case studies

Levels of analysis	Impacts highlighted	Methods mobilized	Benefits considered
Global food market	Variation of the international market prices and their repercussions on the consumption of nutritional quality of food	Through international trade mechanism: Market partial equilibrium simulation	Tradable and marketed food crops
Local biodiversity benefits	Variation of quantity and nutritional quality of local food commodities Changes in local flora and fauna characteristics	Through the value respondents gave to pollinators: Stated preferences	Local marketed food crops Locally-bounded non-marketed benefits, floristic scenery, and pollinator species.
Farm household production and consumption	Variation of production, income, and food consumption quality within farm households	Through the analysis of the sources of household food regimes via production, auto consumption, market demand: Dependence ratio method	Tradable and marketed food crops Non-tradable farm household own food

Chapter 2 - Incidences of Pollinators Decline on the International Trade: Social Welfare and Food Security Analysis

2.1. Introduction

Since the 2014 Rome declaration on nutrition[12], member countries of the Food and Agriculture Organization of the United Nations (FAO) and the World Health Organization (WHO) together reinforced their understanding of the connectivity of food security goals to nutritious food consumption. The World Food Summit (1996) had declared that "food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life". Food security is thus a concept that incorporates both the quantity and nutritional quality of crops grown and consumed in the world, particularly in developing countries where food security is still an issue (FAO, 2006). Quantity refers to the volume of food crops in metric tons. Nutritional quality refers to nutrients that are food components a human body uses for its maintenance and growth (WHO, 2021). More precisely, these nutrients consist of both macronutrient components, including carbohydrates, proteins, and fats, and micronutrient components, which are essential for human health, including vitamins and minerals (WHO, 2021).

Countries have spent far too long looking solely at staple crops rich in macronutrients such as many categories of cereal that provide calories (e.g., rice, wheat, maize, millet) as the answer to food security (FAO, 2015). Yet, the provision of calories is only one factor among others that contribute to food security. Micronutrient deficiencies, alone, affect approximately two out of seven billion of the world population and are globally considered the underlying cause of a third of child deaths, with impacts on socio-economic development and welfare (Black et al., 2008; FAO, UNICEF, WHO, World Bank Group, 2016). For example, the deaths of 800,000 people per year, mostly women and children, have been attributed to the deficiency of vitamin A in diet (Ellis et al., 2015). East, Central, and West Africa have increasing numbers of stunted (low height for age) children and South Asia has half of the world's wasted (low weight for height) children under age five (IFPRI, 2016).

Thus, as FAO has insisted on, the production of non-staple food rich in micronutrients – e.g., fruits, vegetables, oilseeds, etc. – is another critical factor addressing malnutrition (FAO, IFAD, and WFP, 2015). However, the production of these diverse non-staple crops in many cases requires different forms

[12] http://www.fao.org/3/a-ml542e.pdf; last access October, 2020; see also global nutrition report, 2016.

of agricultural management than that of dominant staple crops such as maize and wheat, which more readily lend themselves to production under relatively uniform and monoculture systems. Indeed, the primary objective of farm management under uniform and monoculture systems has been to maximize the production quantity of produced crops while minimizing its costs to maximize its profit (Perfecto et al., 2019). In that respect, as these authors assert, in addition to high capital and trained labors, such farm systems are sought to mobilize high technologies as production factors, including high-yielding seed varieties and using large amounts of inorganic fertilizers as well as pesticides.

Besides, ecological and agronomic scientists have drawn attention to the links between the rich nutritional content in crops and their full or partial dependence on insect pollination services for their natural process of production (Chaplin-Kramer et al., 2014; Ellis et al., 2015; Sluijs et al., 2016). Insect pollination services are particularly beneficial for crops that are non-staple but widely consumed around the world such as many fruits, vegetables, and oilseeds. Moreover, pollinator visits to crops that depend basically on other pollination vectors (e.g., wind, water, etc.) have a positive synergy to their mating and then their production (Klein et al., 2012). Furthermore, pollinator-dependent crops are among the main income-generating crops leading trade commodities in underdeveloped countries (e.g., cocoa, coffee); and a source of employment in developed and developing countries (e.g., fruit harvesting) (IPBES, 2016).

Therefore, insect pollination services play an essential role in the provision of food because insect visits to crops improve fertilization, then productivity and nutritional quality of agricultural products (IPBES, 2016), thereby contributing to the welfare of both producers and consumers.

Unfortunately, the diversity and density of the population of pollinators are, thought to be, declining at a global scale (Potts et al., 2010); while the demand for crops that are dependent on pollinators has been steadily increasing along with the world population since 1960 (Aizen et al., 2008). For instance, the supply of pollinators in Europe is becoming increasingly inadequate (Breeze et al., 2014). Causes of the degradation of insect pollination services are manifold — e.g., insecticide use (Johansen, 1977; Brittain and Potts, 2011; McGrath, 2014; UNAF, 2017), agricultural intensification (Steffan-Dewenter and Tscharntke, 1999; Kremen et al., 2002), pollinators habitat conversion (Aizen and Feinsinger, 2003; Brosi et al., 2008; Quintero et al., 2010), the development of invasive species (Ghazoul, 2004; Schweiger et al., 2010), various introduced pathogens (Cameron et al., 2011), and climate change (Hegland et al., 2009). As described in Chapter 1 (in Section 1.3.2), some of these causes of the decline of pollinators are interrelated and thus mutually reinforcing. Yet, measures to mitigate the decline of pollinators are overlooked in public policies that support land productivity in most countries, given that the social costs and benefits of preserving pollinators and pollination services are not well understood. Furthermore, the consequences of the decline of insect pollination services on the quantity of produced crops and the nutrients contained in those crops are still little known.

In the face of the decline of insect pollination services, countries need solutions to address the impacts of this degradation on food production and nutrient intake, among other things. For food production concerns, for example, these solutions can be based on technological advances (i.e., Genetically Modified Organisms development), mechanical methods (i.e., displacement of managed honeybees on a farm, hand or drone pollination, etc.; see Chaplin-Kramer et al., 2014; IPBES, 2016), etc. For nutrient intake concerns, solutions can be based on a shift in diets (e.g., replacing crop nutrients source with animal nutrients source), fortifying staple food (e.g., rice, wheat, maize, etc.) with micronutrients, using nutrient supplements, reinforcing the importation of agricultural commodities (ibid), etc. These solutions can lead to the thinking that the benefits of insect pollination are substitutable (see, e.g., Bauer and Wing, 2016). Yet, the opportunity cost to replace such benefits generated by an ecological function (i.e., as defined in Chapter 1), by other means, is not fully evaluated.

As such, unless technical developments provide effective alternatives to insect pollination services, otherwise, the decline of pollinators in agroecosystems will, among other things, increase the marginal production cost of the crops that depend on them, thereby threatening agricultural incomes. This decline effect on the market will be higher prices for pollinator-dependent crops (Kevan and Phillips, 2001). Consequently, consumption of pollinator-dependent crops will decrease, and shifts in food consumption may follow. For instance, local consumers can turn to alternative local crops in terms of fruit consumption (e.g., replacing strawberries that depend on pollinators by bananas whose reproduction does not rely on them). Or, local consumers can turn to imported products if their relative prices and the capacity of the country to import such crops allow that shift.

In that respect, the impacts of pollinators decline on food production and nutrient intake, thus to social welfare, can be measured across the variation of market prices. Indeed, the crop markets are not restricted only to the local or national markets but also open, to some extent, to the international market. Thus, international trade may have repercussions on the trajectories through which the decline of pollinators impacts societies (e.g., Kevan and Phillips, 2001; Bauer and Wing, 2016). Hence, agricultural and trade policies could play a crucial role in pollinator management practices as external trade of pollinator-dependent crops, such as coffee, cacao, and some fruits, is important to many countries' agricultural income (see e.g., Gemmil-Heren, 2016).

Currently, the international trade of agricultural commodities, which has been encouraged by public policies, has seen tremendous growth (Josling et al., 2010). For instance, the trade of agricultural commodities tripled during the period from 2000 to 2012, and its export volume increased by 60% (FAO, 2015). Moreover, the aggregated share of agriculture in the world GDP increased from 3.8% in 2012 up to 4.6% in 2016, though its share is more than 50% of the GDP in developing countries (World Bank data, 2018). However, as the international trade theory demonstrates following David Ricardo (1817) (e.g., in Krugman et al., 2012), trade gives rise to specialization. Yet, specialization can in many cases encourage monoculture systems that may contribute, among other things, to pollinator habitat conversion and crop intensification and thereby causing the decline of pollinators. Therefore, if insect pollination services are not well regulated, from a public economic policies point of view, trade can have not only positive impacts on economies but also negative consequences on food security in terms of quantity and nutritional quality aspects.

On the one hand, international trade can avail a new market to an exporting country and, at the same time, allow an importing country to benefit from a diversity of crops that it can produce at relatively higher opportunity costs. For instance, many fruits, vegetables, or cocoa and coffee products are widely consumed in Europe even though their production requires climatic conditions that are not naturally specific to Europe.

On the other hand, trade can lead a country to the expansion of certain types of crops in which they have relatively abundant endowments (e.g., natural environment, technology, etc.). But a vast development of certain crop types may threaten biodiversity in general (Krugman et al., 2012; Vijay et al., 2016), pollinator population included (Kremen et al., 2002). For example, large portions of the oil palm plantations in Southeastern Asia, currently the top region of oil palm world exports, were created from forests that were teeming with biodiversity in a post-1989 era (Vijay et al., 2016).

With this in mind, in this chapter, we draw particular attention to the relation between insect pollination services and the quantity and the nutritional quality of food production and consumption at a global scale through international trade mechanisms.

Various economic studies have analyzed the contribution of insect pollination services to the quantity of crop production and consumption at a global scale (e.g., Kevan and Phillips, 2001; Gallai et al., 2009; Lautenbach et al., 2012; Bauer and Wing, 2016). However, only a few consider mechanisms of international trade of crops. Those addressing the economic valuation of impacts of pollinators decline in international trade include Kevan and Phillips (2001) and Bauer and Wing (2016). Kevan and Phillips (2001) used an analytical economic model of international trade assuming pollination services as a production input to show the impacts of pollinators decline on consumer surplus and producer surplus and thus on social welfare. On the one hand, these authors show that consumers could lose out on a global scale due to price increases that may be associated with pollinators decline. On the other hand, Kevan and Phillips (2001) indicate that even though some countries would lose in terms of producer surplus, other countries would gain following their adaptive capacity to the decline of pollinators. Consequently, the impact of this decline on producers might depend on different factors — e.g., the relative increase in world prices against the relative decrease of pollinators at producers' spatial scale; relative increase in alternative pollination service costs; or the ability of a producer to replace pollinator-dependent crops with non-pollinator dependent crops. Bauer and Wing (2016) extended this illustrative valuation using both partial and general equilibrium simulation models (i.e., as defined in Chapter 1) encompassing the inter-regional and inter-sectoral levels. The model of Bauer and Wing (2016) estimated the economic value of insect pollination services at 10.5 billion US$ attributed directly to the crop production sector and 323.6 billion US$ for the non-crop sector. Bauer and Wing (2016) suggest that replacing pollinators' benefits or insect pollination services, which are free with alternative costly pollination services, can reduce the effects of pollinators decline. Though, such costly alternatives to insect pollination will increase prices as producers adjust to production technologies, which may have consequences on consumers' surplus and producers' profit. Indeed, Gallai et al. (2009) demonstrated that the more consumers prefer the products depending on pollinators, the more utility they will lose, if pollinators disappear. Thus, the substitutability effect can reduce the impact of the insect pollination decline on consumer surplus if the products depending on pollinators are relatively replaced (e.g., through imports).

However, as noted in the general introduction, previous economic studies have not gone far enough to understand the consequences of substitution processes, which may occur as producers and consumers adapt to pollinator decline effects, on micronutrient production and consumption. In other words, these studies did not consider the potential loss of nutrients from pollinator-dependent crops that may be triggered by this decline and then the consequences for the nutritional quality consumption if producers and consumers replace them.

Hence, our objective in this chapter is to raise new questions and extend existing analysis about the benefits of pollinators at a global scale by considering their contribution to not only crop production but also crop nutrients content. More precisely, this chapter proposes an economic valuation of the impact of the decline of insect pollination services on the quantity and nutritional quality of food grown and consumed on a global scale through international trade mechanisms. In doing so, this work is therefore part of the ongoing work to adjust economic valuation tools to account for the benefits of pollinators and the costs of their decline for society in order to support policy-making.

For that, we focus on the following questions:

1) What would be the consequences of insect pollination services' decline on the quantity of food grown and consumed on a global scale and thus their market prices?
2) What would be the consequences of this decline on the consumption of nutritional quality food on a global scale?
3) More broadly, what would be the consequences of this decline on the welfare of both consumers and producers?

To respond to these questions, we mobilize a production function approach by using market partial equilibrium simulation method (i.e., as defined in Chapter 1, Section 1.2.3). This method implies measuring the relative variations in crop market prices, demand and supply quantities, and thus subsequent changes in nutrient consumption that may result from marginal changes in insect pollination services at a global scale (e.g., Gallai et al., 2009). By using a partial equilibrium approach with a focus on the crop sector, we seek to highlight variations specific to marginal changes in insect pollination services, which is relevant for the scope of this thesis. To do this, analytically, we develop an economic model combining Gallai et al.'s (2009) bio-economic model and the international trade model integrating pollination services as expressed by Kevan and Phillips (2001) and Bauer and Wing (2016) in a partial equilibrium model fashion (i.e., as described in Section 2.2.4). In this model, we set two main assumptions. By the first assumption, we consider a total (and other levels of) extinction of insects' pollinators and thus a total (and other levels of) decline in insect pollination services on a global scale to simulate different possible future scenarios. In the second assumption, following previous studies (see Chapter 1, Section 1.2.3), we suppose that insect pollination services play a role in the crop supply as a component of production factors.

From the data collection standpoint, our simulations use the data of countries from world databases (FAO, World Bank) regarding crop quantities produced and the budget that countries allocated to foodstuffs. Furthermore, our analysis will rely on the literature that provide the ratios of dependence of crop production on insect pollination (Klein et al., 2007) and nutrients contained in crops (Chaplin-Kramer et al., 2014). Indeed, although limited, to some extent, these studies offer the possibility to measure the economic value of insect pollination services relative to the quantity and nutritional quality of crops.

Thanks to this methodology, we analyze the potential changes that may occur in market prices, supply, and demand of agricultural production and track the variation in nutrient intake due to the new crop market equilibrium for different scenarios of the decline of pollinators. To evaluate the impacts of pollinators decline on nutritional quality, we extrapolate the value of nutrients in crops based on experimental results from Chaplin-Kramer et al. (2014) about the amounts of various nutrients content. Specifically, we 1) quantify variations in the volume of food crops supply and consumption due to pollination services' decline and thus 2) quantify the relative variation in the nutrients embedded in crop consumption if pollination services decline.

This chapter shows that, under the defined assumptions, the average world price of crops will increase by about 187% if pollinators are totally extinct at the global scale. In this case, the global demand for food may change, and our results confirm that consumer surplus could decrease. Despite such an increase in prices, however, we also found that the amount of food grown globally could decrease with the decline in insect pollination. Our results show that producers may lose and the trade value of crops may decrease under most scenarios of declining insect pollination. In addition, this chapter draws attention to the loss of global nutrient consumption, particularly in regions where food scarcity is already present.

To continue our analysis, we split the rest of this chapter into five sections. The second section introduces the main issues raised in economic studies related to the contribution of ecosystem services, particularly pollination, to international trade. This section also reviews the economic methods used in the economic valuation of the impacts of pollination services in international trade. The third section presents the modeling and simulation approaches we use in this chapter to estimate the impacts of the decline of pollinators. The fourth section presents in detail the results obtained and the fifth section discusses the effects of these findings on social welfare and food security worldwide. Finally, we conclude with the implications of our findings on public policies from national to international levels.

2.2. Literature review on the benefits of ecosystem services to international trade

This section highlights the theoretical and analytical framework in which this chapter falls into. In the first place, we will define and describe the main issues raised in economic studies related to ecosystem services in general and international trade nexus. In the second place, we will introduce the case of insect pollination services in this reasoning. Then, we will introduce the results of some theoretical models simulating the impacts of the decline of pollinators in national and international markets. Finally, we will underline the originality of the approach and economic model we propose in this chapter.

2.2.1. Defining ecosystem services' linkages to international trade

International trade refers to the export and import flows of goods and services across the borders of different countries and more particularly the determinants of these flows (Krugman et al., 2012). The exchange of goods or services is, in many cases, supported by a variety of private and public factors within the exporting and importing country scale, including capital, labor, and natural environment assets. Natural environment assets refer to the living and non-living entities occurring on the Earth that provides multiple benefits to human society (UN, European Commission, IMF, OECD, and World Bank, 2005). These assets include ecosystems with their ecosystem services, biodiversity, and other natural resources (Peskin, 1989; Brown et al., 2016).

In this work, we focus on ecosystem services. Ecosystem services support the human population within and beyond their local boundaries through provision services (e.g., food provision), regulation services (e.g., pollination, climate regulation), and cultural services (e.g., tourism; MEA, 2005). However, when ecosystems are misused or naturally in a bad state, they can create negative externalities and thus costs to human societies (i.e., as defined in Chapter 1). The costs of negative externalities from damaged ecosystems can be located within defined territorial boundaries or spread up across territories and on a global scale. A typical example of a borderless negative externality of a damaged ecosystem is greenhouse gas emissions that may occur when a local ecosystem resource, like a forest asset, is damaged. A damaged forest gives rise to poor regulation of greenhouse gas emissions causing global warming and, thereby, resulting in climate changes worldwide, which threaten the lives of many species on Earth, including pollinators. As for localized damage, negative externalities are, specifically, felt in an area where an ecosystem service locates - for example, the impacts of the decline in insect pollination on a floristic landscape, local customs, and traditions related to the benefits of pollinators (insect-pollinated plants and foods, etc.). When ecosystems are well maintained, they support the life system of all species on Earth by creating positive externalities, which benefit human societies. As mentioned above, for example, a well-maintained agroecosystem provides a habitat for pollinating insects that offer, in turn, pollination services to crop production.

International trade plays a role in spreading the consequences of local ecosystem externalities (costs and benefits) across the scales due to their repercussions on exchanged goods or services (see, for example, Drakou et al., 2017). For example, insect pollination declines may decrease crop production in an area, which may increase imports - as marginal production costs and prices of these crops at local scale may increase (Gallai et al., 2009) - and thus modify international trade flows. It is, therefore, of concern to consider the mechanism of international trade in assessments of the changes that the ecosystem degradation may generate in national and international markets.

In the next section, we will describe concerns regarding ecosystem services addressed in the international trade context.

2.2.2. Describing ecosystem service concerns addressed in the international trade context

Concerns about ecosystem services linked to international trade are often addressed through government interventions using public policies, notably environmental and trade policies. Therefore, the main questions addressed in economic studies focus on the efficiency and competitiveness of environmental and trade policies. An efficiency analysis of environmental and trade policies tackles the extent to which these policies are keeping the social costs down by protecting the ecosystems and their services aimed at improving social welfare (see Stuart, 1986). On the other hand, competitiveness analysis assesses the impacts of such environmental and trade policies on the ability of a country to compete effectively in global markets. Several traditional economic studies combining the natural environment with international trade have analyzed the impacts of both trade policy on ecosystems and, inversely, environmental policy on trade patterns (see, for example, Pethig, 1976; McGuire, 1982; Siebert, 1977, 1985; Baumol and Oates, 1988). One of the main results of these studies highlights the fact that policy-makers are in the first place concerned with the ways to improve social welfare by increasing the level of income per capita through market systems. Yet, improving social welfare in that way is a twofold challenge. For, on the one hand, an economic competitiveness race in market systems can generate environmental degradation, or negative externalities, and, on the other hand, environmental degradation can lead to economic damage.

In an economic competitiveness race, there is a risk to deplete ecosystem services, as is the case for pollination. Such risk is most likely when these services contribute to production but do not cost a thing in the production processes. Indeed, as Vatn (2005) argues, while private and public goods or services jointly contribute to production processes only private factors are accounted for production costs. Yet, impoverishing ecosystem services may generate social costs at local, national, and global scales (like for air pollution, biodiversity depletion, crop production costs, etc.; Zilberman et al., 2008). This may especially be the case for private actors operating in market systems, but also some government interventions can threaten ecosystems. For instance, subsidies to exports that support crop production surpluses and exports push countries to intensify their production, thus increasing damages on the ecosystem and the ecosystem services.

Impact of ecosystem damages on social costs at the global scale (see Chapter 1, Section 1.3.2) comforts the establishment of governmental interventions via, for example, countries' environmental regulations on trade (even though some environmental policies can be as proxies to involuntarily or voluntarily protectionism). Theoretically, optimal interventions should be objective and should serve as a tool to internalize environmental externalities into market systems and then on prices (Vatn, 2005). However, the development of optimal environmental-related policies for countries has challenges from methodological and practical points of view.

From a methodological point of view, it is challenging to estimate the optimal environmental policies internalizing the total social costs and benefits of Nature following conventional economics. As discussed in Chapter 1, the economic valuation of a benefit that Nature generates or cost of maintaining this benefit depends on how a pool of actors (and/or users who may have different agendas) perceive the contribution of Nature in serving private or public interests (Chapter 1, Section 1.2). Different perceptions of the benefit at stake imply a range of value types that cannot always be depicted in market systems (Chapter 1, Section 1.4.2).

From a practical point of view, it is also challenging to measure the strengths of these policies in sustaining the competitiveness level of a country given that there is a risk that some countries may stick to unfriendly environmental practices. Environmental regulations are different across countries due to disparate factors, such as differing R&D level or capacity, level of information, level of income, and the unbalance of power relationships between actors in terms of environmental considerations (e.g., Witter et al., 2015). For example, the level of income (high, middle, low) of a country is an important factor that can dictate behaviors towards the use of ecosystems and ecosystem services. A high-income country can have the technology and capital to invest in meticulous practices that respect ecosystems and, at the same time, maintain its competitiveness. Conversely, some developing countries may lack mechanisms or required capital resources to assess and regulate their ecosystems and ecosystem services. Several studies (see Cole et al., 1997; Munasinghe, 1999; Nasreen et al., 2015) argued, using the Environmental Kuznets Curve, that economic development at early stages contributes to the deterioration of the natural environment. The consequences of such disparate factors between countries imply that stricter environmental regulations in one country can reduce its competitiveness in the short-term, which may then lead to an industrial leakage or an increase in the likelihood of relocation of unfriendly economic activities to a less regulated country (Dean, 1992); this is referred to as "environmental dumping".

However, the race for economic competitiveness can also be undermined by the degradation of ecosystem services, which give rise to negative externalities generating both higher production costs and income uncertainties over the longer term. For a country, these dynamics threaten GDP. As for consumers, this deterioration can lead to an increase in market prices, which hampers consumption. Consequently, ecosystem services degradation will have an impact on the whole economy (i.e., Sumaila et al., 2014).

Therefore, tying up the quest for economic competitiveness and the preservation of the benefits that natural ecosystems grant human society is of concern. As a response to that concern, for example, some studies (see, for example, Krutilla, 1999; Tol, 2018) examine the evolution of the competitiveness of countries in the trade of natural environment products taking into account the effects of the degradation of Nature services on productivity. Also, some economists (e.g., Ngo Van Long, 2011; Sampaolesi, 2010) argue that the possible extinction of various ecosystem services reveals that the economy should account for these resources as stocks of natural capital.

This chapter is in line with this economic assessment context that aims to account for natural ecosystem service factors into competitive market patterns as one of the ways of valuing the benefits of these services on human welfare. In doing so, it focuses on the marketed benefits of insect pollination services as an agricultural production factor.

2.2.3. International trade and the case of insect pollination services

Pollinator visits from one plant to another result in pollen transfer between plants. This process ensures their fertilization and reproduction when pollen is transferred between flowers of the same plant species of different sex, notably food crops, hence the contribution of insect pollination to food provision. Insect pollination is, thus, an essential ecosystem service to agriculture production (Gemmil-Herren, 2016). The benefits of insect pollination services to crop production differ among crop species and national economies based on the types of crop countries produce naturally (e.g. Bauer and Wing, 2016). As demonstrated by Gallai et al. (2009) and then Lautenbach et al. (2012), the decline of pollinators would, however, impact almost all countries in the world. Using data from Gallai et al. (2009), Gallai mapped the distribution of world agricultural vulnerability confronted with the decline of pollinators, as shown in Figure 2.1 below. In this study, the vulnerability is expressed as a function of exposure, sensitivity, and adaptive capacity of countries to the decline of pollinators (i.e., as defined in the General introduction). From this map, we can observe two main results: 1) impacts of pollinators decline are global; very few countries are spared by this decline i.e. with vulnerability levels lower than 2.2%, and 2) such impacts are heterogeneous among countries.

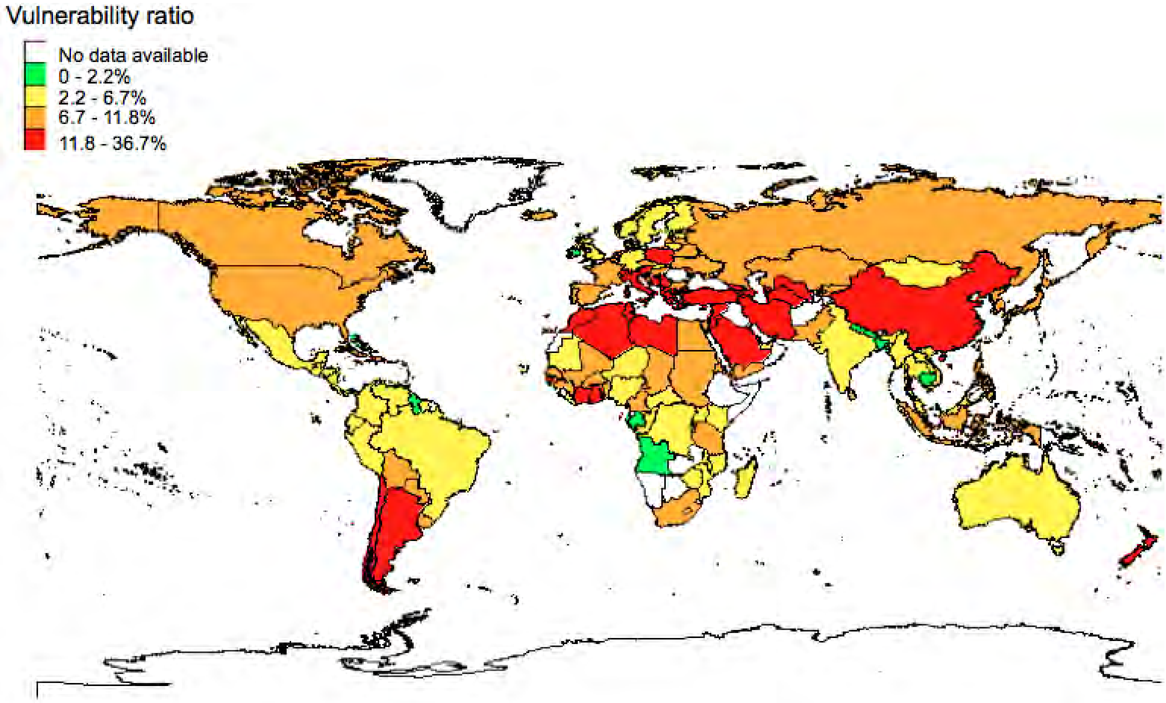


Figure 2. 1. Map of the distribution of agricultural production vulnerability confronted with pollinators decline

Source: data taken from Gallai et al. (2009)
Note: Although unpublished, this map was made by Gallai based on Gallai et al. (2009) dataset.

At first glance, this distribution underlines the fact that the benefits of pollinators and their pollination services can be relatively abundant in some countries and scarce in others, hence the interest in trade mechanisms. Likewise, even though pollen transfer processes occur at a local scale, the lack of such transfer may induce both localized damages and non-localized damages on crop patterns through national and international markets. Following Siebert's (1974) model of comparative advantage that considers the environment as a determinant of trade, for example, the decline of pollinators can impact the prices of crops in perfect competition models. More broadly, the degradation of pollinators in individual countries can generate not only an increase in relative market prices of crops but also an overall biodiversity loss and a decrease in the variety of food products, and thus threaten social welfare globally (IPBES, 2016).

Finally, given the disparities among countries in terms of the variety of factors including natural aspects like climate, soil, plant genetics, etc. countries are initially endowed with different crop production factors, which is among the reasons why the impacts of the decline of pollinators are heterogeneous among countries (for example, see Bauer and Wing, 2016; Gallai et al., 2009). As a result, countries produce different crops, thus the trade of pollinator-dependent crops across countries can be welfare improving on a global scale. For instance, countries that are not initially endowed with a certain pollinator-dependent crop, their local consumers can still benefit from imported pollinator-dependent products if their relative prices and capacity to import such crops allow that (e.g., cocoa or coffee crops). Also, as Bauer and Wing (2016) and Gallai et al. (2009) argue, the ability of countries to replace a good or service with another one may reduce its dependence on insect pollination. Similarly, Kevan and Phillips's (2001) analysis shows that the impacts of pollinators decline on social welfare are less important in the case of traded agricultural commodities relative to an absence of trade. Thus, pollinator issues should be considered in decision-making processes by economic actors (e.g., producers, consumers, States, etc.) at different scales to sustain pollinators and their pollination services benefits for all. But, how can the issue of pollinators be specifically taken into account in the mechanisms of international trade? By integrating, for example, protection measures of pollinators and their pollination services into the reasoning concerning environmental or trade policies?

For clarification, let us provide an example on how to do this integration in Box 2.1 that follows.

Box 2.1. Example of measures related to pollinators and their pollination services coupled with environmental or trade policies

In many cases, producers are not equipped to consider the contribution of insect pollination services in their production processes because such services are usually free in many countries, particularly when offered by wild pollinators. Consequently, without public policies to protect pollinators, international trade risks to accentuate the causes of pollinators decline such as crop intensification practices as farmers may specialize in certain types of crops in which they have advantages in producing them. In that respect, pollinator issues can necessitate the regulation of human interactions with the ecosystems to halt the degradation of pollinators at the international level using international trade mechanisms.

As such, can regulations concerning international trade of hazardous substances (i.e., as in Scherr, 1987) includes compounds that are prejudicial to pollinators? Or, through trade instruments (e.g., standards, welfare-improving tariffs, labeling, subsidies, etc.), can regulations of pollinator-dependent crops influence their trade patterns but also the management of pollinators and insect pollination services (i.e., as proposed in Koellner [2013] for ecosystem services)? Indeed, in Koellner's (2013) instruments for global governance of ecosystem services such as environmental labeling, trade bans, payment for ecosystem services, etc., are discussed more in depth.

These environmental regulations may engage producers to consider insect pollination services in their decisions and imply production changes, for example, in the use of external-farm inputs like chemical fertilizers, pesticides, and the choice of crop cultivars. Besides, state interventions through trade policies can reinforce standards of information between worldwide producers and consumers about crop production practices, which may allow the identification of products according to production methods.

As stated by Zilberman et al. (2008), these measures can influence market outcomes by permitting efficient signaling of consumer preferences for environmental preservation to producers.

Finally, the regulation of human-environment interactions with public policy interventions can incite producers in incorporating the costs of the degradation of pollinators in their production decision-making. Analysis of the economic impacts of pollinators and their pollination services decline on traded goods is, therefore, one of the ways to respond to this need; which is the aim of this chapter.

In the next section, we describe the theoretical and analytical approaches used in economic studies to model and simulate the economic impacts of pollination services in the national and international market systems.

2.2.4. Theoretical models simulating the impacts of pollination services' decline in national and international markets

The economics of insect pollination services has been broadly studied in the scientific literature at large (see, for example, IPBES, 2016, Ch. 4). These studies mainly value the contribution of pollination service in monetary terms and are incorporated into economic models and market systems. Economic models that include pollination services are developed assuming that, in a rational way, consumers aim to maximize their utility and producers aim to maximize their profit (e.g., Gallai et al., 2009; Bauer and Wing, 2016). Thus, various economic valuations simulated the impacts of pollination services' decline on social welfare through market systems (see Chapter 1, Section 1.2.3).

As mentioned earlier, insect pollination plays a role in crop production amidst other production factors (Kleftodimos et al., 2021). Thus, the decline of pollinating insects raises the marginal costs of crop production. Simulations consist of analyzing the consequences of such decline on crop produce supplies and consumption given that the decline of pollinators may increase the price of pollinator-dependent crops, which may impact market equilibrium.

In economic theory, the market equilibrium is reached when demand equals to supply. Once this equilibrium is attained, the quantity of a good exchanged and its unitary price are determined. Consequently, while a higher price can compensate for production cost, it affects consumption because consumers consume less as price increases. We illustrate this phenomenon in figure 2.2 below, where P1 and Q1 are, respectively, the price and the quantity exchanged at the initial equilibrium. Insect pollination contributes to the yield of various crops (see Klein et al., 2007). Hence, if pollination services decrease due to the decline in the abundance of pollinators in the agroecosystem, the crop yield decreases. Consequently, the marginal cost of farmers will increase, which will result in supply shifts to the top left (Supply 2) in figure 2.2. This shift creates a new equilibrium supply/demand into the economy and therefore new equilibrium values, which are P2 and Q2. The economic impact of the decline of pollinators is thus depicted by the shift from the initial equilibrium to the new equilibrium.

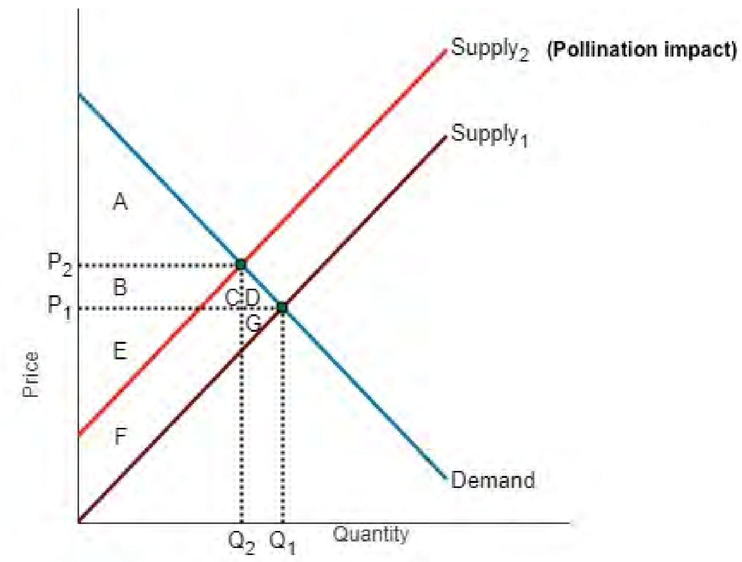


Figure 2. 2. Illustration of variations resulting from pollination service decline on market equilibrium within a closed market

Source: Kevan and Phillips (2001)

We can evaluate this shift by using indicators such as consumer and producer surpluses and by comparing their variations. Consumer surplus is the difference between his willingness to pay and the market price. On figure 2.2 above, consumer surplus corresponds to the ABCD area at the initial equilibrium. Producer surplus is the difference between the marginal cost and the market price. On the same figure, producer surplus corresponds to the EFG area at the initial equilibrium. In economics, the sum of these two indicators measures the social welfare (i.e., ABCDEFG area). In this example exposed in figure 2.2, when the supply curve shift leads to new equilibrium where the market price increases (from P1 to P2) and the quantity exchanged into the economy decreases (from Q1 to Q2), the producer and consumer surpluses change and so is social welfare. As this figure shows, in the case of increase in price as supply curve shifts upwards on top left, there will be a net loss in consumer surplus that equals the BCD area (initial equilibrium area ABCD - new equilibrium area A), while consequences on producer surplus will depend on a relative increase in price because producer surplus variation equals to the FG-B area (initial equilibrium area EFG - New equilibrium area BE).

However, this analysis is realized in a closed market. In international trade theory, a closed market refers to a country not impacted by international demand and supply; this country is said to be in autarky. This closed market situation differs from an open market situation. An open market refers to a situation where imports and exports with other countries are allowed[13].

[13] In a more general sense, the term "open market" refers to a market that is accessible to all economic actors, inside and outside the considered country, and that provides an equal opportunity for entry. Thus, in the international trade theory, a world market refers to the situation where many or all national markets are open and interact through trade for goods, services and even economic factors.

Theoretically, a traded product may result in increased competition between domestic product and imported product, which may widen the gap between national supply and demand of such a product and thus affect consumers and producers in different ways in each country. Figure 2.3 below illustrates a model of international trade for a crop. In this model, the world market price is greater than the domestic market price of country A at local equilibrium. The firms would produce Qa quantity while people would consume Xa (Xa < Qa). The difference between quantity produced and consumed, Qa-Xa, would be exported. In the case of country B, the domestic market price is greater than the world price. Then the consumers would demand a higher quantity Xb, while the companies would produce less. Thus, B will need to import Xb-Qb units in order to respond to the national demand.

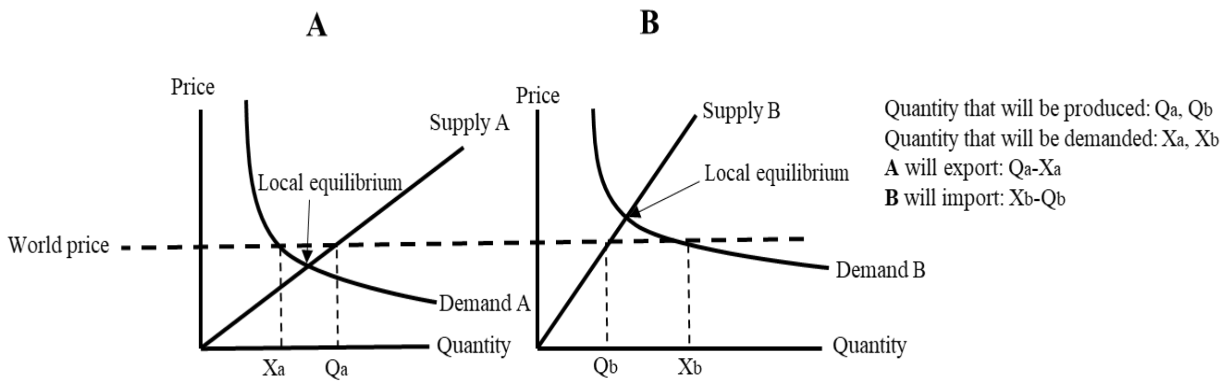


Figure 2. 3. Illustrative schema of international trade model

Like in the previous model of a closed market, the decline of pollinators increases production costs, which increase in turn the domestic and international price of a pollinator-dependent crop under consideration. The contrast is that an importing country can decide to decrease its supply and increase its imports if the import price is lower than the domestic price for that crop. In that respect, the loss in consumer surplus can be reduced. On the other hand, despite the increase of production costs, an exporting country can decide to increase its supply to increase its export if export price is higher than domestic price for that crop, and thus increase its production surplus. Therefore, the impacts of the decline of pollinators on the social welfare loss are ambiguous when we consider an open market case (see Kevan and Phillips, 2001).

However, a more complex model of analysis would integrate simultaneously the case of various crops and international trade. Thus, two important considerations in an analysis of impacts of insect pollination services' decline can be: the international trade of various crops and the substitutability of these crops. The substitutability is the ability of economic agents (e.g. consumers, producers, etc.) to replace a good or service with another one in their preferences and so in their final consumption (or/ and production).

The substitution processes that may occur as producers and consumers adapt to the effects of a decline in pollinators can mitigate such issues. Indeed, Gallai et al. (2009) extended studies produced by previous authors who mainly focused on local levels. In their study on a global scale, Gallai et al. (2009)

demonstrated that the more consumers prefer the products depending on pollinators, the more utility they will lose, if pollinators disappear. Thus, the substitutability effect can reduce the impact of the insect pollination decline on consumer surplus if the products depending on pollinators are relatively replaced (e.g., through imports). In the same vein, Bauer and Wing (2016) suggest that replacing insect pollination services by other means of pollination can reduce the effects of pollinators decline on production, and thus on producer surplus.

To conclude this section, economic models simulating the impacts of pollinators decline on social welfare through both national and international market mechanisms show that this decline can decrease the supply of agricultural products and increase their market prices. These models depicted the impact of this decline on producer and consumer surpluses for a country. Their results show that in all cases, whether in a closed market or for internationally traded agricultural products, consumers may lose in welfare if pollinators decline because of an increase in either local or world price. This may not be the case for producers who can adapt their production and avoid such loss. Indeed, impacts of this decline on producers can depend on different factors, including the relative increase in world prices against the relative decrease of pollinators at the producers' spatial scale, relative increase in alternative pollination service costs, or the ability of a producer to replace pollinator-dependent crops with non-pollinator dependent crops (Bauer and Wing, 2016), etc. These models also suggest that if consumers and producers replace a pollinator-dependent crop (and/or insect pollination services) with another one (e.g., alternative local crops or imported products) in their preferences and so in their final consumption (and/or production), pollinators decline effects can be mitigated.

However, as mentioned in the introduction, ecological and agronomic scientists present insect pollination services as an element that contributes not only to the quantity of crop production but also to nutritional quality of the crop produced (see Eilers et al., 2011; Chaplin-Kramer et al., 2014; Ellis et al., 2015). In other words, the decline of pollinators has two bold negative consequences on the quantity and nutritional quality of crops grown and consumed around the world, thereby accentuating negative consequences on the consumer side. First, consumer surplus will continue to decrease as consumer demand decreases due to price increases resulting from pollination decline. Then, the decline of pollinators can also lead to substitution processes as producers and consumers adapt to it, which may accentuate the issue of deficiency in crop nutrient consumption as mentioned in the introduction. Hence, this decline has negative consequences on both social welfare and food security. Yet, the potential losses of nutrients embedded in the pollinator-dependent crops that may be triggered by this decline are not, previously, captured in the economic models.

This gap fed our motivation to propose a new approach to integrate the impacts of pollinators decline on human well-being in economic valuation of pollination through international trade on a global scale, which we describe in the following sections.

2.2.5. Capturing nutrient elements into economic simulation of pollinators decline impacts on human well-being: A way towards a new valuation approach?

Overall, the above literature review on the benefits of ecosystem services generated by pollinators to international trade shows that their decline can decrease the supply of agricultural products and increase their market prices. Such consequences are part of the reasons why the issue of pollinators decline should be considered in the mechanisms of international trade as well as environmental and trade policies at the global scale. In that respect, we propose an analytical approach that considers the dependence of countries on insect pollination services not only in terms of agricultural production but also in terms of consumption of nutritious food through the mechanisms of international trade. This approach is made possible thanks to the other fields of studies (agronomy, biology, ecology, etc.) that provide the ratios of dependence of agricultural production on insect pollination (e.g., Klein et al., 2007) and nutrients contained in crops (e.g., Chaplin-Kramer et al., 2014). The work of other fields of studies does indeed provide experimental results that offer economists the possibility of estimating, to some extent, the monetary and nutritional values of insect pollination services. In spite of these advances, however, it is important to recognize that the application of experimental results on a global scale can be limited.

The main limitations of the data linking insect pollination to quantity and nutritional quality of the yield of crops at a global scale, as found in the aforementioned literature that we used, are fourfold. First, the data available on nutrient ratios in crops are homogeneous and generalized to all countries while in reality nutrients contents in a crop may be different depending on the crop varieties and national soil, climate characteristics, etc. (Eilers et al., 2011; Ellis et al., 2015). Second, some countries consume, importantly, local indigenous crops, which are indeed nutritious (Gemmill-Herren et al., 2014) but not previously captured in such studies. This restriction can distort results in the sense that it can overrate impacts of the decline of pollinators on nutrients intake in some areas of the world and underrate them in other areas given the local crop species and particularities. Third, the data available on the pollinator-dependence ratios at the world level are homogeneous across countries; this is not true in reality given the environmental, species, and other differences. Finally, the dependence of some crops on pollinators is still unknown - for example, on the African continent in general, there are edible native crops, such as African eggplant (Solanum macrocarpon and Solanum gilo), that are dependent on pollinators, but their dependence ratio is still unknown (Gemmill-Herren et al., 2014). We will come back on these particularities of the only data available concerning our enquiry later in our discussion section.

In the next section, we present our economic model simulating pollinators decline impacts on global social welfare.

2.3. An international agricultural trade model simulating the impacts of pollinators decline on social welfare

To model an international agricultural trade considering the decline of pollinators, we combine Gallai et al. (2009)'s bio-economic model and the international trade model integrating pollination services as expressed by Kevan and Phillips (2001) and Bauer and Wing (2016). As described in Section 2.2.4, in doing such a combination, our model can take into account the reallocation of crops (and/or their trade) between countries in the case of pollinators decline in agroecosystems. In the first place, we present the assumptions made in the structuration of our model. In the second place, we describe the simulation approach used in the development of our model. Then, we present the structure of our model. Finally, we present the data necessary for this analysis and where we have collected them.

2.3.1. Defining our model assumptions

Given that we propose to simulate the international markets of crops rooted in very diverse contexts, some simplifications are necessary. We propose a theoretical model based on the following assumptions:

Assumption 1: Our analysis refers to free trade mechanisms and the market considered combines national and international markets of edible crops.

Assumption 2: All crops that are produced are assumed to be consumed somewhere in the world in the same year and transport costs are not integrated into the model, which implies that there are no stocks because the markets are cleared in the period.

Assumption 3: Our model supposes that each crop is sold at the same world price whether on the national or the international market.

Assumption 4: In this exercise, only crops for which pollinator visits contribute to produce crops that are consumed by humans are attributed a level of "dependence on pollinators" greater than zero. In Klein et al. (2007)'s results, from which we base our analysis, the dependence of a crop on insect pollination services is represented by three ratios, including its minimum, average, and maximum dependence ratios. For simplicity, however, in our model, we use one ratio among those three. Specifically, we use average ratios of the dependence of a crop on insects, say D, as calculated by Klein et al. (2007). The pollinator dependence ratio concept expresses the vulnerability level of a crop to insect pollination services (see Chapter 1, Section 1.2.3).

2.3.2. Simulation of pollinators decline using economic modeling approach

To analyze empirically the incidences of pollinators decline on international trade, firstly, the partial equilibrium approach which we use in our analysis is defined, then scenarios simulating the decline of pollination services generated by insect pollinators are defined, and lastly, an international trade model is developed.

a) The partial equilibrium approach

In this analysis, we only consider production and trade of crops in a partial equilibrium context. The partial equilibrium approach takes into consideration only a part of the market mechanism, the prices of all complements and substitutes, as well as income levels of consumption are assumed to be exogenously determined and constant. Specifically, the partial equilibrium, prices and quantities, of a specified good or service market is obtained regardless of other products markets. It is worth noting that partial equilibrium modeling is appropriate for empirical analysis in the trade and environment context (Krutilla, 1999, Ch. 27 and Ulph, 1999, Ch. 29). As Krutilla (1999) points out: "In the trade and environment context, partial equilibrium models are particularly useful: [1] for studying the consequences of terms of trade effects; [2] and for indicating how much factors such as a country's commodity trade balance, and the type of the externality problem, affect the normative properties of environmental policy action."

Thus, a partial equilibrium approach, which focuses on the trade of crops, indicates consequences specific to marginal changes in insect pollination services, which can support policy actions towards pollinator decline issues. However, this kind of modeling is not sufficient to determine in which crops a country would specialize in. Nevertheless, this is beyond the scope of this thesis.

To analyze possible consequences of the decline of pollinators and then their pollination services in the future, we propose to use scenarios, which we define in the following section.

b) The scenarios

The red list assessment of the International Union for Conservation of Nature (IUCN) indicates that around 40% of world bee species are threatened while the levels of the decline of other insect pollinator species are re-evaluated (IPBES, 2016), but not yet well identified. In the sense that pollinators decline concerns managed bees, wild bees, and other insects and is not yet well understood all over the world, the design of the scenarios of pollinators decline is needed for simulation. On the one hand, we assume this decline to be on a global scale. On the other hand, we assume the decline from a lower to higher density of pollinators and depict different possibilities. To represent the level of the decline in density of pollinators we use α. In the first place, we create a scenario that depicts $\alpha=0$, which may refer to the current situation as a no decline (0%). Then, we create scenarios that represent both $\alpha= 0.05$, for a small level of pollinators decline (5%), and $\alpha= 0.5$, for a half level of pollinators decline (50%). And finally, we create a scenario that depicts $\alpha=1$ for the total extinction of pollinators in the agro-ecosystems (100%).

Thereafter, we develop an economic model that can represent the link between the decline of these pollinators and the level of social welfare at a global scale by considering the flows of crops across the borders of different countries through international trade.

c) **The structure of the model**

Analytically, we mobilize the international trade model of crops integrating pollination services as in Kevan and Phillips (2001) and Bauer and Wing (2016). Specifically, this model consists of the supply and demand curves reflecting the quantity (Q) and price (p) of crops exchanged on an international market in a partial equilibrium context (see, e.g., Figure 2.3, Section 2.2.4). As in most economic valuations of insect pollination services including Bauer and Wing (2016); Lautenbach et al. (2012) and Gallai et al. (2009), we assumed that the production of each crop j exchanged, where $j \in [1; J]$, have a certain level of positive synergy with insect pollinator visits. Following Gallai et al. (2009)'s bio-economic model associating pollinators to crop j production, using pollinator dependence ratio $D_j \in [0; 1]$ from Klein et al. (2007), any level of the decline of insect pollinators $\boldsymbol{\alpha}$ results in a variation from the total (100%) volume of output of crop j, say Q_j, to $(1 - \alpha D_j)Q_j$. This variation in the volume of output of crop j will have repercussions in nutritional quality consumption (e.g., Eilers et al., 2011), if nutrients contained in crop j consumption (X_j) are not relatively replaced as consumers adapt to the effects of the decline of pollinators. Using different nutrient ratios contained in a crop j (found in Chaplin-Kramer et al., 2014), the loss in each nutrient intake that may result in any $\boldsymbol{\alpha}$ level of the decline of insect pollinators equals $Nutrient\ ratio_j * \Delta X_{j;\,(\alpha \in [0;\,1]\ )}$.

To make the analyses clearer and more geographically specific, we first gathered all world countries in 22 sub-regions and accounted 121 best-known crops for human consumption based on FAO classification as in Gallai et al. (2009) and Bauer and Wing (2016) (See appendix 2.1 for more details on the sub-regions). The aggregated production function of each sub-region is the sum of the quantities of a variety of crops produced within the considered sub-region. Thus, we assume that a sub-region is represented by one firm whose production is the sum of the countries' crops production within the same sub-region. Note that, in that respect, a sub-region is not specialized initially in production of a specific crop. The same for the demand side, for which we assume that a sub-region is represented by one consumer whose demand is the sum of the crop demands of countries within the same sub-region. The aggregated demand function is the result of the sum of the quantities of a variety of crops consumed which maximize the utility of each country in the considered sub-region. Based on aggregated production and consumption demand for each sub-region, we theoretically determine market price at the equilibrium allowing us to define its supply function for the producers' side and a demand function for the consumers' side.

Based on this set of criteria, we were able to structure the theoretical demand and supply at: i) the sub-regional scale and ii) on a global scale as follows.

i) The theoretical sub-regional demand and supply

For the producers' side, each sub-region i is represented by a supply Q_{ij} of a crop j whose production requires total production costs including fixed costs and variable costs. The profit function of the sub-region i for the crop j can hence be written as follows:

$$\Pi_{ij} = p_{ij} * (1 - \alpha D_j) Q_{ij} - \frac{a_{ij} Q_{ij}^2}{2} - Fixed\ costs \quad (1)$$

Where:

- When D_j, tends to 0, the crop does not depend on pollinators and when D tends to 1, the crop depends highly on pollinators.
- When α tends to 1, it means that pollinators are declining. When α = 1, it means that pollinators are totally extinct.
- P_{ij} is the price of crop ***j*** in the sub-region ***i***.
- The index ***a*** stands for an adjustment index, namely the price competitiveness index, which characterizes a sub-region and corresponds to characteristics of macroeconomic aspects. For example, a general level of wages in countries inside each sub-region. In addition, this index can represent information about the general cost of living or social or environmental protection in a country. In our case, for example, it may represent more or less restrictive regulation on the use of phytosanitary products. All these characteristics are in general different between the various countries. Therefore, they have an influence on the marginal and average costs, and thus on the competitiveness of the farms inside each sub-region. The marginal cost of production is thus adjusted as follows, $Cm = a_{ij} Q_{ij}$.

Sub-regions maximize their profit by equalizing the marginal cost and the price, p_{ij}. As a result, the supply function of the sub-region *i* is the following (see mathematical details in appendix 2.2):

$$p_{ij} = \frac{a_{ij} Q_{ij}}{1 - \alpha_i D_j} \quad (2)$$

As for the consumers' side, the demand function is the result of the maximization of the utility of a sub-region under the revenue constraint of this sub-region. To define the demand function of the sub-region *i*, the preferences of each sub-region can be represented by a Cobb-Douglass utility function. We suppose that this Cobb-Douglas function is a function of the quantities of the crops consumed in this sub-region. It implies the characterization of preferences relations and substitution[14]. For simplicity, we assume that preferences of sub-region *i* for all crops available are the same. As a result, each sub-region *i* spends the same fraction of his budget on each crop *j*. Hence, the utility of sub-region *i* depends on the consumption level of all the *k* crops demanded amongst all crops available on our international market, say $k \in j:\{1, 2, 3, \ldots, 121\}$. Thus, the utility function for the sub-region *i* can be written as follows:

$$U_i = x_{i1}^{\frac{1}{k}} * \ldots * x_{ij}^{\frac{1}{k}} \text{, with } \sum \frac{1}{k} = 1 \quad (3)$$

Where $x_{i,j}$ is the consumption of the crop *j* in the sub-region *i* and, since the sub-region *i* preferences for all crops are the same, the constant 1/k is the same for all *k* crops demanded.

[14]In our case, it allows us to represent how the sub-region *i* chooses among a number of competing alternatives (domestic and imported) crops that are available on the international market.

A sub-region *i* maximizes its utility under the budget constraint, R_i, denoted as:

$$R_i = \sum_1^{Kj} p_{i,j} x_{i,j} \ .$$

The optimization problem results in the following sub-region *i* demand function (see mathematical details in appendix 2.2):

$$x_{ij}(p, R) = \frac{R_i}{k_j * p_{ij}} \quad (4)$$

ii) The world supply and demand

Our model represents the world market price for each crop *j* at the world equilibrium $(p_{w,j*})$[15], (i.e., as in Section 2.2.4, see Figure 2.3). To determine the world market equilibrium we aggregate the demand and supply of countries in the following three steps (adapted from Kevan et al., 2001).

First, we find the theoretical sub-regional demand and supply at the market equilibrium of crop *j* and its corresponding price at that market (see Appendix 2.2 for mathematical details).

Second, the world supply and demand equilibrium is identified as follows:

The world supply of crop *j*, denoted Q_{wj^*}, is the sum of the sub-regional supplies of this crop, where N_j is the number of sub-regions that produce the crop *j*. This global supply of crop *j* at the equilibrium is approximated as:

$$Q_{wj^*}(p, a) = \sum_1^{Nj} Q_{ij^*}(p, a), \text{ where } p_{ij^*} = \ p_{wj^*}. \quad (5)$$

The world demand, denoted X_{wj^*}, is an aggregate of the sub-regional demands for the crop *j*. The global demand of crop *j* at the equilibrium is calculated as follows:

$$X_{wj^*}(p, R) = \sum_1^{Nj} x_{ij^*}(p, R). \text{ Where } p_{ij^*} = p_{wj^*}. \quad (6)$$

The price competitiveness index $\boldsymbol{a_{ij}}$ of each sub-region ***i*** for crop ***j*** is then calculated. We assume that $aij = aij;_{\alpha=0}$= constant as the characteristics of macroeconomic aspects remain constant while pollinators are declining in our partial equilibrium model. Thus, $(1 - \alpha_i D_j) = 1 \ where \ \alpha_i = 0$ as a result the index $\boldsymbol{a_{ij}}$ is expressed as follows:

$$aij(R, Q, D) = \frac{R_i}{ki * Q_{ij^*}{}^2} \text{ , with } Q_{ij^*} = x_{ij^*} \quad (7)$$

Finally, the equilibrium world price for each crop ***j*** was derived from world supply and world demand of this crop at the world market equilibrium. The world price p_{wj*} is thus approximated as following (see Appendix 2.2 for mathematical details):

[15] At the world supply and demand level, we will use stars* on *j* indice to specify that crop quantities are at the sub-regional equilibrium.

$$p_{w,j*}, (D, R, \alpha) = \sqrt{\frac{\sum \frac{R_i}{Nj}}{(1-\alpha D_j)\sum_{j=1}^{Nj} \frac{1}{a_{ij^*}}}} \quad (8)$$

Referring to equation (8), we can deduce that in a global tendency of pollinating insect extinction (when α tends to 1) the crops with a greater dependence on pollinators (D_j) will see their world market price rising. Also, due to this decline, the supply curve of crop *j* will shift inward – meaning that the crop *j* production volume will decrease (see Figure 2.4 below).

As a result, consequences of pollinators decline can be felt in two ways that we will build on in our measurements. On the one hand, the consequence will be measured in terms of producer and consumer surpluses change and thus in economic social welfare (SW) where SW is the sum of producer surplus (PS) and consumer surplus (CS). On the other hand, the consequence will be measured in terms of nutrients embedded in food crops. Indeed, as mentioned earlier, in this study, we propose to go further in evaluating this decline's consequences in terms of nutrient loss.

1) Consequences of pollinators decline in terms of producer and consumer surpluses

The developed model aims to simulate the social welfare variations with declining pollinator services specifically on a global scale. The measure of the social welfare variation (ΔSW) is the difference between the SW at α≠0 and the one at α=0. For instance, $\Delta SW = SW_{\alpha=1} - SW_{\alpha=0}$. When $\Delta SW > 0$, there is a gain in social welfare and a loss when $\Delta SW < 0$. Figure 2.4 represents the ΔSW following the shift from the initial supply function to the new one due to the decrease in the level of the density of pollinators α. The new and initial supply curves are linear functions (see mathematical detail in appendix 2.2).

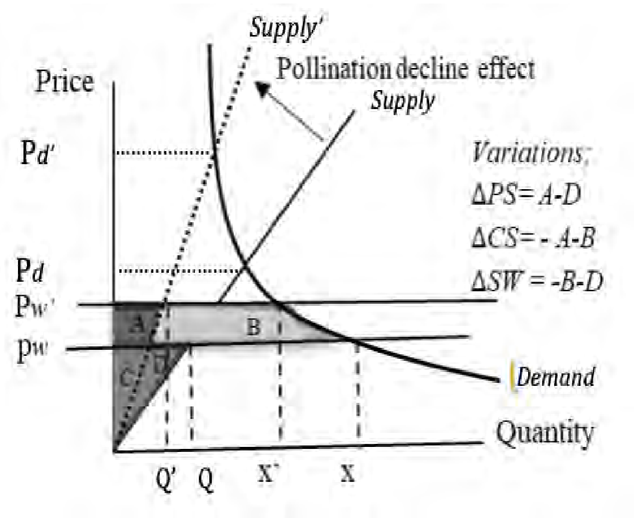


Figure2.4. Impact of insect pollination service decline on a global scale in the social welfare variation for an importing sub-region

Source: adapted from Kevan and Phillips (2001)

> This figure illustrates impacts of pollination services decline in crop supplies as a shock in production, which shifts the supply curve of a sub-region inward. As a result, supply and demand at the new equilibrium go downward. The sub-region's supply decreases from Q to Q' and demand decreases from X to X'. However, impacts are different for importing and exporting sub-regions. For illustration purposes, this figure shows impacts in a sub-region where domestic price $P_d > P_w$, thus an importing sub-region (as illustrated by figure 2.3 before in the case of B, in Section 2.2.4). In this example, variations in producer and consumer surpluses are ΔPS= A-D and ΔCS= - A-B, as a result the variation of social welfare is $\Delta SW = -B - D$.

2) Consequences of pollinators decline in terms of nutrient loss

Impacts on the sub-regional demand of crops may also induce changes in the consumption of food rich in micronutrients in the different countries around the world. As noted in the introduction of this chapter, this issue came to our attention because pollinator decline would exacerbate micronutrient deficiencies worldwide, while the prevalence of malnutrition remains high in some sub-regions (Chaplin-Kramer et al., 2014). Therefore, we simulate the impact of this decline on malnutrition based on the variation in crop demand, by incorporating in our model the related ratio of nutrients contained in crop consumption. This is possible because food products contain different quantities of nutrients allowing us to measure the overall quantity of each nutrient consumed in a crop. Thanks to Chaplin-Kramer et al.'s (2014) data on different amounts of nutrient components in each edible crop (such as vitamin A, vitamin C, vitamin B6, iron, folate, protein, etc.); we estimate the variations of each nutrient component in crop consumption as pollinators decline. The nutrient ratio stands for a portion of the amount of a nutrient in a given volume of a crop in their respective units. For example, 100 g of apple fruit contains 4.6 mg of vitamin C and 54 international units (IU) of vitamin A, etc.

In that respect, we match the consumption of each crop *j* in sub-region *i* at the world equilibrium, X_{ij^*}; with its corresponding $Nutrient\ ratio_{j^*}$, to simulate the variation of nutritional quality consumption of this crop in that sub-region assuming a level of global pollination decline represented by the parameter

α (as defined above in this Section 2.3.2, Scenario). For more clarity, we quantify the amounts of each nutrient in all consumed crops per capita given the sub-region population. This implies that at a level α of the decline in density of pollinators, per capita nutritional quality consumption in crop j in the sub-region i, denoted $Nutrient\ intake_{ij^*;(\alpha)}$, can be expressed as follows:

$$Nutrient\ intake_{ij^*;(\alpha)}(per\ capita) = \frac{Nutrient\ ratio_{j^*}\, X_{ij^*;(\alpha)}}{Population_i} \tag{9}$$

To estimate the variation in nutrient intake ($\Delta\ Nutrient\ intake\ _{ij^*}$), we assume the difference between the $Nutrient\ intake_{ij^*}$ at any level of the decline in density of pollinators when $\alpha \neq 0$ to the $Nutrient\ intake_{ij^*}$ at a situation of no decline when $\alpha = 0$.

Based on above mathematical expressions, summarized in table 2.1 below, necessary data were identified and then collected. Next, we present the sources of data used in our analysis.

Table 2. 1. A synthesis of mathematical expressions in the international trade model

Variable or parameter	Mathematical expression
Domestic Demand	$x_{ij}(p,R) = \dfrac{R_i}{k_j * p_{ij}}$
Domestic Supply	$Q_{ij} = (1-\alpha_i D_j)\dfrac{p_{ij}}{a_{ij}}$
Adjustment index	$aij(R,Q,D) = \dfrac{R_i}{ki * {Q^*_{ij}}^2}$
World Supply	$Q_{wj^*}(p,a) = \sum_1^{Nj} Q_{ij^*}(p,a)$
World Demand	$X_{wj^*}(p,R) = \sum_1^{Nj} X_{ij^*}(p,R)$
World Price	$p_{w,j*,}(D,R,\alpha) = \sqrt{\dfrac{\sum \frac{R_i}{Nj}}{(1-\alpha D_j)\sum_{j=1}^{Nj}\frac{1}{a_{ij^*}}}}$
Trade balance value	$Trade\ balance\ value_{ij} = ({Q_{ij}}^* - {X_{ij}}^*)P_{wj*}$
Nutrient intake	$Nutrient\ intake_{ij^*;(\alpha)}(per\ capita) = \dfrac{Nutrient\ ratio_{j^*}\, X_{ij^*;(\alpha)}}{Population_i}$, $\Delta\ Nutrient\ intake\ _{ij^*} = N.intake_{ij^*;(\alpha=0)} - N.intake_{ij^*;(\alpha-1)}$

2.3.4. Data collection

To quantify the impacts of the decline of insect pollination services on food production and consumption on human well-being in each world sub-region, some data were necessary. The data collected cover crop production quantities, the population of countries, the budget that countries allocated on foodstuffs, crop dependency ratios to pollinators, and ratios of some nutrients contained in crops. Likewise, to depict more clearly impact of this decline on food security given the current level of malnutrition in some sub-regions, as mentioned in the introduction, we also propose to plot the distribution of malnutrition prevalence in the world relative to simulated pollinators decline impacts on nutrient intake. Hence, malnutrition prevalence data of each country were collected.

For a matter of data homogeneity, most of these data were mainly collected from most known official and reliable world databases (See Table 2.1 below). Specifically, as Table 2.2 below summarizes, we used three categories of data and inputs including official data, data from the literature, and also our own chosen scenarios assuming different levels of pollinators decline.

Concerning sub-regions data, data were collected in the 193 FAO member countries, which are aggregated in 22 sub-regions following FAO classification. We used 2010 data (http://faostat.fao.org/) since they were the most completed at the time of our data collection. The data on the volume of crops produced in each country as well as on the population of each country are collected from FAOSTAT. For the budget constraint data, we estimated it through the revenue spent exclusively on food and beverages in each country. These revenues were primarily collected from the World Bank database, and were aggregated at sub-region level. Furthermore, data on the prevalence of malnutrition were collected from FAOSTAT to highlight the actual nutritional needs of the population in different countries and sub-regions.

Concerning crops data, our analysis includes 121 best-known crops for human consumption and, for clarity purposes in the presentation of our simulation results, these crops will be assembled into 10 crop categories as in Gallai et al. (2009) and Bauer and Wing (2016). The crop dependence ratios on pollinators are collected from the paper of Klein et al. (2007). They are available in the Tool for Valuation of Pollination Services on http://www.fao.org/pollination/resources/pollination-assessment/economic-value/fr/. And data on nutrient ratios in crops that we used to measure pollinator decline impacts on per capita nutrient intake as a result of sub-region consumption variation are collected from Chaplin-Kramer et al.’s (2014) supplemental material, in xls file.

Table 2. 2. A summary of our data sources

Indicators	Units considered	Data source
	From official databases	
World	22 Sub-regions	FAO database
Crop production quantity	121 Edible crops in metric tons	FAO database
Budget	Revenue spent on food and beverages in US dollar	World Bank database, Eurostat, United nation Stat database
Population	Number of people per country	FAO database
Malnutrition prevalence	%	FAO database
	From the literature	
Dependency ratio	%	Klein et al. (2007)
Nutrient components ratio	Vitamin A in IU (International Unit) and Vitamin C, Vitamin B6, Iron, Folate, and Protein in mg	Chaplin-Kramer et al. (2014)
	From our scenarios	
Density of pollinators	5%, 50% and 100% relative to current density of pollinators	Own scenario inspired by the red list assessment of the IUCN and IPBES which warned about widespread decline of pollinating insects (see IPBES, 2016)

The results presented in the next section are the simulation of the impacts of the decline of pollinators on social welfare and food security through international trade mechanisms. Specifically, we simulate three possible future scenarios under declining pollination services compared to the current situation, based on the mathematical expressions in our model above, collected data, and using the EXCEL features.

2.4. Results

Our mathematical results show that if pollination services decline, a volume of crops will be decreased on domestic and international trade. Thus, the world prices will increase as crop production decreases due to a global tendency of extinction of pollinators. Our findings show a substantial decline in consumer surplus as well as in sub-region profit as pollinators decline, and thus an overall loss in social welfare. Moreover, our results draw attention to a loss in global nutritional quality food consumption, which is particularly concerning in sub-regions where malnutrition prevalence is already at a high level.

In light of the research questions addressed in this chapter, results are organized in three parts. In the first place, we will present our results regarding the impacts of the decline of pollinators on the value of the international trade balance, say $\left(Q_{ij}{}^{*} - X_{ij}{}^{*}\right) P_{wj*}$. As noted earlier, the analytical results of Kevan and Phillips (2001) indicate that even though some countries would lose in terms of producer surplus, other countries would gain relative to the increase in prices (Section 2.2.4, Figure 2.2). In contrast, our results show that all sub-regions may lose and their trade balance values may decrease in all scenarios of the decline of pollinators. Through trade balance values, we highlighted the dependence of countries to the decline of pollinators not only subject to their specialization in the production of pollinator-dependent crops, but also in terms of their demand for such crops.

In the second place, we will analyze the impact of this decline on the relative price effects, and then on social welfare. Kevan and Phillips (2001) showed that consumers could lose out on a global scale due to price increases that may be associated with the decline of insect pollination, but the impact of this decline on food consumption considering the ability of consumers to replace a good with another one was not addressed. Our results also support that the decline of pollinators would decrease consumer surplus (CS) of sub-regions all around the world while considering substitution among domestic and imported crops.

Lastly, this study stresses on the potential loss of nutrients from pollinator-dependent crops that may be triggered by this decline. Thus, we will show the consequences of pollinators decline on nutrients consumption which is what other studies that integrate international trade mechanisms have not considered so far.

As a reminder, in our simulations we create scenarios that depict the current situation as a no decline (0%), which we refer to as α=0, then, we create scenarios that represent both α= 0.05, for a small level of pollinators decline (5%), and α= 0.5, for a half level of pollinators decline (50%). And also, we create a scenario that depicts α=1 for the total extinction of pollinators in the agro-ecosystems (100%). On the other hand, as stated above in Section 2.3.2, the dependency ratio of a crop on pollinators (D) is between 0 and 1. When D tends to 0, the crop does not depend on pollinators while when D tends to 1, the crop depends highly on the pollinators.

2.4.1. The impacts of pollinators decline on international trade

Our findings, summarized in Tables 2.3 (a and b) below, show that 11 out of 22 sub-regions are the net importers (those with negative sign in tables) of pollinator-dependent crops: all four European sub-regions (Northern, Southern, Eastern, and Western), Northern America and the Caribbean, Southern (except for fruits) and Middle Africa, Eastern, Western (except for oil crops and tree nuts), and Southern-eastern Asia. The rest of the regions of the world are all net exporters (those with positive sign) of pollinator-dependent crops. Although sub-regions play different roles in this market, the decline of insect pollination services, under our model assumptions, yield an overall decrease in the value of international trade of edible crops, i.e. $Trade\ balance\ value_{ij} = ({Q_{ij}}^{*} - {X_{ij}}^{*})P_{wj*}$, at a global scale. Specifically, the level of this decrease in trade balance value is greater than the level of the decline in the density of pollinators in all scenarios studied (Table 2.3.a, Table 2.3.b). In doing so, we take the partial equilibrium analysis of Bauer and Wing (2016) a step further by adding impacts of the decline of pollinators not only on the producer and consumer sides but also on crops trade balance values for countries.

Our model approximated 14.7% of loss on average in crop trade value if pollinators became totally extinct. However, the trade values vary heterogeneously, whether in the sub-regions or the crop categories. The trade balance values of some crop categories may increase (see table 2.3.a). For example, our simulation shows that the import value of vegetables may increase drastically if pollinators are extinct. This may especially be the case on vegetable import in Middle Africa where our results approximate up to a 7 billion US $ increase in the trade balance. On the other hand, the value of vegetable exports of Eastern Asia and Northern Africa would increase (see details in Table 2.3.a). Moreover, the export value may increase for Southern Africa's fruits, for edible oil crops from Southern Europe and Western Asia and Northern Africa, and for tree nuts from Central America, Eastern Africa, and Western Asia. Some sub-regions may lose almost half of their total trade balance values; this is the case of Western Africa and South-Eastern Asia. On the other hand, trade balance values of sub-regions such as Western Europe and North America (see Table 2.3.b) slightly vary. Such a slight change may reflect the fact that the budget of these sub-regions are relatively high enough to be significantly constrained by the price increase caused by the decline of pollinators (see, e.g., Eq. 4 in Section 2.3.2), meaning that high-income level may attenuate the effects of the decline for importing sub-regions.

Table 2. 3. Trade balance value (Billion US$)

a. Trade balance value (Billion US$) before and after pollinator's total extinction

Subregion	Fruits		Oil crops		Pulse		Spices		Stimulants		Tree nuts		Vegetables	
Eastern Africa	-18	-12	-5	-4	22	16	42	6	3	3	13	**14**	-16	-13
Middle Africa	-11	-7	-4	-3	-3	-3	-3	-3	1	0	-3	-2	**0**	**-7**
Northern Africa	53	43	0	**1**	19	15	48	48	-4	-3	-6	-4	19	**21**
Southern Africa	2	**4**	-2	-2	-2	-2	-2	-2	-1	-1	-1	0	-5	-4
Western Africa	-18	-10	52	39	48	48	-4	-4	99	**19**	22	**5**	37	**-4**
AFRICA	8	19	41	32	84	75	81	47	98	18	25	12	34	-6
Caribbean	-8	-5	-5	-4	-4	-3	-3	-3	-2	-1	-3	-2	-9	-8
Central America	59	35	-4	-3	1	1	7	7	6	5	9	**10**	-4	-2
Northern America	-56	-69	-26	-26	-6	-5	-48	-42	-30	-19	-43	-32	-139	-111
South America	-11	-15	-31	-27	-24	-23	-22	-19	69	67	28	-15	-8	5
AMERICA	-16	-53	-66	-60	-32	-30	-66	-57	44	52	-9	-39	-160	-115
Central Asia	9	0	6	6	-4	-4	-3	-3	-2	-1	-3	-2	-2	-2
Eastern Asia	-407	-281	-249	-215	-186	-181	-176	-155	-110	-69	-112	-83	42	**51**
South-Eastern Asia	-42	-18	-5	-6	-15	-14	60	55	1	0	2	0	-45	-35
Southern Asia	717	517	322	277	230	225	234	231	53	53	174	157	447	363
Western Asia	-33	-24	10	**14**	-20	-19	-20	-17	-12	-8	34	**39**	-45	-34
ASIA	244	194	85	77	5	8	94	111	-70	-25	94	110	397	343
Eastern Europe	-25	-15	6	2	-33	-32	-35	-31	-22	-14	-35	-27	-74	-72
Northern Europe	-61	-38	-21	-18	-16	-15	-15	-13	-9	-6	-15	-11	-43	-35
Southern Europe	-40	-29	8	**13**	-28	-26	-25	-22	-16	-10	-23	-17	-42	-27
Western Europe	-113	-66	-46	-40	-31	-29	-34	-29	-21	-13	-34	-26	-97	-78
EUROPE	-239	-148	-52	-42	-107	-103	-109	-95	-68	-43	-107	-81	-257	-212
Australia & New Zealand	0	-11	-7	-6	51	50	-5	-4	-3	-2	-3	-1	-11	-8
Melanesia	3	0	0	-1	-1	-1	2	-1	0	0	-1	0	-2	-2
Micronesia	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Polynesia	-1	0	0	0	0	0	4	0	0	0	0	0	0	0
OCEANIA	2	-11	-8	-7	50	49	0	-5	-4	-2	-3	-2	-14	-11

Note: These results are based on our model ($\boldsymbol{Trade\ balance\ value_{ij}} = (\boldsymbol{Q_{ij}}^{*} - \boldsymbol{X_{ij}}^{*})\boldsymbol{P_{wj*}}$) and FAOSTAT production data in 2010. Bold figures in grey represent increases in trade balance values, which are exceptions, and bold figures in black represent the important decreases in trade balance values.

b. The average trade balance value (billion US$) in different scenarios of pollinators decline based on our model among the 22 sub-regions of the world

		Scenarios of pollination service declines			
Region	**Sub-region**	***Current***	***- 5%***	***- 50%***	***- 100%***
AFRICA	Eastern Africa	41	40	33	17
	Middle Africa	-23	-23	-24	-25
	Northern Africa	129	129	128	127
	Southern Africa	-11	-11	-10	-8
	Western Africa	236	233	196	131
Total Africa		**372**	**368**	**323**	**241**
AMERICA	Caribbean	-33	-33	-31	-29
	Central America	75	74	69	62
	Northern America	-348	-347	-335	-312
	South America	1	0	-7	-23
Total America		**-306**	**-306**	**-305**	**-301**
ASIA	Central Asia	1	0	-1	-3
	Eastern Asia	-1198	-1192	-1125	-1022
	South-Eastern Asia	-43	-43	-36	-26
	Southern Asia	2177	2168	2080	1949
	Western Asia	-86	-86	-76	-61
Total Asia		**849**	**849**	**841**	**836**
EUROPE	Eastern Europe	-219	-218	-210	-193
	Northern Europe	-179	-178	-167	-150
	Southern Europe	-165	-164	-152	-134
	Western Europe	-375	-372	-349	-311
Total Europe		**-938**	**-933**	**-878**	**-788**
OCEANIA	Australia & New Zealand	21	21	20	16
	Melanesia	0	0	-1	-3
	Micronesia	-1	-1	-1	-1
	Polynesia	2	2	1	-1
Total Oceania		**22**	**22**	**19**	**12**

Note: These results are based on our model ($Trade\ balance\ value_{ij} = (Q_{ij}^* - X_{ij}^*)P_{wj}$) and FAOSTAT production data in 2010. And current decline of pollinators is assumed to be 0%, and the sign (-) illustrates a decline. Thus, - 100% simulates the total extinction of pollinators.

This table 2.3.b shows that the average trade balance value (billion US$) decreases progressively as pollinators decline in all different scenarios studied and in all the 22 sub-regions of the world.

2.4.2. The impacts of pollinators decline on relative market prices

Our results show that the overall world price of crops could increase up to 186% if pollinators became totally extinct, by 22% if a half of all pollinators disappear, and by 1% if 5% of the pollinator density is affected. Table 2.4.a below presents the different categories of crops, and this decline impacts on their prices, under different pollinator decline scenarios. For instance, if pollinators were to become extinct, prices may increase up to 288% for spices, 212% for tree nuts, 57% for stimulant crops, 48% for fruits, and 26% for vegetables. As a consequence, there may be a decrease in the overall demand volume of edible crops. However, the relative increase of world prices of pollinator-dependent crops could compensate for the decrease of their production and thus increase the trade balance value of a few categories of crops in some sub-regions - e.g., Tree nuts in Central America and Western Asia (see Table 2.3.a). But, as noted above, the overall trade value decreases in all sub-regions.

Table 2. 4. Pollinators decline impacts on price, consumer surplus, and producer profit

a. Percentage increase in the world prices of crops as an impact of the pollinators decline among the 10 crop categories

	Pollination service declines impact (%)		
Crop category	***-5%***	***-50%***	***-100%***
Fruits	1	15	48
Oil crops	0	1	2
Pulse	0	2	3
Spices	2	32	288
Stimulant crops	1	14	57
Tree nuts	2	24	212
Vegetables	0	4	26
Overall average	**1**	**22**	**186**

Note: These estimations are based on the Equation 8 (Section 2.3.2) and 2010 FAOSTAT data on production volume

2.4.3. The impacts of pollinators decline on consumer surplus and producer profit

Our findings highlight that consumer surplus and producer profit may substantially decrease as pollinators decline (see Table 2.4.b). Thus, in general, social welfare would suffer due to the decline of pollinators, but impacts may be felt differently in world regions and sub-regions. While the trade balance value of some European and American sub-regions is not so reduced (Table, Section), the European consumers would suffer more than other regions and the producers in all American sub-regions, as defined here, would also suffer significantly. West African producers would suffer, in particular, with a decrease in profit. The particular dependence of West African producers on insect pollination services have been explained by Bauer and Wing (2016) based on the fact that this area has specialized in the production of pollinator-dependent crops to a great extent – e.g., cocoa, which according to Klein et al. (2017) has D (the dependence ratio) = 90% in average. And for the Oceania region, producers and consumers would both be impacted negatively.

Table 2. 4. Pollinators decline impacts on price, consumer surplus, and producer profit

b. Per capita relative variation of consumer surplus and producer profit in US dollars if insect pollinators decline among the 22 sub-regions of the world

		-5%	-50%	-100%	-5%	-50%	-100%
Region	**Sub-region**	**Variation CS (US$)**			**Profit variation (US$)**		
	Eastern Africa	-1	-16	-51	-3	-34	-68
	Middle Africa	-2	-22	-71	-2	-21	-41
	Northern Africa	-3	-31	-100	-3	-34	-67
	Southern Africa	-2	-29	-94	-1	-6	-12
	Western Africa	-1	-17	-54	-13	-129	-257
AFRICA		**-2**	**-20**	**-67**	**-6**	**-59**	**-117**
	Caribbean	-6	-71	-232	-1	-15	-29
	Central America	-2	-28	-91	-6	-55	-110
	Northern America	-11	-131	-427	-7	-73	-147
	South America	-5	-55	-180	-6	-63	-125
AMERICA		**-7**	**-79**	**-257**	**-6**	**-63**	**-126**
	Central Asia	-4	-51	-166	-7	-66	-132
	Eastern Asia	-9	-106	-347	-4	-44	-89
	South-Eastern Asia	-2	-25	-82	-1	-10	-20
	Southern Asia	0	-1	-2	-5	-53	-105
	Western Asia	-7	-81	-263	-3	-26	-52
ASIA		**-4**	**-49**	**-161**	**-4**	**-42**	**-84**
	Eastern Europe	-9	-113	-369	-7	-66	-133
	Northern Europe	-11	-137	-448	0	-2	-4
	Southern Europe	-13	-154	-501	-5	-49	-98
	Western Europe	-14	-168	-548	-1	-13	-27
EUROPE		**-12**	**-139**	**-453**	**-4**	**-40**	**-81**
	Australia & New Zealand	-15	-178	-581	-18	-182	-364
	Melanesia	-7	-84	-275	-18	-185	-370
	Micronesia	-7	-83	-269	0	-4	-9
	Polynesia	-11	-139	-452	-95	-951	-1902
OCEANIA		**-13**	**-152**	**-497**	**-20**	**-198**	**-397**
WORLD		**-5**	**-59**	**-193**	**-5**	**-48**	**-96**

Note: These results relate to figure 2.4 (Section 2.3.2) and are based on 2010 FAOSTAT data on production volume

2.4.4. The impacts of pollinators decline on essential nutrients consumption

Here we present an assessment of the impact of insect pollination service declines on nutritional values and, thus, malnutrition. Specifically, we assessed the impacts of this decline on the amount of crop nutrients provision as a percentage loss of six micronutrients, including vitamin A, Vitamin C, Vitamin B6, Iron, Folate, and Protein (see Figure 2.5). Our results are built on a decrease in the demand volume of edible crops due to price increases, thereby resulting in a decrease in nutritional quality consumption. Under the total pollinator extinction scenario, our simulation shows that there could be a per capita average loss in consumption of 6.7% of vitamin A, 5.2% of vitamin C, 3.4% of iron, 2.9% of folate, 1.7% of protein, and 0.2% of vitamin B6 (Figure 2.5).

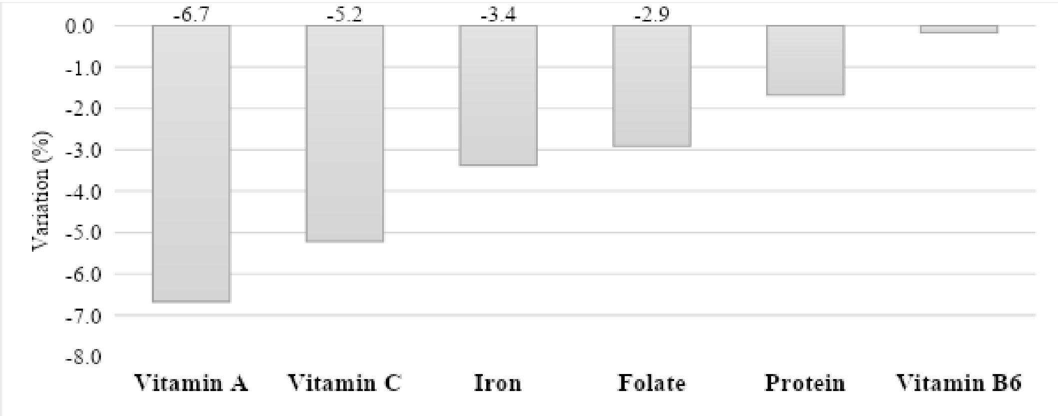
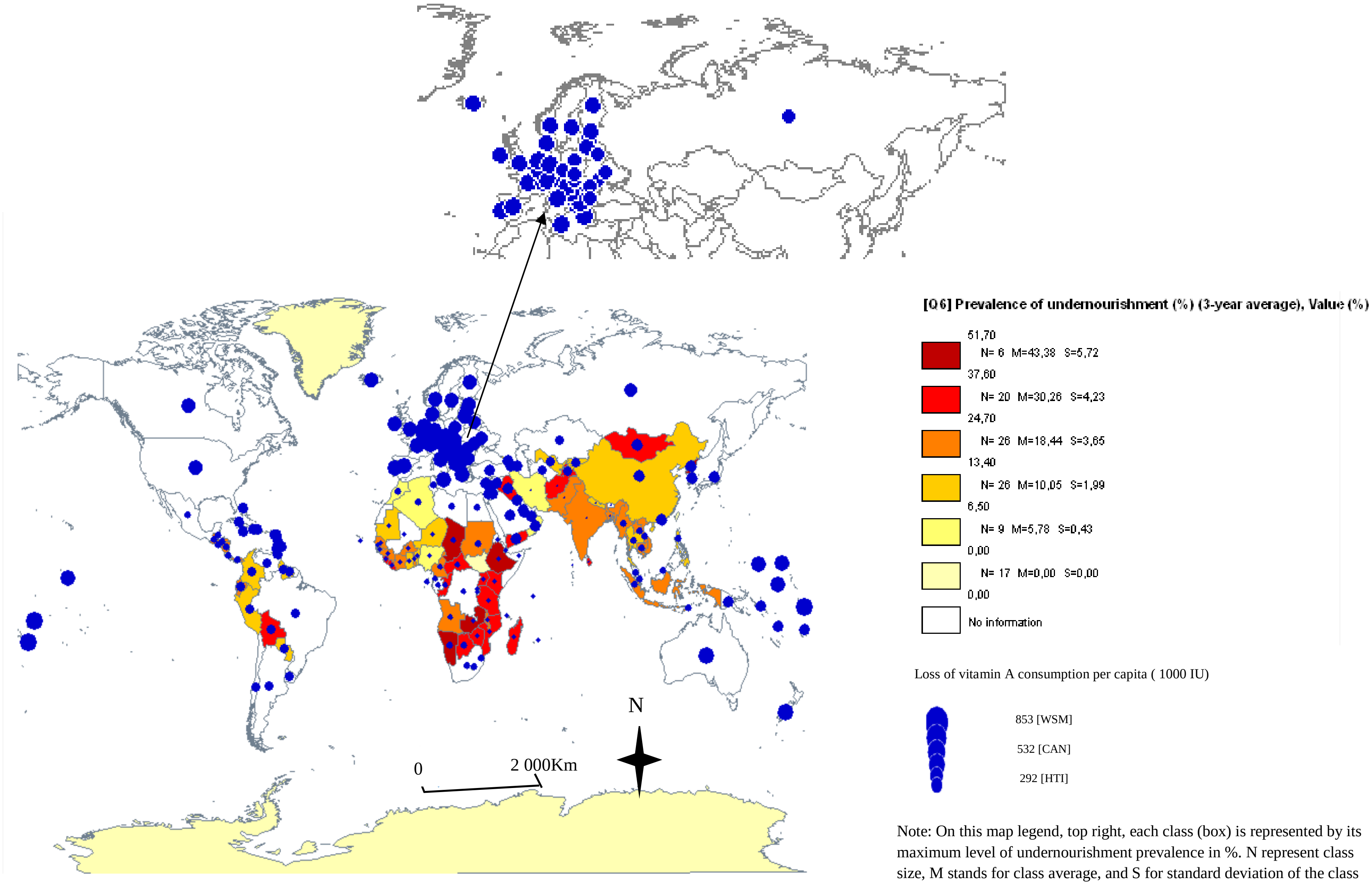


Figure 2. 5. Percentage loss in nutrient consumption per capita if pollinators are extinct

Global percentage decrease in amounts of nutrients contained in edible crops consumption per capita in the scenario representing total extinction of pollinators; based on Equation 9 (Section 2.3.2), 2010 FAOSTAT data on crop production volume and Chaplin-Kramer et al. (2014) nutrients ratio datasets.

Furthermore, it is interesting to highlight the actual undernourishment levels in the world to understand the implications of these possible future outcomes. Unsurprisingly, low levels of nutrient consumption and thus high levels of undernourishment are particularly prevalent in the sub-regions where many low-income countries are located, in “global south countries”. For instance, FAOSTAT data from 2010 shows that some countries have an alarming rate of the undernourished population including, for example, 52% of the population in Zambia, 51% of the population in Haiti, 37% of the population in Rwanda, etc.

Using spatial representation, we coupled the data of FAO that show the undernourishment prevalence worldwide and our results on changes in amounts of nutrients consumption in sub-regions, as a result of a total decline of pollinators. For illustration purposes and a matter of clarity, we focus on the case of a total decline of pollinators using vitamin A. However, note that this vitamin A nutrient is only one component of a complex synthetic indicator of nutritional quality that a crop might encompass. The map below represents two things (see Figure 2.6). First, by the contrast of colors, it illustrates the current undernourishment level in countries. Second, by blue dots of different sizes, this map locates the loss in vitamin A availability per capita (see equation 9), throughout the world, as a result of total extinction of pollinators. These dots represent the lost amounts of vitamin A in International Unit (IU) if pollinators become totally extinct.



Done with Philcarto * 1/8/2018 12:40:50 * http://philcarto.free.fr; Data source: FAOSTAT, 2010

Figure 2. 6. Loss of vitamin A consumption per capita per year in sub-regions (blue dots, 1000 IU) as a result of total extinction of pollinators in comparison to the three years average undernourishment prevalence (color contrast).

Note that the concentration of the small dots in the "global south countries" on the map does not mean that the impact of pollinators decline on the Vitamin A consumption is less important than those in northern countries. On the contrary, relative to their current state of undernourishment (see, the color contrast), this impact may be catastrophic for the food security of the population in these countries. Indeed, not only the global south countries will have less and less available food and access to food, but also this food will be of lower nutritional quality if insect pollination services decline in agricultural systems.

2.5. Discussion of the results and limitations of our model

This chapter simulated the impacts of the decline of pollinators in terms of social welfare and nutrients consumption across the world sub-regions using an international trade model. It showed that all sub-regions may be impacted by this decline in different aspects as producers and/or consumers (exporters and/or importers), and through nutritional quality consumption of crops. First, we discuss our results. Then, we discuss the limits of our theoretical and analytical model, as well as its assumptions.

i) Discussion of our findings

Our results highlighted that a decline in pollinators could increase the world market prices of pollinator-dependent crops as, locally, each farmer may suffer a marginal cost increase due to reduced insect pollination services. Based on the impacts of this decline on market prices, we measured the consequences in terms of producer profit, consumer surplus, trade balance value, and micronutrients consumption.

Our findings highlighted that the deterioration of the abundance of pollinators would decrease consumer surplus (CS) and producer profit and thus the social welfare of sub-regions all around the world. That is in line with the results of various economic studies such as Gallai et al. (2009) and Southwick and Southwick (1992) whose studies also presented the CS loss due to the decline of pollinators. Gallai et al. (2009) demonstrated that the more consumers prefer the products depending on pollinators, the more utility they will lose, if pollinators disappear. Our results show that in international trade settings, where traded products are suitable substitutes, this decline would decrease consumer surplus (CS) of all sub-regions in all scenarios studied. So far, only Bauer and Wing (2016) have analyzed, empirically, the impacts of pollinators decline on both value of lost production and consumer surplus loss on a global scale, which they found negative. But Bauer and Wing (2016) suggest that replacing insect pollination services with alternative pollination services can reduce the effects of pollinators decline on economic loss. Yet, costly alternative pollination to free pollinators will contribute to the increase of prices, which can impact consumption in every sub-region.

In this chapter, we proposed to further these previous analyses by measuring pollinator decline effects not only on the producer and consumer sides but also on the trade balance of each sub-region. Our results show that the trade value of crops may decrease under most scenarios of declining insect pollination since less pollinator-dependent crops will be traded. In doing so, we highlighted the dependence of countries to the decline of pollinators not only subject to their specialization in the production of pollinator-dependent crops but also based on their demand for those crops. These considerations are of importance because, by focusing on the trade effect on the crop sector, we indicated consequences specific to marginal changes in insect pollination services for each sub-region, which can trigger policy actions towards pollinator decline issues using international trade mechanisms or environmental and trade policies on a global scale.

Moreover, previous economic studies do not analyze the consequences of substitution processes that may occur as producers and consumers adapt to the effects of pollinators decline on micronutrient consumption. In this chapter, we focused on the impacts of pollinators decline on the provision of crop micronutrients all around the world under the total pollinator extinction scenario. Our findings show a global decrease in the availability of micronutrients provided by crops due to a decrease in the supply of pollinator-dependent crops and, thus, a relative reduction in micronutrient intake per capita in crop consumption (see Figure 2.6). For instance, around 6% in per capita global consumption for Vitamin A in crops may decrease. The decrease in insect pollination services may impact the food security of the poor and undernourished countries at a critical point given the fact that these countries spend important shares of their revenue on food; their purchasing power will be threatened by an increase in prices. For instance, to address obesity, which is a public health concern also in developed countries like the USA (Tilman et al., 2014), and hunger that is still striking in developing countries (FAO et al., 2020) a balanced diet is of utmost importance. Therefore, the decline of pollinators can potentially induce changes in food consumption habits from micronutrient supplying crops, depending on insect pollination such as fruits and vegetables, to cereals and sugar crops. This shift can increase serious diseases that lower global life expectancy (Tilman et al., 2014).

To our knowledge, an empirical study taking into consideration international trade mechanisms to analyze all together the impacts of pollinators decline on malnutrition, consumer surplus, and producer profit is new. However, many simplifications were necessary to conceptualize the world agriculture market rooted in very diverse local and country contexts. These simplifications have repercussions on our results. Therefore, some simplifications must be discussed.

ii) The limitations of our model

The main simplifications made in our methodological framework can be discussed in two ways: first, we have set severe assumptions and second, we have made important simplifications in developing theoretically and analytically our model of international trade we used.

1) The limits related to the strong assumptions underlying our model

It is necessary to note the limits of our results related to the strong assumptions underlying the model of international trade we have developed, which cannot fully reflect current realities. These assumptions are threefold.

In the first assumption, we assumed that the world crops exchange takes place in a free trade framework while, in the real market, protectionism is often applied. Thus, the effects of the declining trends of pollination services on human welfare on a global scale can be different in reality. For example, government subsidies on the crops, which is often the case in some countries (e.g., through Common Agriculture Policy in E.U., Farm Bill in U.S, etc.), can decrease the impact of pollinators decline on market prices, production, and consumption.

In the second assumption, we assumed that supply equals demand at the market equilibrium. Yet, in reality, the stocks and inventories of agricultural products are a common practice in a food chain, which can contribute to adaptation strategies to the impacts of pollinators decline within a country at least for some period. However, it should be noted that some agricultural raw products, particularly the ones that depend on pollinators (e.g., fruits and vegetables), are perishable goods. So, such crops are either not storable or they may alter their nutritional characteristics to some extent if they are stored.

In the last assumption, we assumed that crops are exchanged internationally at the same world prices. Within an imperfect, rather than a perfect, market this is not feasible. For example, crop product differentiation in terms of quality is a strategy that serves to split the market and thus sell at different prices a product (with perhaps the same nutritional values) on the different targeted markets. Furthermore, our model does not consider specific resources of sub-regions, which may imply important different production costs for different crops and, thus, price differences between varieties of crop qualities. In other words, we did not consider the real specificities of regions. For example, the price differences for Robusta and Arabica coffee varieties (World Bank, 2018). Another example is French “guariguette” strawberries (Fragaria ananassa “Guariguette”), which are produced only in some French regions, are expensive compared to other varieties of strawberry (Bosc, 2007). Thus, in reality, the market prices of strawberries, like is the case for other crops, are different in the markets. Considering these price differences would give more accurate results about the extended impacts of the decline of pollinators.

2) The important simplifications made in developing theoretically and analytically our model

The following four simplifications made in developing theoretically and analytically our international trade model should be discussed.

In the first simplification, we assumed that preferences of each sub-region for all crops available are the same which imply that each sub-region spends the same fraction of his budget on each crop. By doing so, we suppose that the elasticity of demand for each crop is the same for all available crops within a country, while in reality, it is not true. For instance, some countries produce some crops mainly for export to earn an income and import and/or produce other crop commodities for consumption. For example, Rwandan farmers produce coffee mainly for export while they buy and/or produce other local food for their consumption. Through this example one can understand that, the elasticity of demand for coffee cannot be the same for all available crops in Rwanda. Indeed, consumers do not spend their revenue equally on all crops, at least because they have different tastes. This simplification implies that the impact of a decline of pollinators on consumer surplus loss may be weaker than predicted.

For the second simplification, we assumed that consumers would not replace pollinator-dependent crops by alternative crops, which does not depend on pollination as replacing strawberries by bananas or coffee by tea. Instead, they can buy the same crops in the international market, following the Cobb-Douglas utility function. However, substitutability[16] between crop species or crop categories could represent better the adaptability of economic actors in the face of insect pollination declines. Unfortunately, we do not have the necessary data to integrate the substitutability inside the crop demand function within each sub-region (for example, data on the budget allocated to each crop category).

Then, the third simplification leads us to consider only crops used for human food and do not consider the production of animal feed and biofuels or ornamental flower products, for example. Indeed, the data at the world level on the quantity of crop production, which we used, does not segregate the volume allocated to animal feeds and that allocated for human consumption. Thus, our results on the impacts of pollinators decline can be distorted. For instance, this simplification could explain why, in our model, some sub-regions are net importers of certain crops, whereas, in reality, they are net exporters of those crops. Indeed, South America is a net exporter of oil crops (FAOSTAT, 2010), while in our model it is a net importer of oil crops. Also, this simplification may skew our results on the nutritional impacts of

[16] This substitutability can be integrated by using a constant elasticity of substitution (CES) utility function developed by Arrow et al. (1961).

pollinators decline, as the quantities of crops produced for human consumption would be reduced in our sample. Similarly, in addition to data limits listed earlier (in Section 2.2.54.3), data limitations on the current status of pollinator density and population in different countries led us to consider using scenarios. For simplicity, we considered the same level of decline in all sub-regions, which may not be the case, not least because of the different farming patterns in the sub-regions. Likewise, we used only one severe scenario to illustrate the relative loss in nutritional consumption quality, which implies that such loss in other scenarios can be relatively lesser than in our predictions.

The last simplification is the omission of the transport costs. This variable can increase the prices heterogeneously in sub-regions, which may create different specialization of crops around the world than the one in our model. For example, the countries in Oceania would have higher costs to import crops due to the long transportation distances from the rest of the world. As a consequence, considering transport costs would have increased the negative consequences of pollinators decline since it has an immediate impact on the quantity and price of insect-pollinated crops, particularly on some traded fruits, vegetables, tree nuts, or cocoa and coffee, etc.

Finally, although the data limitations or restrictive assumptions of the model we developed for simplicity cannot be ignored, this model provides relevant implications of the decline of insect pollination services on human welfare on a global scale that require further consideration and analysis at different scales. Indeed, the decline of pollinators may increase prices for pollinator-dependent crops, which may threaten their accessibility and availability. As a consequence, consumers, constrained by fixed revenue, would decrease their demand for such crops. Also, the increase in the market price of pollinator-dependent crops can result in the substitution of locally produced crops by imported foodstuffs, where possible, which may enhance current health issues worldwide.

In conclusion below, we will highlight the implications of our results to policy making.

2.6. Conclusion

This study examined the consequences of the decline of insect pollination services on the quantity of agricultural products trade and nutritional quality consumption, and thus more broadly on global food security and social welfare. Using a partial equilibrium approach, we demonstrated that domestic and international prices of pollinator-dependent crops might increase as each sub-region will face a marginal cost increase due to the lower availability of pollinators and thus the decline of pollination services. Consequently, consumers, constrained by fixed revenue, would decrease their demand for such crops.

Summarizing, we highlight our main results, and underline their implications for the literature as well as for public policy development.

Our findings show that this decline of pollinators may result in a substantial decrease in farm profit and consumer surplus, and thus in an overall loss in social welfare. These results align with the literature on the economic valuation of the consequences of the decline of pollination services at a global scale which also indicated such tendencies of the impacts of pollinators decline on social welfare (e.g., Gallai et al., 2009; Bauer and Wing, 2016). However, these mentioned studies suggest that substitution possibility can mitigate impacts of pollinators decline. But, by introducing substitution between domestic and traded crops in case of global decline in insect pollination, our simulations showed that producers and consumers will both be negatively impacted. In addition, we show that trade balance values may decrease in general, except for a few crop categories in some sub-regions. Furthermore, our results warn of such substitution processes consequences on micronutrients production that may result in a loss in global nutrients' consumption as pollinators decline. And yet, many people in some sub-regions of the world today still suffer from hunger and malnutrition due to the lack of viable food in quantity and nutritional quality (FAO et al., 2020).

Would countries that promote the protection of such ecosystem services create a comparative advantage in ecosystem services in the long run? (see Pething, 1976 and Siebert et al., 1985). In a partial equilibrium context, this is plausible, if pollinators in these countries are preserved while their decline in other countries increases prices on the international market of crops. Local farmers will be endowed with free insect pollination generated by pollinators if they are well preserved in local agroecosystems, which may give them an advantage and the opportunity to specialize in pollinator-dependent crops that may be high-priced. Countries that promote the protection of these ecosystem services should also gain a comparative advantage in nutritional quality crops, among other benefits (as developed in Chapter 1, Section 2).

The implications of our results for the literature consists of drawing particular attention to the relation between insect pollination services and the quantity and the nutritional quality of food production and consumption at a global scale through international trade mechanisms. Specifically, we highlight the fact that the economic value of marketed benefits of insect pollination services such as crops should not only be perceived through conventional social welfare indicators (i.e., consumer surplus, producer surplus, profit, etc.) but also through its contribution to human nutrition and thus food security. Indeed, the framework of this analysis can be expanded for every ecosystem service – e.g., agroecosystem services such as soil quality and availability, nutrient cycling, and water purification (see Zhang et al., 2007).

Also, our findings highlight the fact that the dependence of countries to the decline of pollinators depends not only on their specialization in the production of pollinator-dependent crops, as exporters, but also on their demand for these agricultural products, as importers, as global quantity and nutritional quality supply decline. Hence, pollinators decline is a global concern.

Thus, by showing that the consequences of the decline of pollinators are of global concern, the implications of our results for policymaking consist in highlighting the necessity of coordinated actions at a global scale (Chapter 1, Section 1.4.3). This is to say that actions for the protection of pollinators should not only be done locally but also internationally. In this sense, public policy responses need to be a combined effort of countries. Efforts of policymakers operating at country levels and international organization levels are necessary for structuring pollinator protection-related policies. Policy instruments are proposed, in recent research, including raising standards of pesticide risk assessment, rewarding farmers for pollination management practices (see more proposed strategic responses in Chapter 1).

A better understanding of the elements that improve pollination services in local contexts is critical to actors or policymakers that design tools for the conservation of pollination services in local agroecosystems for local as well as global benefits. However, to be as effective as possible, the environmental measures must be the object of a more cooperative international consensus so that the environmental solutions can be shared all over the globe. Moreover, for these solutions to be profitable in ecological matters, all decision-making levels, whether local, regional, national, or international, have to contribute. For example, measures such as the ban on the use of neonicotinoids as required by the European Union (Mcgrath, 2014; UNAF, 2017) would be more effective if applied worldwide and thus not only the ban of its use but also the ban of the production of such products.

Chapter 3 - Economic Valuation of the Maintenance of Pollinators Marketed and Non-Marketed Benefits: The Case of the Comminges Territory in Southwestern France

3.1. Introduction[17]

The economic valuation of the benefits of pollinators gained momentum in the economic literature worldwide triggered by unexplained losses of honey bee (Apis mellifera L.) colonies, called honey bee colony collapse disorder, reported across the United States of America (USA) in early 2000s (vanEngelsdorp et al., 2009; Porto et al., 2020). Since then, various studies have warned of the current threat to the population of insect pollinators and to their benefits (e.g., Breeze et al., 2011 in Great Britain; Zulian et al., 2013 in France). For decades it was understood that insect pollination was primarily provided by bee species, the best known of which is Apis melifera L. (Klein et al., 2007). Still, other insects (e.g., butterflies) with a role in plant pollination are largely re-assessed (IPBES, 2016). For example, Decourtye et al. (2018) report 1,000 species of bees beneficial to pollination in France, only few of which are domesticated and therefore manageable; and Breeze et al. (2011) show that two-thirds of total pollination services in Great Britain result from the activity of wild insects. Insect pollinators stand, therefore, for managed bees, wild bees, and other insect species that facilitate plant mating by transporting pollen from the anther of a male plant's flower onto the stigma of the flower of a female plant of the same species. This pollen transfer process makes pollinating insects a key role-player in the availability and abundance of plant diversity contributing to human well-being in different ways (IPBES, 2016). Approximately 1,000 plants grown worldwide for food, berries, beverages, fiber, spices, medicines, aesthetics, etc., are pollinated by insects (Kearns et al., 1998). In Europe, for example, insect pollinators contribute to the yield of 84% of the species grown (Williams, 1994; Klein et al., 2007; Breeze et al., 2014).

[17] The chapter is based on a research conducted in closer collaboration with Nicola Gallai and Jean-Pierre Del Corso in the framework of the project SEBIOREF (promoting Ecosystem Services rendered by BIOdiversity to agriculture: from the production of REFerences, to advices and proposals of incentive tools). This research was funded by the Occitanie Region, in France, and was coordinated by the French National Institute of Agricultural Research (INRA) and the École Nationale Supérieure de Formation et d' de l'Enseignement Agricole (ENSFEA).

As highlighted in previous chapters, threats to these insect pollinators include the widespread use of systemic insecticide such as neonicotinoids and pyrethroids (Pfiffner and Muller, 2014), agricultural intensification, habitat conversion, invasive species, introduced pathogens, climate change, etc. - and all these are interrelated (Chapter 1, Section 1.3.2). These threats can affect managed honey bee populations around beekeeping environments and the whole array of insects that the natural ecosystem hosts, such as wild bees, butterflies, etc., leading to an increasing loss of pollinator population and density worldwide (IPBES, 2016).

The consequences of the decline of these pollinators on human well-being are multifaceted and can be apprehended through the marketed and non-marketed benefits of pollinators (Chapter 1, Section 1.2.2). Through marketed benefits, as analyzed in Chapter 2, pollinators decline can decrease the supply of pollinator-dependent crops such as many fruits and vegetables, which can increase domestic and international market prices and thus threaten consumers' access to quality and balanced food, etc. Through non-marketed benefits, this decline can threaten biodiversity, generate negative impacts on the availability of landscapes with diverse wildflowers, traditions, or customs that may depend on insect pollination services, etc. (IPBES, 2016.)

Thus, this decline raises concerns about the public policies to be implemented for the conservation of insect pollinators and their benefits for society. Some countries have begun to reflect on public policies in response to the decline of pollinators. This is the case of the French government that has called for public policies that directly or indirectly benefit the maintenance of both pollinators and pollination services. In 2016, the French government launched a national initiative and action plan, "France, Terre de Pollinisateurs 2017-2020," aimed at specifically preserving wild bees, which stems from the "European Pollinator Initiative" of the E.U.'s 2014-2020 rural development program. This initiative consists of various actions, including monitoring and investigating the dynamics of wild pollinators; evaluating their importance; raising public awareness of the benefits of wild pollination services; and encouraging all stakeholders (e.g., farmers) to adopt new practices for the protection of wild pollinators. In the same context, the maintenance of pollinators and pollination services relies directly or indirectly on the Agri-Environmental Schemes (AES), a component of the E.U. Common Agricultural Policy (CAP) dating back to 1993, to promote public policies with positive impacts on pollinators. Amongst agri-environmental measures implemented in France, we can highlight those aimed at maintaining the current floristic diversity and promoting permanent grasslands (HERBE 07), reducing the use of herbicides (PHYTO 02), and creating and maintaining buffer strips within agricultural land for biodiversity conservation (COUVER 07) (European Parliament, 2015). In addition, the maintenance of pollinators is supported by the E.U. Pesticides Directive 2009/128/E.C., which member States are encouraged to implement as it is the cornerstone of E.U. policy to reduce the negative environmental impacts of pesticides (European Parliament, 2016). In France, this was done through neonicotinoids regulation, and a national action plan called Ecophyto, which is an effort to reduce the use of chemical plant protection products (Lamichhane et al., 2019). With this effort, France aimed at reducing pesticides in French arable crop farms by 50% until 2025 (Ministère de l'Agriculture Et de l'Alimentation, 2015).

However, despite the critical policy efforts need at the national scale, more strategized solutions at the local scale are also required to effectively address the impacts of this decline (Chapter 1, Section 1.4). As we argued in Chapter 1, these solutions must be tailored to a range of different local actors who benefit from pollinators and their services, with diverse social practices, priorities, and sometimes competing or conflicting interests within the same territory. Ecosystem services, such as pollination, are part of a territory and benefit various actors differently (Fisher et al., 2009), including consumers and producers (i.e., citizens, farmers, regional authorities, associations, etc.). Coordination and cooperation of local actors in large numbers are therefore necessary to inform local collective actions (see, e.g., Prager, 2015; Del Corso et al., 2017), which are needed to address shared concerns such as pollinator decline issues effectively.

In this regard, examining the impacts of pollinators decline in well-being of actors operating at the local scale may require consultation with a variety of actors to include a plurality of pollinator-related values and take into account the levels of their preferences which may differ among actors. Such values are important to understand because adequate pollinator protection in a territory can depend on the value that actors operating in that territory place on pollinators (Chapter 1, Section 1.3.1). Yet, since concerns about the degradation of ecosystems were raised in significant debates in political, social, and scientific spheres (MEA, 2005; Kenter et al., 2015), one of the fundamental questions is: how to measure the value actors place on the benefits they derive from elements of Nature, like pollinators?

In economics, various studies have attempted to answer this question (e.g., Krutilla, 1967; Costanza et al., 1997; Breeze et al., 2015) developing economic valuation tools. Economic valuation looks to inform on the value of goods and services or the relative costs and benefits of the different choices that would modify the flow of these goods or services (National Research Council, 1999). Theoretically, the economic value of the benefits that Nature generates has been measured based on their utility and scarcity (see Chapter 1, Section 1.2). In that respect, economic values reflect the individual preferences and perceptions that local actors place on benefits they get from Nature (IPBES, 2016). Hence, economic valuation can provide information about the priority of local actors towards marketed and non-marketed benefits they get from Nature and the distribution of such benefits among actors. Such information can be useful to understand how actors' coordinated decisions toward Nature features could be most effective (e.g., Gomez-Baggethun et al., 2013; Martín-López et al. 2019).

In this context, the economic valuation of the benefits of pollinators to human welfare has been conducted in various economic studies (see Chapter 1, Chapter 2). Indeed, as noted in these chapters, most of such studies focused on the marginal utility of marketed benefits of pollinators using production function approach, whereas only few economic valuations considered non-marketed benefits of pollinators in their analyses (Chapter 1, Section 1.2.3). Stated preferences approach has been the most used approach in assessing such non-marketed benefits of pollinators, which is based on respondent's preferences survey (Diffendorfer et al., 2014; Breeze et al., 2015; Mwebaze et al., 2018). This approach consists in assessing the individual willingness to pay towards a set of attributes (benefits) of pollinators. Thus, preferences surveyed depict the importance respondents place on the benefits they get from pollinators and their pollination services. Using this approach, Mwebaze et al. (2018) measured the public perception and preferences for pollination services by asking the WTP to support the bee protection policy in the U.K. The results of this study show that the respondents' WTP for bee conservation alone was £71.24 (approximately €81.55)[18] per household per year (i.e., £1.37/week/household). Based on that, Mwebaze et al. (2018) estimated the mean WTP to support this policy at £43 (approximately €49.2) per household per year in the UK, which is equivalent to £842 million per year (approximately €964 million). Relatedly, Breeze et al. (2015) used stated preferences valuation approach to analyze the U.K public willingness to conserve bee pollinators in U.K. in relation to their benefits. This study considered the local crop produce supplies; which is a marketed benefit of pollinators and the aesthetic benefits or amenities they may get from diverse wildflowers; which is a non-marketed benefit of pollinators. Using Kent, Lincolnshire and North Yorkshire samples, Breeze et al. (2015) found out that each interviewed respondent was willing to pay in total about £95.83 - £175.88 per year (approximately €110 - €201). On this basis, this study estimated that the U.K. population may be willing to participate to the conservation of insect pollination services up to 435 million euros, equivalent to a tax increase of £13.4 per U.K. taxpayer (approximately €15.3).

However, even though previous studies attempted to assess the economic value of the benefits that can be derived from pollinators, the focus remains on some use-values, notably their pollination services to marketed crop production and non-marketed wildflowers as amenities. Yet, as Chapter 1 (Section 1.2.2) showed, the role of pollinators in maintaining biodiversity richness in ecosystems and ultimately in

[18] Using an average exchange rate of £1= €1.1447 from December 11, 2020 to August 10, 2021 based on the European Central Bank rates.

human well-being can not only be understood through a variety of their use values (i.e., marketed and non-marketed goods or services) but also through their non-use values (i.e., non-marketable goods or services). As a reminder, these values were depicted under the Total Economic Value (TEV) framework of the benefits of pollinators (Chapter 1, Section 1.2.2). Indeed, pollinators can have non-use value such as bequest value and 'existence value' (i.e., Chapter 1, Section 1.2.2). Although definitions of 'existence value' keep evolving in the literature (Krutilla, 1967; Aldred, 1994; Attfield, 1998; TEEB, 2010; Davidson, 2013), as a non-use value, the existence value can depict the satisfaction that individuals can derive from the mere knowledge of the existence of pollinating insects (i.e., Davidson, 2013). And bequest value may come from the preservation of pollination services for one's descendants (i.e., Kolstad, 2000).

Moreover, as mentioned above, effective responses to the decline of pollinators must be tailored to a range of different local actors who benefit from them and their services, with diverse social practices, priorities, and sometimes competing or conflicting interests within the same territory (e.g., farmers, Nature users, researchers, etc.). Indeed, the level of engagement to conserve endangered insect pollinator species can be different from one place to another depending, for example, on the perception of local actors and/or the characteristics of the area under consideration (see Chapter 1, Section 1.4). Also, because the level of dependence on insect pollination ecosystem services can be heterogeneous within a country (e.g., rural versus urban areas), local actors' concerns or sensibility about the decline of pollinators can be different (see Chapter 1, Section 1.4.1).

Hence, in this chapter, we propose to focus on economic valuation of both marketed and non-marketed benefits of insect pollinators at the local scale by concentrating on landscape characteristics familiar to local actors. In doing so, we seek to identify the willingness of the general public in a specific local territory to participate in the protection and maintenance of insect pollinators in relation to their overall benefits. For that, we assess the level of local actors' willingness to pay (WTP) for such benefits. To meet this aim, our objective in this chapter is twofold.

On the one hand, in addition to the benefits of pollinators through their pollination services to crop produce supplies and to aesthetic benefits offered by wildflowers as in Breeze et al. (2015), this chapter proposes to take the economic valuation of pollinators a step further. It proposes first to specify crop produce in quality and quantity, second to address the existence value. Specifically, it estimates the willingness to pay (WTP) for the benefits of pollinators incorporating quality and varieties of agricultural production, as well as the existence value of insect pollinators. Going beyond the benefits of pollinators to crop supply (Chapter 2), by specifying their contribution to the quality (Eilers et al., 2011; Klatt et al., 2014) and variety of such marketed crops is necessary since it can help the general public in expressing values and its perception for the benefits of pollinators. It should be noted that while the quality and diversity of crops is well identified by the market price of crops, the marginal value of that quality and diversity provided by insect pollination is not. The WTP ought to provide some idea of this marginal value. Also, as noted above, although the existence value of insect pollinators is a non-use value and as such completely non-marketable, it can be the motivation of people's value expressions. Consequently, it is necessary to assess people's perception regarding the value they place on the existence of pollinators to better analyze the drivers of their willingness to participate in the maintenance of marketed and non-marketed benefits of pollinators and thus inform public decision-makers.

On the other hand, this chapter suggests conducting an economic valuation of the benefits of pollinators at a local scale in French context. More precisely, the study was carried out in the Comminges territory, in Southwestern France, aimed at supporting pollinator protection policies in this territory. The population of this territory lives in rural villages and maintains, as such, a still strong link with Nature and agriculture. A significant fraction of the inhabitants has its own kitchen-garden and/or buys local fruits and vegetables from the open-air markets and spends an important amount of time out in Nature either for work or a walk. As a result, this population is not, a priori, insensitive to pollinators. The characteristics of the population were of crucial importance since the level of information, sensitivity, usefulness, etc., one has on a good or service reflects a different value attributed to them. This is especially the case for environmental goods or services, which are often constrained by knowledge and awareness (see e.g. Meyhoff and Liebe, 2009; Bateman et al., 2006). In other words, it requires a lot of motivation and cognitive effort from respondents to express a value they place on environmental goods or services (Lienhoop et al., 2007).

Thus, the novelty of this chapter is that we suggest taking into account a non-use value of pollinating insects among their other marketed and non-marketed attributes at the local scale in the economic valuation. In other words, this chapter presents the first economic valuation of pollinators benefits conducted with local actors in France and it is unique in that it focuses on the aspects of quality and variety of available crops as well as the existence value of pollinators, which is new as far as we know.

Specifically, we address the following questions:

1) Are local actors in the Comminges well aware of the roles of insect pollinators for their well-being?

2) If so, what are their concerns about the current trend of the decline of pollinators?

3) What might be the economic value that local actors associate with the benefits they derive from pollinators?

4) What is the hierarchy of their preferences towards these benefits?

To investigate these questions, we build methodologically on the work of Breeze et al. (2015) in which lines of research focused on a stated preferences assessment of benefits of pollination services was explored in the U.K context. As in Breeze et al. (2015), our analysis is based on the random utility theory to examine the willingness to pay (WTP) and individual preferences towards the benefits of pollinators. Also, like this study, we used a choice experiment (C.E.) survey, which is well suited to assess quantitatively the value that local actors may place on the benefits (marketed and non-marketed) of pollinators. However, as noted above, we highlight some additional pollinator benefits specific to a C.E in French local-level context, as in our case study.

From the data collection standpoint, the study was conducted in two steps. In the first step, we engaged with local panels of "experts" (farmers, beekeepers, government field officers, elected officials, and members of environmental associations) to gather data on the motivations for C.E respondents’ choices and WTP, which is crucial to understanding the needs of local actors (Engel and Palmer, 2008). In the second step, we conducted a Choice Experiment survey amongst the general public. We assessed four attributes of the benefits of pollinators in the studied territory context, identified during the first step, which include: 1) varieties of the local fruits and vegetables, 2) “quality” of the local fruits and vegetables, 3) diversity of local wildflowers, and 4) existence value of insect pollinators. For simplicity, this existence value attribute was submitted to the general public for evaluation using the term of “endangered insect pollinator species”. The quality attribute refers to the contribution of insect pollination services in improving the shape (Klatt et al., 2014) and nutrients content (Eilers et al., 2011) of the crops they pollinate, particularly a variety of fruits and vegetables. The variety attribute refers to the role of pollinators in boosting productivity of such a diverse local crops (Klein et al., 2007), thereby making them quantitatively available and accessible in local markets.

This chapter shows that the respondents, from the general public in the studied area, strongly prefer to avoid scenarios where the density of pollinators declines so that they continue to benefit from them. They are willing to pay up to 516 euros per household as a share of their overall annual expenditure to maintain all insect pollinators in relation to overall benefits of pollinators studied; this is equivalent to 43 euros per month, per household. Significantly, individual preferences and choices favor safeguarding the attributes of the marketed and non-marketed benefits of pollinators we studied.

The chapter is divided into five sections. The next section describes the methodological framework on which we based in assessing the plurality of the economic value that local actors in the Comminges associate with the benefits of pollinators and describes this study area. The third section presents the results we obtained. The fourth section discusses the results and draws attention to the limits of our analysis. Finally, the fifth section concludes by underlining value expression factors for benefits of pollinators for local actors and the implications of such findings to the design of pollinator protection policies at a local scale.

3.2. Methodological framework

This section describes the method we used to assess the local benefits of pollinators and associated values. In the first place, we introduce the economic valuation method in which we base to measure the value of pollinating insect. In the second place we describe our field of study. And finally, we demonstrate the analytical and methodological framework mobilized for the design of our Choice Experiment (C.E.) survey and its implementation.

3.2.1. Measuring the value of insect pollinators: Choice Experiment (C.E.)

As Kurt et al. (2013) points out, the question of the valuation of Nature arises with the concept of ecosystem services initially introduced in the fields of conservation biology and landscape design referring to the multiple benefits that the natural ecosystem provides to humans, as is the case with pollinating insects. In economics, natural ecosystem benefits are measured in terms of marginal utility to support decision-making by evaluating the efficiency, in terms of social welfare improvements, of ecosystem management (Schaafsma et al., 2017). Traditionally, the marginal utility of one of these benefits (good or service) measures the impact of the change in state of a good or service on satisfaction (e.g., if an ecosystem service is degraded, it will decrease our marginal utility). This may imply 1) specifying the benefits of the Nature considered in the valuation and, on this basis, 2) constructing a hypothetical market that highlights the characteristics of the environmental benefits concerned by a valuation. The same approach is applied to the estimation of the value of insect pollinators in this chapter. However, that being said, pollinators generate a variety of benefits for which there is no generally agreed-upon valuation method that would effectively capture them all (Winfree, 2011).

1) Specification of pollinators benefits through TEV

From a marginal utility perspective, we specify the total benefits resulting from the pollinating insects using the Total Economic Value (TEV) framework as described in Chapter 1. Paved by Krutilla (1967), the TEV concept was formerly introduced in Nature’s valuation framework by several economic studies such as TEEB (2010), Davidson (2013), etc. Yet, the use of the TEV framework in environmental assessment remains controversial, at least on two grounds.

On the one hand, what this TEV of Nature features should include remains open to debate (see, e.g., Aldred, 1997; Davidson, 2013). For instance, Davidson (2013) argues that the TEV consists of both human-centered benefits and nature-centered benefits, and stresses on the fact that human-centered benefits include use and non-use values. Whilst, for Aldred (1997) TEV, built in context of social welfare improvements, cannot include some Nature benefits such as those with non-use values to humans. On the other hand, its use has been challenged at times for technical, psychological, and philosophical reasons (see e.g. Spash, 2009; Chan, 2012). For instance, Spash (2009) argues that traditional economic values measured in terms of marginal utility cannot depict environmental values implying incommensurability. Also, for Spash and Aslaksen (2015), using such economic methods of measuring environmental values involves implicit commodification of Nature and is based on a narrow idea of value. As for Chan (2012), the risk is that only the utilitarian dimension of ecosystem services would be taken into account, to the detriment of other hard to quantify values, such as socio-cultural and relational values. However, various studies (e.g. Loomis, 2011; Carson, 2012; Vossler and Watson, 2013) have argued that some of these controversies can be improved by appropriate survey design and valuation methods.

Following these considerations and for the sake of clarity, it is crucial to specify the benefits of the natural environment taken into account in the valuation. As noted earlier, this chapter aims to support pollinator protection policies at a territorial scale. Therefore, we propose to focus on the human-centered benefits of pollinator for the purpose of analyzing the impacts of the decline of pollinators on human well-being. However, the boundaries between human and nature-centered benefits remain open-ended (see Davidson, 2013). Using Figure 3.1 below, we mark the theoretical values that pollinators can offer to humans based on their use and non-use values as mobilized in IPBES (2016).

In theory, in use-values, there can be both marketed and non-marketed benefits from the direct consumption of goods or services resulting from pollination such as honey and other hive products, crop production, or the production of landscape amenities. By contrast, in non-use values, there can only be non-marketed benefits, including bequest value, the existence value of pollinators (i.e., as defined in Davidson, 2013), etc. Yet, one can value pollinators not exclusively for the sake of their existence but also for their importance for biodiversity preservation purposes, their current unknown contribution to Nature, and for the sake of future generations (see Aldred, 1994); - i.e. all linked together. Therefore, in practice, differentiating values that people may place on the benefits they get from pollinators is challenging.

Although challenging, however, the respondents' preferences can be elicited based on territory-specific attributes consistent with the TEV framework, as illustrated in figure 3.1 below, to support their learning process about the various characteristics of the poorly known environmental goods or services at stake. Figure 3.1 is related to the TEV of the benefits of pollinators that we have presented in Chapter 1 (see

Chapter 1, Section 1.2.2, Table 1.1). However, we mark the attributes considered specific to the context of our case study, which we will come back to later in Section 3.4.

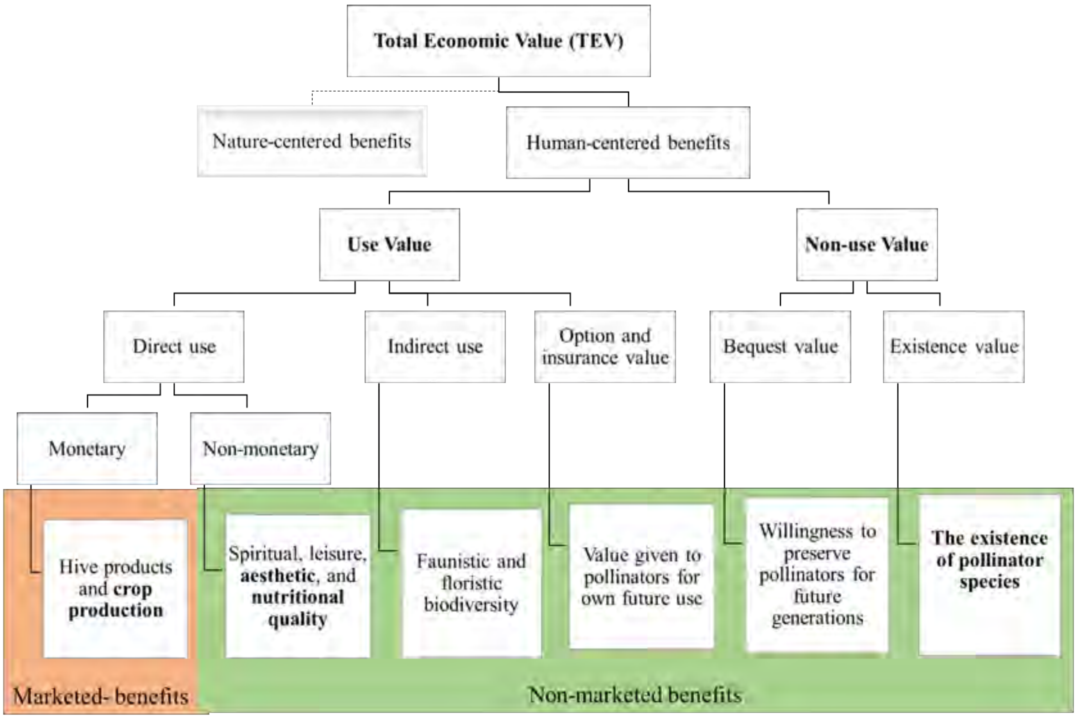


Figure 3. 1. TEV representation of the marketed and non-marketed benefits of pollinators

Source: Adapted from Davidson, 2013 and the IPBES report, 2016

To mark out the attributes of the pollinators considered and those not considered in this chapter, the benefits of pollinators taken into consideration in our assessment are specified in bold.

Given the non-marketed characteristics of most of the benefits of pollinators (as either public or common goods or services) (see Chapter 1); individual preferences for these goods or services can be elicited through a hypothetical market (i.e., Hanley et al., 2001). The construction of a hypothetical market has resulted in the increasing use of the so-called Choice Experiment (C.E.) method based on the stated preferences approach (i.e., Chapter 1; Carson and Czajkowski, 2014).

2) Choice Experiment (C.E.) design

The C.E. method consists in collecting the preferences of individuals by presenting them with several scenarios with different levels of environmental attributes. Focusing on the benefits of pollinators, the respondents are invited to choose their preferred scenario or rank these scenarios and to indicate their willingness to pay (WTP) for the performance of each of them in relation to the different levels of attributes of pollinators. The analysis is thus used to determine the marginal WTP for the various attributes under consideration. C.E. is powerful in revealing, through the estimation of marginal values, the extent of individual preferences, their tendency convergence, and their heterogeneity. At present, it is considered the most suitable for assessing quantitatively the value of benefits of ecosystem services (Adamowicz, 2004).

The next part exhibits how C.E. is applied based on the specificities of our area of study.

3.2.2. Study area: The Comminges territory in Southwestern France

As noted in the introduction, our study area, presented in figure 3.2 below, was the Comminges territory in the South-West of Toulouse, Southwestern France.

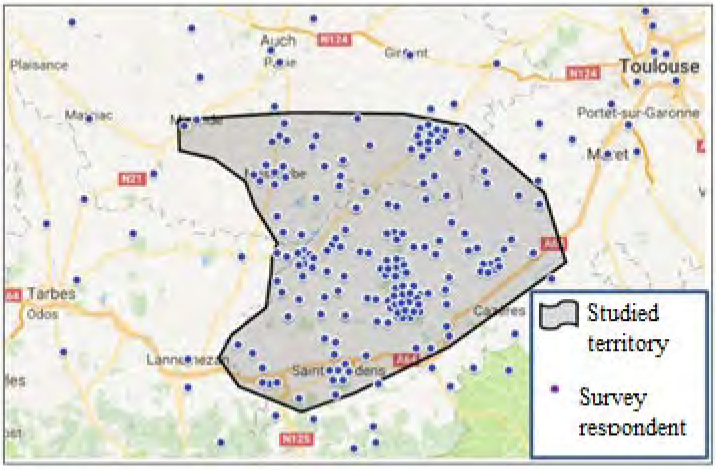


Figure 3. 2. Location of the study area

Note: The study considered both permanent residents and non-permanent residents who often spend time in the study area as a second home or for work. The blue dots on the map represent the permanent residence address of each respondent.

According to Zulian et al. (2013), nearly 62% of the lands of the former Midi-Pyrénées Region shows a pollination deficit. This deficit is particularly pronounced in areas dominated by intensive farming practices. This is partly the case in the Comminges and its surroundings. This territory is structured around two main activities. To the south, in the hillsides, it is dominated by mixed farming and livestock feed crops. Further north, in the plains, the landscape is dominated by more or less intensive cereal crop farming. In addition, market-oriented gardening, specifically horticulture, highly dependent on the pollination services, is also practiced in the territory.

From a socio-demographic point of view, the population of this territory lives in rural villages and still maintains, as such, a strong link with agriculture. Another fraction is buying local fruits and vegetables from the open-air markets. As a result, by these characteristics, this population is not, a priori, insensitive to pollinators. By their daily practices, people can be able to observe directly the effects of pollinators decline (less abundance of crops in vegetable gardens, lower quality of fruits and vegetables in local markets).

It is in this context that we seek to measure the value that the citizens of this territory attribute to the preservation of pollinators. For this, we mobilize an economic valuation approach based on a C.E. presented in the following section.

3.2.3. Choice Experiment analytical and methodological framework

Using C.E. in this chapter, we seek to specifically estimate the willingness of the general public in the Comminges territory to pay for the marketed and non-marketed benefits of insect pollinators. Improvements in the density, diversity, and population of pollinators and thus pollination services are expected if local actors bear the costs in terms of alternative investments in the management of pollinators. This presupposes that, on the one hand, well maintained pollinators in ecosystems might generate local marketed and non-marketed benefits including food products, flora and fauna diversity, floristic landscape, cultural services offered by Nature use, etc., as well as the satisfaction their existence may provide as the TEV of pollinators suggests (see Chapter 1, Section 1.2.2). On the other hand, the decline of pollinators increases marginal costs of crop production and may hamper quantity and nutritional quality consumption (Chapter 2), or threaten biodiversity, aesthetic amenities, etc. In this part, the analytical framework of our C.E. is presented in the first place, and the method used to lead the C.E. assessment is shown in the second place.

3.2.3.1. Analytical framework of our Choice Experiment

This study was designed based on four key steps referring to the characteristics of C.E. (Hanley et al., 2001; Breeze et al., 2015): 1) selecting and defining attributes of pollinators, 2) assigning the different levels to those selected attributes, 3) C.E design development, and finally 4) implementation of the survey.

1) Selecting and defining pollinators attributes in a local context

The first step consisted of selecting and defining attributes of pollinators found in people’s everyday lives in the study field. Such attributes help to survey respondents’ WTP for the preservation of pollinators. Our starting point was the selection of attributes representative of different pollinator benefits based on the values presented in the TEV scheme (Figure 3.2). To delineate these TEV benefits (attributes) more precisely and adapt them to the characteristics and realities of our case study, consultations with panels of local experts were organized. Such consultations were necessary to assess the motivation for expressing values for local actors (Christie et al., 2012) and to identify relevant hypotheses, as well as to inform, test beforehand, and improve the survey design (e.g. Hanley et al., 1998; Johnston et al., 2017; Kenter et al., 2016). In total, five panels of discussions were conducted geographically in our study area with local farmers, beekeepers, members of environmental associations, field experts, and elected officials. To keep consistency in our discussions within different groups, an interview guide and checklist were developed. These materials were done based on the above literature, one of which is TEV scheme as noted above and they were adapted from the questionnaire used by Breeze et al. (2015)[19]. Specifically, our interview guide included open-ended questions about local knowledge of pollinators and their environment, local perceptions about the decline of wild pollinators and other insects, their benefits, and actions to take regarding their decline[20] (the list of local panels of experts and the interview guide are attached in appendix 3.1 & 3.2). Through these discussions, we were able to identify and define, in the local context, the list of attributes that may represent marketed and non-marketed benefits of pollinators in relation to literature.

From marketed attributes specified in the TEV of pollinator benefits, discussions focused on local products that may be well represented in a direct local economy involving monetary value. In line with the literature (e.g., Chambers et al., 2007; Brown et al., 2009), these discussions reveal that local consumers' concerns, regarding biodiversity and environmental degradation awareness as well as local economic impacts (e.g., to local farmers), have increased preference for locally produced foods. Also, for many people, local foods are also associated with tasty and quality food, especially for fruits and vegetables. Consequently, as Breeze et al. (2015) argue, "even if produce can be substituted with imports (as analyzed in Chapter 2), loss of [local insects'] pollination services will reduce the availability of this preferential characteristic." Indeed, the production of certain fruits and vegetables is dependent on pollination by insect pollinators (zucchini, strawberries, etc.), unlike others (salad) (Klein et al., 2007). Likewise, insect pollination affects agricultural yields (Klein et al., 2007) and the quality of fruits and vegetables in terms of their shape (Klatt et al., 2014) and nutrients content (Eilers et al., 2011). Thus, the disappearance of pollinators will change their supply, diversity, and quality on the stalls compared to the present. Therefore, the variety of local fruits and vegetables and the quality of local fruits and vegetables were identified and supported by the local panels of experts as attributes that can be the motivation of people's value expressions, which emphasizes the role of these panels in this step (Christie

[19] We express our sincere thanks to Tom Breeze for his support in this matter, as our request for their questionnaire (i.e., the one used in Breeze et al. (2015)) was very well received and fulfilled as soon as it was possible.

[20] The analysis on local actions to address pollinators decline has not been further developed in this chapter, as consideration should eventually be given to including a larger population sample in these discussions.

et al., 2012). Moreover, these panels helped us identify local varieties that matched well with the season of our field survey.

For non-marketed benefits, while it could have been reflected by a bunch of attributes as TEV of pollinators benefits show[21], our consultations with the local “experts” revealed that many of these attributes can be difficult to interpret. As a result, this has, for example, led to the fact that the contribution of the pollination services to biodiversity is considered here only by the attribute “landscape aesthetics” (value of non-market direct use). Indeed, pollination contributes to the production of wild flora (Vamosi et al., 2006). Thus, the decrease in pollinators affects the level of biodiversity, observable here by the aesthetics of the landscape — e.g. the loss of Coccolico, flowers that are common in the Comminges landscapes. In particular, insect-pollinated wildflowers can provide welfare benefits by improving local area amenities (Akbar et al., 2003), flora and fauna habitats (Junge et al., 2011), thus biodiversity, etc. In addition, the aesthetic quality of landscapes has substantial impacts on landscapes' use and thus on people's perceptions towards Nature features, which can reinforce the sociocultural values associated with it and the connectivity of local actors to Nature (Kellert, 1996; Natural England, 2009). Therefore, pollinators decline can have a negative impact on wildflower species, which can diminish these benefits for local actors. As such, local wildflowers, to which insect pollinators can contribute to their maintenance, were identified as an attribute of pollinators that can be the motivation of people's value expressions.

Besides, these panels representing local actors turned out to be quite concerned with the decline of insects themselves rather than their use-values. Hence, even if local insect pollinators can be replaced by alternative pollination methods (e.g., drone technology, pollen dusting, the market for bee pollination, etc.), the loss of the insects themselves as part of their ecosystem is a problem. Indeed, managed bees can be reinforced to optimize insect pollination services (see Burgett et al., 2004). However, Kleftodimos et al. (2021) argued that the substitution of wild pollinators by managed bees may be ineffective as the production cost may be higher and the efficiency may be lower. The panel of local experts was aware of the consequences of the decline of pollinators in their area. For them, there is a growing awareness and sensitivity to this issue at the level of producers and consumers in their territory. Such an increased awareness can be explained by many factors. For example, this concern was motivated by the fact that the recent French National Action Plan on wild pollinators or debates on impacts of neonicotinoids use on declining bee populations at European level, as noted in the introduction, was covered by the French media. Also, in our study area, there is a well-known association named “Les Fous du Bois” (i.e. the madmen of the wood), which aims, among other things, to raise

[21] For example: "food intake for wildlife" (indirect use value).

awareness of the endangered insect problem through various means, including the initiation of citizens to the conception of insect refuges using woods, which they call “hôtel à insectes” (i.e. insect hotels). Commissioned by a farmer-led association called “Vivre En Comminges” (i.e. living in the Comminges), also a local radio program that addresses environmental issues among other community problems in the local area raises awareness of “living in harmony with Nature.” Or another initiative that organizes local meetings to, for example, collect cigarette butts and other environmentally harming waste, manually weed public spaces thereby limiting the use of pesticides and raising awareness and sensibility of local actors to Nature features. In this context, the degradation of pollinating insects can have consequences for their non-use values, and thereby reducing the satisfaction local actors obtain for these insects as a part of Nature. Based on this understanding, this study expects that respondents' willingness to pay for the management of pollinators will increase in line with improvements in the quality of their existence value, which is a non-use value (See TEV figure 3.2), thus we acknowledged endangered insect pollinator species as an attribute. This attribute allows a priori to estimate the existence value that people attribute to pollinators. As noted in the introduction, this value is defined as the satisfaction that individuals can derive from the mere knowledge of the existence of pollinating insects (i.e. Davidson, 2013).

Furthermore, following the recommendations of the “experts” consulted, we introduced a time attribute to account for the temporal sensitivity of preferences. This recommendation is in line with various studies on the value discount rate, which also highlight a strong preference of individuals for the present (Feldstein, 1964; Cline, 1999). Indeed, time was regarded as an attribute that can help to reduce hypothetical bias on the side of respondents since the impacts of pollinators decline will be experienced in a longer time frame compared to the present. Thus, the time attribute expressed in years was considered in our assessment.

Moreover, it is compulsory from the point of view of the CE technique to define a payment vehicle in order to realize the experiment. Thus, it was crucial to assess a monetary cost that respondents are willing to bear for the realization of their preferred scenarios and transaction mechanism as well as the acceptability of the approach in the study area (Powe, 2007, Ch. 5). Even though the protection of public or common goods or services, such as pollinators and pollination (see Chapter 1), has always been part of the government's tax-dependent budget (e.g., Breeze et al., 2015), such a transaction mechanism was not viable in our case study given the existing reluctance to pay additional taxes[22]. According to the local panels of “experts,” actors in the studied area may show less interest in contributing through this

[22] This point can be supported by the existence of the Yellow Vests Movement ("Mouvement des Gilets Jaunes"), which, a year after our survey, emerged in France as a reaction to government tax reforms on oil.

channel because they are not sufficiently knowledgeable or assured about the utilization of their tax in implemented national public policies. In other words, there are at least two reasons why payment by tax vehicles may not be a fit: first, local actors think they are paying too much in taxes and second, they are not sure that if they pay a new tax, the budget will be allocated to pollinator protection. Thus, through discussions with these experts, suggestions pointed to a payment vector such as a contribution to be paid to a locally governed pollinator protection fund, which we used. For them, such a tool was supposed to make the payment more realistic than the tax. Therefore, an annual contribution paid per household to a local pollinator protection funding was agreed upon as a payment attribute in order to realize our C.E. experiment.

In conclusion, as a result of these consultations, we selected a payment vector attribute and five main attributes that are well suited to the design of a C.E. in the context of our case study. Four attributes refer to the different values of pollinators benefits underlined in the TEV framework in Figure 3.1 above. Two of these, namely the variety and the quality attributes, relate to the value of local fruits and vegetables as direct marketed benefits of pollinators that local actors use. Another concerns the non-marketed benefit of direct use-value of pollinators, namely the wildflower diversity attribute. And the last one concerns completely non-marketable benefit, which integrates non-use value as an existence value of pollinators, namely the attribute endangered insect pollinator species. The remaining attributes, which were relevant for the design of our C.E., include the attribute time and the attribute annual contribution per household as a payment vector. These attributes are summarized in Table 3.1 below.

With this information, this study hypothesizes that respondents' willingness to pay for the maintenance of pollinators will increase as the satisfaction they obtain from the benefits of these pollinators attributes improves. In addition, improvements will be preferred in a relatively short time frame compared to a longer time-frame.

2) Assigning the different levels to selected attributes

The second step consisted of assigning the different levels to the selected attributes. As in the previous step, qualitative data are again valuable. Thus, we also used preliminary interviews with local experts to define levels that are both achievable and realistic. In doing so, as Table 3.1 below summarizes, the "beneficial" and "less beneficial" levels of identified attributes are defined.

Table 3.1. A synthesis of the levels assigned to selected attributes

Attributes	"beneficial" levels	"less beneficial" levels	Description
Time	5 years	20 years	The time it will take to realize the scenario.
Varieties of local fruits and vegetables	A lot	Little	The available choice of fruits and vegetables from local production.
Quality of local fruits and vegetables	Good	Not good	The quality (in terms of shape and nutritional value) of locally grown fruits and vegetables.
Wild flowers diversity	100 %	70 %	The aesthetic aspect of the landscape in terms of local wildflower diversity.
Endangered insect pollinator species	0 %	50 %	The percentage of wild pollinator species extinction.
Monetary contribution	100 €	0 €	The cost to be borne; to make the scenario a reality as local actions are invested.

Note: This table illustrates two dominant alternative scenarios. As such, it cannot provide details on the priority local actors place on the marketed and non-marketed benefits they derive from pollinators, or on the hierarchy of their preferences for these benefits.

If additional efforts are made to preserve pollinator benefits, the levels of their attributes that respondents may consider "beneficial" to them are: more diverse local fruits and vegetables, good quality local fruits and vegetables, maintenance of 100% of local wildflowers, and 0% of endangered insect pollinator species (Table 3.1). Such improvements can be expected in a relatively short-term, which local experts defined as 5 years. And as a contribution to the realization of a scenario preferred by each respondent, local panels of experts proposed a maximum of 100 euro per year, which is 8.3 Euros a month, per a household expenditure.

If no additional efforts are made, the "less beneficial" levels of identified attributes are to be expected, and thus the status quo "do nothing" scenario is maintained. In this study, the "do-nothing" scenario corresponds to the situation where nothing is done to protect pollinators in the years to come, which implies bearing no cost to maintain pollinator benefits. Consequently, we considered in the questionnaire that all the levels of the attributes of this "do-nothing" scenario are relatively low in a longer-term. Local panels of experts suggested to consider status quo attribute levels as following: 20 years as a longer-term, few varieties and poor quality of fruits and vegetables, less diversity of wild flowers, and loss of about a half of pollinator species. But to keep realism, consulted local actors suggested accounting ongoing individual efforts in maintaining flowers in local landscape. As a result, we used 70% as a less beneficial attribute level of diversity of local wildflowers in case nothing is done.

A further important point addressed is the connection that people might make between the attributes studied and specifically between existence value and other attributes. Indeed, one might think that if 50% of wild pollinators disappear, the quantity and diversity of crops and/or the diversity of wild flora should automatically decrease. Obviously, this is not the case, since even if wild pollinators disappeared; honeybees would still be present to provide pollination services. Thus, the questionnaire should be sufficiently explicit about this so that these attributes remain independent.

3) Choice Experiment design development

The third step was about the development of a Choice Experiment design. Respondents' expression of preferences for each of the attributes representing the benefits of pollinators and formulation of choices require having different options, which involves designing different choice sets. By varying and combining the attribute levels in different possible ways, a number of different choice sets were built (see an example in Figure 3.3 below). For this purpose, we used €100, €50, €25, and €0 as the levels of monetary contribution attributes that respondents would be willing to pay for the realization of their preferred alternative scenarios from different choice sets.

Mathematically, the combination of the five attributes and these variation levels of the monetary contribution attribute leads to 128 (combination of $2^5\ 4^1$) different choice sets. In order to have a more statistically robust set of choices by minimizing the standard error or standard deviation of the parameter estimates, we adopted the "Fractional Factorial Design". The use of a Fractional Factorial Design allowed us to reduce the alternatives to 16 choice sets (example below, others in Appendix 3.3).

In addition, as recommended and widely applied (see e.g., Rasid and Haider, 2003; Schaafsma et al., 2017), we used pictographs and images in our survey to visually illustrate the meaning of the variation in the different attribute levels and facilitate the interpretation of the choice sets.

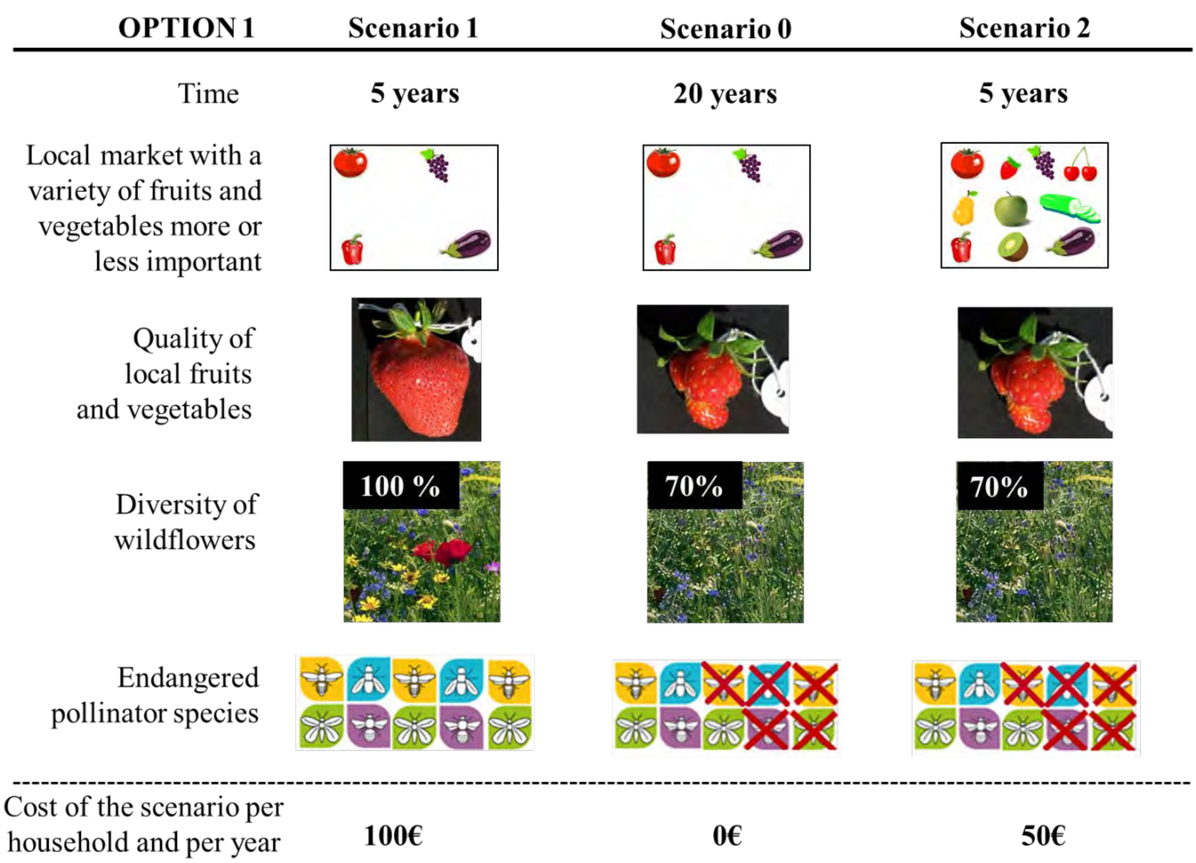


Figure 3. 3. An example of a choice set

Note: Scenario 0 corresponds to “do nothing” and keeps a status quo scenario. It is identical for all the choice sets, where pollinating insect populations and their pollination services decline in a longer term. Scenario 1 and scenario 2 are alternative scenarios to elicit if something is done to avoid the status quo scenario. For consistency, information adapted from the above literature has been provided to explain what is being referred to with the variety and quality pictograms.

Indeed, the different combination of the attributes and their levels across the choice sets serve to identify the preferences of the respondents. For instance, in the choice set above (see Figure 3.3), scenario 1 proposes pollinators in abundance but a decrease in the density of fruits and vegetables in the local market and scenario 2 suggests the opposite. Therefore, the choice made by the respondent provides information on their preferences for one or the other of these two attributes. The choices made by respondents make it possible to classify the attributes according to their level of importance for the population surveyed.

4) Survey implementation

The last step consisted of questionnaire-based interviews. An average 30 minutes survey was conducted with 256 participants during the summer of 2017. Our sample population was composed of random individuals that we met at local public spaces including markets (local open-air markets), shops, and other public spaces. Our approach was to conduct the interview directly with respondents, or, if that was not possible, to make an appointment and conduct the interview from their home. If this data collection method does not guarantee a perfect representativeness of the surveyed population as a real draw could allow, it relies on a sufficiently large sample to make results reliable (Johnson et al., 2013)[23].

To avoid biases related to learning opportunities and fatigue (Dachary-Bernard, 2007), only five choice sets were randomly submitted to each respondent. Each choice set included two different alternative scenarios and the "do-nothing" scenario.

However, it is known that responding to a C.E. exercise for ecosystem services is a demanding task that requires a lot of motivation and a meaningful cognitive effort from respondents (Lienhoop et al., 2007). To mitigate this issue, each interview was conducted in three phases.

First, after clarifying the main objectives of the study, the interviewer provided each respondent with basic information on pollinating insects, pollination services, and the decline of wild pollinators, etc. (see questionnaire sections in appendix 3.4). This was to avoid too strong asymmetries of information between respondents on a subject still poorly known. In that sense, our surveys allow not only data collection but also knowledge acquisition. This seemed necessary to homogenize the knowledge of the respondents and to reduce lexicographic preference bias.

Then, the investigator made the monetary assessment by presenting each interviewee with choice sets. It was stated that the completion of each scenario would involve an annual household contribution to a local fund to finance actions to protect wild pollinators.

Finally, information on the socio-economic characteristics of the respondents was collected. This step is the last one because it is the one that requires the least concentration for the respondents.

3.2.3.2. Theoretical basis and econometric analysis: The model

As a reminder, in this study, each respondent from the general public was asked to repeatedly choose his preferred scenarios from 5 random choice sets (in Appendix 3.3). Each choice set consisted of two

[23] Johnson et al. (2013) report that "marginal gains in the precision of estimated coefficients increase sharply for sample sizes below 150 and increase weakly for sample sizes 300 observations".

different alternative scenarios and the "do-nothing" scenario and each of these scenarios was characterized by five attributes with varying levels (i.e., time, the benefits of pollinators, and a monetary cost) (see Figure 3.3 above).

To analyze respondents' choices about the benefits of pollinators within these alternative scenarios, we based our analysis on the random utility theory and econometric model dealing with discrete choices. Specifically, the implemented C.E. builds on Thurstone's theory of random utility (Random Utility Theory: RUT) (1927) and is complemented by the work of various economists such as McFadden (1968). This theory postulates that people generally choose what they prefer; the utility accorded to an alternative of choices depends on preferred attributes of a good or service, in our case scenario, and on random factors. With U_{in} to represent the utility of individual *n* choosing alternative *i*, *i* will be chosen if and only if $U_{in} > U_{jn}\ for\ \forall j \neq i\ \in C$. As researchers do not know the individual's true utility (Louviere, 2010), U_{in} consists of a predicted utility that can be expressed as follows (Louviere et al., 2000; Dachary-Bernard, 2007; Breeze et al., 2015):

$$U_{in} = V_{in} + \varepsilon_{in} \quad (1)$$

U_{in} is composed of a vector of observed characteristics, V_{in}, based on observed attributes of *i* affecting choice of *n*, and a vector of unobserved random characteristics, ε_{in}, depending upon the heterogeneity and variation in respondents' tastes or preferences, measurement errors, and functional misspecification. Since ε_{in} is unknown, the final outcome is predicted in terms of probability. Based on the expression given in (1), the probability of choice that maximizes the utility of the individual *n* is the alternative *i* if:

$$P_{in} = P\ (V_{in} - V_{ij} > \varepsilon_{jn} - \varepsilon_{in})\ \forall j \neq i\ \in C \quad (2)$$

To derive an explicit expression for this probability, it is necessary to specify the distribution of error terms (ε_{in}). In this case study, respondents' demand heterogeneity should be considered because, as noted in the introduction, the individuals that benefit from pollinators and their services includes a range of different actors, with sometimes competing or conflicting social practices, priorities, and interests. Indeed, respondents may also have different levels of information, sensitivity, usefulness, etc. regarding benefits of pollinators.

Following Breeze et al. (2015), to consider the heterogeneity of the respondents, we have mobilized a mixed logit model, in which the stochastic components follow any type of statistical distribution. The mixed logit model assumes that the error terms ε_{in} are independent and identically distributed, while it allows parameter estimates to vary across individuals (Audibert et al., 2013)[24]. In other words, mixed logit model relaxes the typical restriction that parameter estimates are the same for each individual, allowing it to be stochastic instead. As Audibert et al. (2013) points out, "through attributing each respondent a random term, taste variations, unobserved heterogeneity in alternatives and unobserved heterogeneous choice sets are allowed". Consequently, an individual's choice probability can be estimated. As such, parameter estimates (β) differ across individuals and the utility of individual *n* choosing alternative *i* can be expressed as follows:

$$U_{in} = \beta_n X_{in} + \varepsilon_{in} \tag{3}$$

Where:

β_n is a normally distributed vector of marginal utility parameters for individual *n*.

X_{in}: is a vector of the attributes levels of alternative *i* presented to respondent *n*.

Eventually, the probability that an individual chooses scenario *i* becomes:

$$P_{in} = \frac{e^{\beta_n x_{in}}}{\sum_{j=1}^{J} e^{\beta_n x_{jn}}} \; ; \tag{4}$$

The vector of marginal utility parameters for individual *n* (β_n) encompasses each mean, say δ, of the parameters of studied attributes for each individual respondent with their standard deviations. Hence, following Hanley et al. (2001), we note the marginal utility of an attribute A (WTP_A):

$$WTP_A = \frac{-\delta_A}{\delta_C} \tag{5}$$

Where:

δ_A is the coefficient of attribute A and δ_C is the marginal utility of an annual monetary contribution per household to finance actions to protect insect pollinators.

An analysis of the standard deviation estimate allows determining whether there is significant heterogeneity in respondents' preferences for any of the attributes studied. To do this, the model needs to be specified, first by creating the interaction variables between the attributes studied and the

[24] Mixed logit model relaxes a typical hypothesis of the IIA (Independence of Irrelevant Alternatives) that could have been necessary in resolving equation (2) using standard logit models (e.g., Multinomial logit model) (Audibert et al., 2013). The IIA hypothesis states that the relative probabilities of the selected alternatives are not affected by the introduction or removal of other alternatives. This property follows from the independence of the Weibull error terms (Hanley et al., 2001).

characteristics of the individuals, and then by introducing these variables one by one into the model to test their significance (Hanley et al., 2001). Thus, based on standard deviations, the heterogeneity of respondents' preferences among pollinator benefit attributes can be analyzed. The use of standard socioeconomic variables as well as other variables such as respondent attitudes, environmental ethics, and knowledge of the different scenario attributes can potentially explain this heterogeneity in preferences.

Based on the insights from this section, our hypotheses are that levels of non-monetary attributes, which offer improvements, ceteris paribus, are expected to positively influence the probability of choosing alternatives, albeit heterogeneously.

Collected data are analyzed using Stata software. Coding and organization of the database was performed for analysis of respondents' answers. To facilitate data entry on Stata, we organized the database in such a way that each row represents an alternative. The variable to be explained "choice" is a dichotomous variable that takes the value 1 when the alternative is chosen and 0 otherwise (see datamatrix overview in appendix 3.6). The coding of the attribute levels is summarized in table 3.2 below. Thereafter, we present our results.

Table 3.2. Coding of attribute levels

Attributes	Levels	Codes
Time	5 years	1
	20 years	0
Varieties of local fruits and vegetables	A lot	1
	Little	0
Quality of local fruits and vegetables	Good	1
	Not good	0
Wild flowers diversity	100 %	1
	70 %	0
Endangered insect pollinator species	0 %	1
	50 %	0
A monetary contribution to the realization of a scenario	0 euro/household/an	0
	25 euros/household/an	25
	50 euros/household/an	50
	100 euros/household/an	100

3.3. Results

To analyze the importance local actors may associate with marketed and non-marketed benefits of pollinators and their concern about the current pollinators decline situation, we addressed three questions about: 1) What is the economic value that local actors associate with the benefits they derive from pollinators? 2) What is the hierarchy of their preferences towards these benefits? 3) Are they concerned with pollinators decline impacts on both marketed and non-marketed benefits?

In doing so, we surveyed a sample of 256 individuals (255 of whom are useful), asking them their preferred scenario among different alternative scenarios. We analyze the significance of these respondents' preferences based on time of a realization of a scenario, varieties and quality of local fruits and vegetables, local wildflowers, endangered insect pollinator species attributes, and the monetary contribution for each of their preferred scenarios. Since each participant makes a choice among three alternatives and repeats the same exercise for the five sets of choices, we have a total of 255*5= 1275 choice situations (3741 observations)[25]. We calculated the WTP values as the ratio of all parameters and the monetary contribution coefficient. Through the results of these surveys we seek to determine the role played by each attribute in the choice of the preferred scenario.

In the first place, we present the main sociodemographic characteristics of the respondents. Next, we present the estimated coefficients of attributes and WTP estimates for the benefits of pollinators analyzed. Then, we present some descriptive results regarding the qualitative questions to provide insight into the motivations of C.E. respondents' choices and their WTP (further descriptive analysis in appendix 3.5). Finally, we investigate heterogeneity in preferences of respondents among these pollinator benefit attributes.

1) Main socio-demographic characteristics of the respondents

More than 90% of our sample is made of permanent residents of the study area, 58% of whom are men, and 42% are women. "Farmer" and "Craftsmen, merchants, entrepreneurs" are the socio-professional categories most represented in our surveys: more than 50% of our sample. The highest level of education of about 70% of our sample was Secondary Education Certificate (Baccalauréat) level and less. And 40% of respondents declare to earn less than 9000 € per year. The main socio-demographic characteristics of the surveyed population are summarized in Table 3.3 below.

[25] Note also that 27 of the 1275 choice situations (2%) represent no choice.

Table 3. 3. Main socio-demographic characteristics of the respondents

Economic variable	Characteristics	Freq.	Percent	Cum.	Population
Residents of the study area	Permanent residents	241	94.51	94.51	91%
	Non-permanent residents	14	5.49	100	9%
Gender	Men	141	57.65	57.65	47.84%
	Women	108	42.35	100	52.15%
Age groups	16 to 29	32	12.55	12.55	12.9%
	30 to 44	74	29.02	41.57	14.2%
	45 to 59	85	33.33	74.90	21%
	60 to 74	62	24.31	99.22	21.8%
	75 and more	2	0.78	100.00	15.2%
Education level	BAC + 5 and more	40	15.69	15.69	5.2%
	BAC +3	39	15.29	30.98	7.4%
	BAC, BTS, DUT, or equivalent	75	29.41	60.39	17.4%
	Less than bac	101	39.61	100	35.5% (24.5 % has no degree or primary certificate)
Socio-professional categories	Farmers	71	27.84	27.84	3.1%
	Beekeepers	7	2.75	30.59	
	Craftsmen, merchants, and entrepreneurs	65	25.49	56.08	6.6%
	Senior Professional and other professionals	19	7.45	63.53	6.5%
	Intermediate occupation	8	3.14	66.65	13.4%
	Employees	29	11.37	78.04	20%
	Workers	4	1.57	79.61	15.9%
	Retired	35	13.72	93.33	28.4%
	No profession	17	6.67	100	5.8%
Respondent income levels per year	Less than 9000 €	99	40.57	40.57	Disposable income /consumption unit
	10 000 to 18000 €	77	31.56	72.13	Median: €19,900
	19 000 € to 28 000 €	35	14.34	86.13	Inter-decile ratio (without unit) 3.2.
	29 000 € to 40 000 €	19	7.79	94.26	1st decile: €10,750
	41 000 € to 55 000 €	5	3.69	97.95	9th decile: €33,930
	More than 56 000 €	5	2.05	100	
Member of an environmental association	Member	70	27.45	27.45	-
	Non-member	185	72.55	100	

Note: Population represents mean characteristics of the population of reference to this study area in 2018 (see https://www.insee.fr/fr/statistiques/2011101?geo=EPCI-200072643, accessed 06 September 2021).

2) Estimated coefficients of attributes and the values of WTP for pollinators benefits

The results of the mixed logit (Table 3.4) show that the attributes of the choice sets are all normally distributed. The coefficients for the pollinator benefit attributes (i.e., the variety of fruits and vegetables, their quality, the diversity of wildflowers, and the existence of insect pollinators) are significant and all have a positive sign, while the coefficients for monetary contribution attribute is significant and have a negative sign. Thus, the probability of choosing an alternative is positively influenced by improving these attribute levels and negatively impacted by an increase in monetary contribution. However, even if the time attribute is normally distributed, it is not significant. Consequently, time attribute does not impact the probability of choosing an alternative from a choice set for the individuals surveyed, or its complexity makes it difficult to take into account by respondents.

Table 3. 4. Estimate of the coefficients of attributes by the mixed logit model

Attributes	Coefficients
Time	0.36 (1.06)
Variety of local fruit and vegetables	2.79 *** (-2.85)
Quality of local fruit and vegetables	1.40*** (-2.33)
Diversity of wild flowers	1.43*** (-2.58)
Endangered insect pollinator species	4.96*** (4.48)
Monetary contribution	-0.02* (-0.01)
Number of obs 3.741	
LR chi2 (6) 594.13	
Prob > chi2 0.0000	
Log likelihood -554.0067	

Legend: * p<0.05; ** p<0.01; *** p<0.001
Note: The figures between parentheses are the standard deviations (SD). Since the SD represents a distance, the sign of the estimated SD that are negative are irrelevant, thus interpret them as being positive (source STATA)

The overall economic value that respondents associate with the benefits they derive from pollinators represented by the value of their total WTP was 516 euros per household per year, which is 43 euros monthly. The hierarchy of respondent preferences and choices towards these benefits were safeguarding endangered pollinator species first, then availability of local varieties of fruits and vegetables, then wildflowers, and finally local fruit and vegetable quality. The WTP per year, per household for each of these benefits breaks down as follows: €248 for endangered insect pollinator species, €133 for local varieties of fruits and vegetables, €68 for local wildflowers, and finally €67 for local quality of fruits and vegetables, respectively. Our results of WTP values are reported in table 3.5 below.

Table 3. 5. WTP estimates for pollinators benefits

Variables	WTP in euro per household		Interpretation (all else equal)
	Yearly	**Monthly**	
Variety of local fruits and vegetables	133	11.1	To have a lot of diversified local fruits and vegetables, households are willing to pay 133 euros/year.
Quality of local fruits and vegetables	67	5.6	To have a good quality of local fruits and vegetables, households are willing to pay 67 euros per year.
Wildflowers diversity	68	5.7	Households are willing to pay 68 euros/year to have 100% wildflower diversity.
Endangered insect pollinator species	248	20.7	Households are willing to pay 248 euros/year for the existence of all pollinator species (existence value).
Total	**516**	**43**	Respondents are willing to pay 516 Euros as a share of their overall household spending per year (about 43 Euros per month).

3) Analysis of the motivations for C.E respondents' choices and WTP: combining econometric data with open questions and qualitative perceptions

Overall, we note that the existence value largely takes precedence over use values studied. This result confirms, in a sense, the data on the sensibility and motivations for C.E respondents' choices and WTP; we collected from local panels of expert (see Section 3.2.3.1). Based on the first part of the questionnaire (see appendix 3.4), as table 3.6 summarizes, our results can be explained by many factors including the fact that 76.7% of the respondents declare to have a vegetable garden and that 83.2% of them indicate buying local fruits and vegetables. For 87.2% of respondents, this choice is to preserve quality and taste (see figure 3.4 below). Also, the risk of contamination of imported food by pollution from transport and the adverse economic impact of food imports on the local economy justify, in a sense, the respondents' preferences for local production. The reduction of wild flowers is experienced as a loss of well-being (degradation of the aesthetic quality of landscapes, habitats, and road borders) since nearly 64% of respondents say they appreciate the abundance and diversity of flowers.

Table 3. 6. Descriptive analysis of the motivations for C.E respondents' choices and WTP

Questions	Answer	Freq.	Percent	Cum.
Do you usually (from April to August) grow fruits and vegetables at home or in a shared garden?	Yes	195	76.47	100.00
	No	60	23.53	23.53
Do you usually buy local fruits and vegetables?	Yes	214	83.92	100.00
	No	41	16.08	16.08
How often do you buy local fruits and vegetables?	+1once/week	40	18.69	18.69
	Once/week	119	55.61	74.30
	One/2weeks	26	12.15	86.45
	-1once/month	25	11.68	98.13
	Don't know	4	1.87	100.00
How often do you visit natural areas such as green spaces, forests or woods and surrounding natural parks?	Always	37	14.51	14.51
	Once/week	57	22.35	36.86
	Once/month	52	20.39	57.25
	-1 once/month	73	28.63	85.88
	Never	33	12.94	98.82
	Don't know	3	1.18	100.00
In the natural spaces of the territory, you appreciate the diversity of flowers present, if yes how much from 1 to 4 scale?	1	3	1.18	1.18
	2	27	10.59	11.76
	3	62	24.31	36.08
	4	163	63.92	100.00

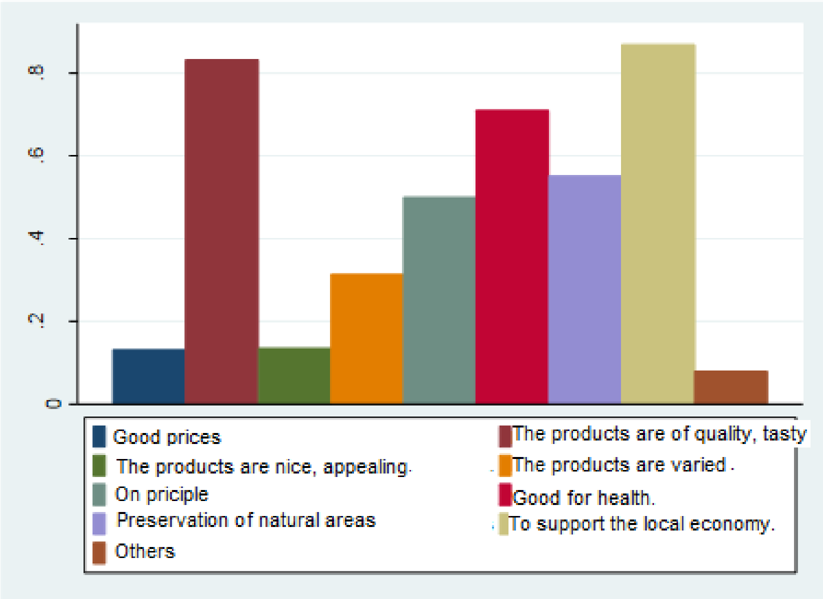
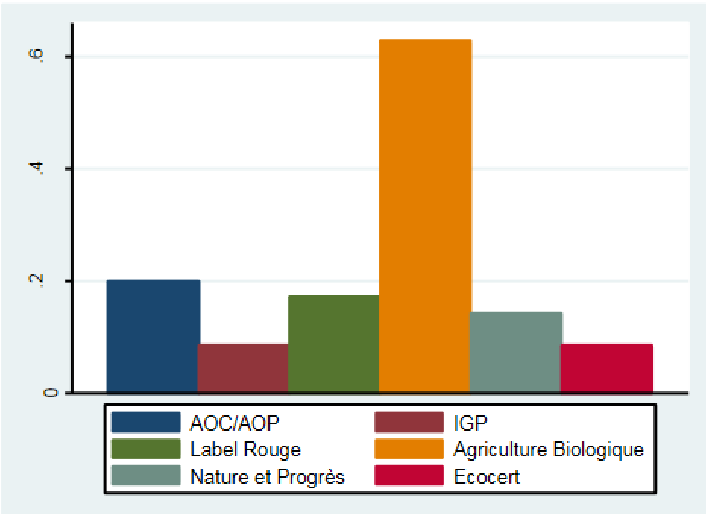


Figure 3. 4. Reasons expressed for choosing local fruits and vegetables

In addition, in our sample, we interviewed 27.8% of farmers, 15.8% of whom were engaged in market gardening and 17.5% in arboriculture. Likewise, the farms of more than a half of farmers 71 farmers interviewed have biological farming labels (see Figure 3.5 below), which is susceptible to enhance their sensibility to the issue of pollinators decline and hence motivate their willingness to participate in protection of their benefits and/or in local products.



AOC/AOP:
Controlled/Protected Designation of Origin
Label Rouge: Red Label
Nature Et Progès: Nature and Progress
IGP: Protected Geographical Indication
Agriculture Biologique: Organic agriculture
Ecocert: an organic certification organization

Figure 3. 5. Agricultural production labels of the farmers interviewed

4) Heterogeneity of preferences among the attributes

However, the analysis of the standard deviation estimates reveals the existence of a relatively higher variation in respondents' preferences and significant heterogeneity of preferences for all the attributes. To explain this heterogeneity, we first created the interaction variables between attributes and characteristics specific to individuals (Hanley et al., 2001). Then, we introduced these variables one by one into the model to test their significance. Only the coefficients of the interaction variables between attributes and individual characteristics of respondents are presented in table 3.7.

As table 3.7 shows, most of the interaction variables between the attributes of the benefits of pollinators and individual characteristics (occupation, gender, income, age, level of education, etc.) are not significant. Only education, income, and membership of respondents in environmental association prove to be characteristics capable of reinforcing the sensitivity of an individual vis-à-vis the preservation of wild pollinators. Our results show that membership in an environmental association has a beneficial effect on this attribute, while low education and low income detract from this attribute.

Table 3. 7. Coefficients of interaction variables between attributes and individual characteristics

Interaction variables	Time	Variety of local fruits and vegetables	Quality of local fruits and vegetables	Wildflower diversity	Endangered insect pollinator species	Monetary contribution
Years old	0.12	-0.34	-.000	0.06	0.28	0.00
	(0.17)	(0.27)	(0.21)	(0.11)	(0.87)	(0.00)
Gender	-0.18	-0.64	-0.67	-0.89	-1.22 *	-0.01
	(0.42)	(0.48)	(0.47)	(0.50)	(2.56)	(0.00)
Education	0.05	0.32	-0.25	-0.32	-0.98 ***	-0.007 *
	(0.22)	(0.26)	(0.20)	(0.18)	(0.10)	(0.00)
Sector	-0.43 *	0.06	-0.15	-0.25	0.64*	-0.00
	(0.18)	(0.20)	(0.17)	(0.21)	(1.51)	(0.00)
Profession	0.11	-0.06	0.15	0.03	-0.29	-0.00
	(0.08)	(0.11)	(0.09)	(0.09)	(-0.12)	(0.00)
Revenue	0.08	0.00	0.60 *	-0.39	-1.00 ***	-0.00
	(0.17)	(0.17)	(0.24)	(0.23)	(-0.84)	(0.00)
Partner revenue	-0.01	0.10	0.06	-0.38	-0.22	-0.00
	(0.14)	(0.19)	(0.15)	(0.20)	(0.30)	(0.00)
Member of an environmental association	-0.37	-0.02	-0.28	1.27 *	2.61 **	0.01 *
	(0.45)	(0.47)	(0.64)	(0.59)	(4.36)	(0.00)
Type of actor	0.53	1.69 **	-0.67	0.77	1.75 *	0.00
	(0.51)	(0.62)	(0.55)	(0.67)	(3.69)	(0.01)
Resident	0.11	-0.10	0.08	0.03	-0.12	-0.00
	(0.07)	(0.09)	(0.10)	(.008)	(0.60)	(0.00)
Place of birth	0.07	0.31	0.43	0.00	-0.013	0.00
	(0.20)	(0.29)	(0.31)	(0.34)	(0.36)	(0.00)

Legend: * p<0.05; ** p<0.01; *** p<0.001. Figures in parentheses are standard deviations. Age = age group, gender = female (1) and male (0), and education = respondent's education level category (BAC level and less (1) and BAC + 3 and above (0)). Sector = sector of activity relating to the profession according to the INSEE classification; Revenue = respondent's income and partner's income category (Lesser than 18000 € (1) and More than 19 000 € (0)); Member of an environmental association (1) and non-member (0), Type of actor = farmer (1) and non-farmer (0); resident = permanent resident on the field of study (1) or not resident (0), and place of birth between a city and rural area.

3.4. Discussion of the results and limits of our analysis

The results highlight the importance that local actors place on a range of the benefits of pollinators by expressing their preferences and WTP for various attributes of the benefits of pollinators submitted for their assessment. In other words, these values can reflect the judgments of the respondents about the role of pollinators to their well-being and their concerns about pollinators decline (Breeze et al., 2015). Here we discuss our results and the limits of our analysis concerning the methodology used and the context of our case study by discussing the implications of these limits for the WTP results we obtained.

Our results suggest that the respondents prefer strongly to avoid scenarios where the density of pollinators decline and then continue to benefit from them. In doing so, they are willing to pay €516 as a share of their overall household spending per year, which is equivalent to €43 per month, to a locally governed pollinator protection fund. Significantly, among the attributes assessed, the WTP for the existence value of pollinators represented by the “endangered insect pollinator species" attribute was €248, followed by the varieties of local fruits and vegetables, €133, then €68 for local wildflowers, and €67 for local quality of fruits and vegetables. The attribute of time was not significant probably because it was not well presented to the respondent or because time is not an important variable for people. However, this could also be because the time attributes (5 years, for a short period of time, versus, 20 years, as a long period of time) that were chosen were not broad enough. Our WTP estimates appear to be in line with the results of studies estimating WTP for pollinator benefits using the stated preference valuation approach in the European context (see Breeze et al., 2015 and Mwebaze et al., 2010, 2018). However, the total WTP we obtained is far greater than those of these studies. As noted in the introduction, in the U.K., Mwebaze et al. (2018) found that the respondents’ WTP for bee conservation alone was about €81.55 per household per year. While Breeze et al. (2015) estimated a total WTP of €110 (and €201 using a different model) per respondent per year for the conservation of crop products and wildflowers as use values for pollinator attributes.

Aside from the fact that in this chapter, we considered more attributes of the benefits of pollinators than those considered in previous studies, these WTP differences can be explained primarily by the difference in our respective i) methodologies and ii) case study contexts.

i) Limits related to our study methodology

Results are subject to three main typical limitations (see further details in Breeze et al., 2015) which are the lack and heterogeneity of information for respondents of targeted sample, specification of non-monetary attributes, and the design of a suitable payment vehicle and transaction mechanism.

The first limitation is the fact that, while it is necessary to base observations on the general public to account for the concerns of different actors regarding pollinators decline, initial information, consciousness, understanding, responsibility, etc. among respondents from the general public may differ (Mwebaze, 2010). The general public includes actors (producers, consumers, or environmentalists, etc.) who may have different responsibilities or conflicting agendas with respect to the problem of pollinators decline. Such considerations make the C.E design more complex and imply heterogeneity in the preferences of respondents, which our results confirmed. In this study, we sought ways to overcome such a limit, by providing basic information about the current trend of pollinators decline at the beginning of the interview with each respondent (see the first part of the questionnaire in appendix 3.4). This effort to provide basic information aimed at reducing the heterogeneity of initial information about the benefits of pollinators among respondents. However, such information may have influenced our WTP results by increasing the potential sensitivity of respondents to pollinators and subsequently the attribute “endangered insect pollinator species”. Likewise, even though the “endangered insect pollinator species" attribute was represented as the satisfaction that individuals can derive from the mere knowledge of the existence (the present and the future) of pollinating insects (i.e., Davidson et al., 2013), it is necessary to note that people do not necessarily make this distinction themselves. Thus, the respondents’ inherent consciousness or understanding towards this existence value can still differ, which is supported by other definitions that exist in the literature (see for example Aldred, 1994; Attfield, 1998; Davidson, 2013, TEEB, 2010). Indeed, in economic literature, as mentioned in the introduction, the definition of this value remains controversial. For instance, for Aldred (1994), existence value can be defined as a person’s willingness to pay to preserve a resource for which he has no current or future plans for use, simply because it is seen as a practical indicator of moral value. But, for Davidson (2013), existence value refers to the satisfaction that individuals can derive from the mere knowledge that Nature (part) continues to exist. And in TEEB (2010), existence value represents the marginal utility that a species brings us just because it exists. Or, as mentioned earlier, people can value pollinators not exclusively for the sake of their existence but also for their importance for biodiversity preservation purposes, their current unknown contribution to Nature, and for the sake of future generations (see Aldred 1994); - i.e. all linked together. Also, as we argued in Chapter 1 (Section 1.4.1), even for well-informed economic agents, the reason to act can be driven by different forces (i.e. moral or ethical, economic, collective, etc.; See Chapter 1, Section 1.4.1).

The second limitation concerns the specification of non-monetary attributes and the relevance of their definition. As Breeze et al. (2015) pointed out to be one of the limitations they met in their C.E. design, marking and specifying attributes of pollinators in detail is one way to help respondents learn about their preferences in a hypothetical market of the benefits of pollinators. Well-defined attributes are important for respondents to maximally incorporate all attributes presented to them into their decision-making process. Therefore, our study proposes to explicit in the valuation three more characteristics of the benefits of pollinators that were not captured previously in Breeze et al. (2015). These three additional benefits are the quality of local fruits and vegetables, the varieties of local fruits and vegetables, and the existence value of insect pollinators as a component of their biodiversity heritage. Despite this effort to detail the attributes considered in our C.E. design, a high number of attributes makes the scenario analysis closer to reality but more complex for the respondents. In fact, like other methods of monetary assessment, the C.E. invites the respondents to focus on the various end-services rendered by Nature.

However, by the very fact of responding to a series of successive questions in a short time, the C.E. does not always allow the respondents to establish interrelations between these various characteristics of attributes constituting a choice set submitted to them for their assessment. The design of our C.E. does not overcome this difficulty. Thus, some respondents assessed, perhaps, the benefits that they could obtain from each of the attributes independently of each other, thus not as a whole. Thus, we cannot be sure if respondents valued a set of the benefits of each time they made a choice or if they just concentrated on their preferred attribute. If this is the case, the importance of trying to mark and specify the benefits of pollinators in detail may not significantly stimulate complex thinking of respondents. Yet, as de Groot et al. (2002) put it, these interrelations are critical elements in understanding the complexity of ecosystems and measuring their effects on economic activity.

Finally, the third limitation concerns the design of a suitable payment vehicle and transaction mechanism. The monetary contribution attribute we mobilized as a payment vehicle can also have repercussions on our WTP results. As expressed previously (Section 3.4.1) through discussions with the local panels, suggestions pointed to a contribution paid to a local pollinator protection fund in contrast to a tax levied and used under the responsibility of the State. Therefore, it is difficult to ascertain whether the respondents considered this cost attribute, which is perhaps new to their reality, in their budget constraint before the expression of the WTP. In addition, the levels of the monetary contribution attributes we used were higher than those proposed in other studies, which had a significant negative impact on the results of respondents' choices. Thus, if we had proposed lower monetary values in the scenarios, our results would likely have been different.

ii) Limits linked to the case study context

From a contextual perspective, the higher WTP found in this analysis may probably reflect the trust that local actors may have for a locally governed entity in relation to the government taxation system. Or the doubt these actors may have about the readiness and eagerness of public policies to integrate pollinators into a conservation scheme. But also, the population of the studied area has a particular relationship with pollinating insects and is therefore too sensitive to their decline. Indeed, based on the daily occupations or practices of this population, they can directly observe the effects of pollinators decline through a lower abundance of crops in vegetable gardens, lower quality of fruits and vegetables on the local markets, and even the disappearance of wildflowers in their surroundings. In difference to what Breeze et al. (2015) has found when these authors applied a similar method but generalizes their results at a national scale.

In sum, despite the limitations described above, our WTP estimates remain useful for an initial assessment of the economic value of pollinator benefits in France. Using the C.E., we found that in the study area, the general public is sensitive to the issue of pollinators decline and is strongly willing to participate in protecting pollinators to safeguard their benefits. However, C.E. may be less effective at stimulating complex reasoning, promoting critical examination of established beliefs, and supporting the search for common interests. For example, our C.E. does not allow respondents to consider the needs of future generations or the trade-offs between safeguarding pollinators and the direct dependence of some local actors on intensified farming, which can have negative effects on the population of pollinators. Yet, such attitudes are essential given the Nature of the common good that insect pollination services constitute (see Chapter 1). Nevertheless, this study indicates that responses to pollinator decline must take into account the heterogeneity of individual preferences, awareness and responsibility for pollinator benefits, the multiple actors involved, and the many environmental values at stake, including use and non-use values.

In the next section, we conclude this chapter by highlighting its implications for public policy making and the economic valuation literature focusing on pollinator benefits.

3.5. Conclusion

Using the C.E. survey, we studied willingness to pay for marketed and non-marketed benefits of pollinators in Comminges territory, in Southwestern France. Specifically, in this study, the focus was on the assessment that precedes the quest for public policy responses to the issue of pollinators decline at the local scale. We considered that it involves a crucial moment in promoting local actors' preferences or choices in the environmental domain to inform policymaking at that scale. We emphasized, however, that the results of this assessment could vary depending on the context in which the study is conducted. As we conclude, we reiterate our main findings and their implications.

Our C.E. results indicated important sensitivity of respondents to various levels of marketed and non-marketed benefits of pollinators through the stated preference approach in terms of marginal values. In particular, by incorporating the existence value attribute, our hope was to strengthen the scope of economic valuation tools to the non-values dimension, which was demonstrated to be of utmost importance to the rural population. This information can be beneficial to inform the orientation of public policy responses to pollinator decline issues. Also, analyzing the preference heterogeneity of respondents provided important information within a population of individuals. The introduction of interaction variables into the analysis, between the attributes and individual characteristics, helped us better explain this variability, enabling the public policymakers to better target their intervention intended for such a social group. For instance, in the case of this study, respondents' level of education and membership of respondents in environmental association prove to be characteristics capable of reinforcing the sensitivity of an individual vis-à-vis the preservation of wild pollinators.

As such, our results may have implications for the design of public policies and in the economic valuation literature. On the one hand, our results can be used in public policies regarding local agro-ecological transition that focus primarily on insect pollinators, pollination and other ecosystem services. Specifically, our results can be used if public policies need to apply more localized and inclusive measures or actions by considering the preferences of the actors in a territory, which can be more effective. Also, our analysis in this chapter may allow for the consideration of cost-benefit analysis and payments for ecosystem services in future local stakeholder coordination. Indeed, as mentioned in the introduction, it may allow local public authorities to facilitate arbitration within local actors. On the other hand, our results may lead to an improvement of the economic valuation of pollinator benefits and thus trigger further steps in the environmental valuation literature. Indeed, considering a territorial scale is interesting because it allows an in-depth consideration of the interaction between stakeholders and their natural environment.

In future research, it may be worthwhile to translate the preferences recorded in this study into public policy measures. In doing so, the interdependence of pollinator benefits, the multiple actors involved, and the many environmental values at stake should be taken into account to allow for the development of effective pollinator protection instruments that involve all actors in local and collective actions on a territory. In line with other existing studies (e.g., Fleury et al., 2010; Schaafsma et al., 2017), for example, the mobilization of complex thinking and the implementation of social rationality in future economic valuation (such as Deliberative Monetary Valuation) can be useful to design such measures.

Chapter 4 - Vulnerability Analysis of Food Production and Nutrient Consumption on Pollinators Decline: The Case of Smallholder Farm Households in the Huye District in Southern Rwanda

4.1. Introduction

The degradation of pollination; a key ecosystem service in agriculture (Gemmil-Heren, 2016); increases concerns about the availability and the accessibility of diverse and nutritious food (Garibaldi et al., 2011a; IPBES, 2016). This decline is subject to a decrease in the quantity of crop production, an increase in prices of agricultural commodities, and a decrease in nutritional quality consumption (as developed in Chapter 2). This is especially true for fruits and vegetables rich in essential nutrients (see for example Chaplin-Kramer et al., 2014).

The consequences of the decline of pollination services on social welfare are global but heterogeneous across countries (e.g., Gallai et al., 2009; Bauer and Wing, 2016). Countries with fewer adaptation capacities in production can be more impacted (Bauer and Wing, 2010). Indeed, some countries are net exporters of pollinator-dependent crops (e.g., cocoa production in Ivory Coast), while others (e.g., the United States, Switzerland, Belgium, etc. for chocolate production) are net importers of these crops (see, for example, Bauer and Wing, 2016). For exporting countries, pollinators decline will increase the marginal costs of pollinator-dependent crops that result in uncertain income. Importing countries, in turn, will consume less of these imported products if their prices rise. However, imported products that depend on pollinators are very frequently rich in nutrients. Consequently, these importing countries will lose nutrients intake. This can become a problem for countries that are on the verge of malnutrition and, even more so, for countries that are already food insecure. Thus, countries with developing economies can be particularly vulnerable to pollination services decline since 1) they may have less adaptation capacity and 2) most of them have already nutrition problems (Chapter 2).

In this chapter, we draw particular attention to the relation between insect pollination and agriculture in the developing economies context. The agricultural sector in developing economies has some specificities. This sector consists of actors that are “considered” active in agriculture such as individual producers operating big or medium-scale farms, cooperatives of farmers organizing their farms together to increase their competitiveness on the market, and also farm households operating smallholdings. Smallholder farms are more common for low-income households who farm for subsistence (FAO, 2014). A smallholder farm, in general, is defined as a farm with lesser than two hectares (Lowder et al., 2016; Ricciardi et al., 2018; World Bank, 2019), while 72% of the world's farms are smaller than 1 ha (FAO, 2014). Lowder et al. (2016) reports that: "Of an estimated 570 million farms worldwide, almost 475 million are smallholder farms, representing 84 percent of all farms and operating about 12 percent of all farmland. ... almost 80 percent of smallholder farms are in low- and middle-income regions." The production assets of the low-income households are predominantly their small farms, family labors and agroecosystem services (Dixon et al., 2001). These farm households interact daily with and base their livelihood on natural resources (Chen and Ravallion, 2007).

From a theoretical point of view, the particular feature of farm households in developing countries has been the fact that they are both producers and consumers of crops and, consequently, the imperfection of markets in which they operate makes their production and consumption decisions often interdependent (Barnum and Squire, 1979, de Janvry et al., 1991; Sadoulet and de Janvry, 1995). Thus, any shock affecting the production of this type of farm households has direct effects not only on their income but also on the quantity and quality of their food consumption. In the case of farm households that produce diverse crops to cover a large share of their food needs, as is the case of smallholder farm households, pollination services decline may particularly generate the most immediate losses. As stated by Cely-Santos and Lu (2019), smallholder farm households are on the frontline since the diversity of crops they grow on their farm depends on the pollination services more than those in monoculture farming systems.

Hence our interest in this chapter is to focus, specifically, on smallholder farm households in developing economies context, using the Rwanda case study.

In Rwanda, around 80% of the population relies on smallholdings of 0.7 of a hectare on average as a source of livelihood (World Bank data, 2018), the Gross National Income is around $780 per capita, per year, and almost half of the population lives in extreme poverty (i.e. as defined by the World Bank). Moreover, farming activity in this country remains generally dominated by traditional practices aimed at subsistence production (NISR, 2019b). The choice of Rwanda as our field of study was not only motivated by lived experiences[26] but also by the fact that, under FAO partnership, this country seeks effective ways of adopting intensive farming while at the same time it declares to enhance environmental

[26] As noted in the general introduction, I was born and raised in Rwanda in a family and community of small-scale farmers. I also have worked with farmers in this country for five years.

patterns. Intensive farming refers to a system dominated by the introduction of monoculture systems, inorganic fertilizers, and high pesticide use (Perfecto et al., 2019). Rwanda is indeed among few FAO project partners that are actively collaborating for a more integrated way of supporting agriculture development by linking the efficient use of high-value inputs with the use of natural resources for sustainable production (FAO, 2017a). However, for now, this country is experiencing a loss of biodiversity in its agroecosystems throughout the country, particularly where agricultural intensification is taking place (Wong et al., 2005).

This case is of particular interest for our research as the development of economic activities and protection of ecosystem services are both imperative to improve the quality of life of low-income farm households in developing economies like Rwanda. Yet, the management of trade-offs between them, economic activities development and protection of ecosystem services, in an area is a daunting challenge (see, for example, Delgado-Serrano, 2017). On the one side, the improvement of farm household welfare relies heavily on the development of the economic efficiency of agricultural practices. However, on the other side, agricultural practices can also threaten the availability and accessibility of diverse and nutritious food for smallholder farmers if the benefits of pollination - and other ecosystem services - are not taken into consideration in decision-making.

As intensive farming systems come under increasing criticisms worldwide, the feasibility of adopting intensive practices and high-value inputs on small farms and by low-income farm households, which dominate developing economies, is also a matter of controversy. Particularly, several scientists and key stakeholders in agriculture development are generating controversies over efficiency that makes up technical and economic as well as environmental characteristics of farming practices, notably on smallholdings in developing economies context. For instance, the Alliance for a Green Revolution in Africa (AGRA, 2016) reports the importance of adopting intensive farming systems in this context. According to this AGRA's report, the adoption of intensive and high-value input practices is a major way to secure food, raise the level of income, and thus eradicate poverty for smallholder farmers dominating African agriculture.

On the other hand, intensive farming systems face growing criticisms not only due to their negative impacts on ecosystems and ecosystem services (MEA, 2005; IPBES, 2016) but also because they may not be efficient for sustainable production nor nutritious food provision. Poorly regulated crop intensification practices can generate important ecosystem disservices, such as the deterioration of food and habitat of pollinators, which may negatively affect human well-being in a longer-term perspective.

Intensification practices may particularly not be effective for low-income smallholder farm households (e.g., Behrman and Deolalikar, 1990; de Janvry et al., 2009; Musahara and Huggins, 2005; Pritchard, 2013; Gassner et al., 2019). Three main reasons are given. Firstly, it may not be feasible for farmers to rely on economies of scale when operating smallholdings without other solid financial support (e.g., Musahara and Huggins, 2005; Gassner et al., 2019). For Gassner et al. (2019), intensification would not increase in a significant way current smallholder farm household income to more than US$1.90 per capita per day. In fact, according to these authors, these households would remain below the poverty line (i.e. as defined by the World Bank) in the longer term, even if intensification were to increase smallholder households' income in the short term.

Secondly, a large body of literature reports that increased income could not guarantee the consumption of nutritious food for the low-income households (e.g., Behrman and Deolalikar, 1990; Sadoulet and de Janvry, 1995; de Janvry et al., 2009; Sibhatu et al., 2015; Jones, 2017). Sadoulet and de Janvry (1995) demonstrate that as the income of poor people rises, it is likely that they will trade nutritional quality consumption of food for quantity consumption of food. If the income of these households increases, they could replace nutritious food with other characteristics of food such as better taste. Also, it is increasingly recognized that increasing the quantity of staple crop production alone can reduce the diversity of production, and thus deteriorate the nutritional quality of consumption, especially in the rural food systems (Global Panel on Agriculture and Food Systems for Nutrition, 2016, Jones et al., 2014; Bogard et al.; 2018). As Bogard et al. (2018) note, "many [nutritious] foods in rural food systems, such as fruits, vegetables, … still pass from production to consumption relatively unchanged in terms of nutritional value".

Thirdly, the adoption of efficient crop intensification systems has challenged smallholder farm households as their low level of income limits their ability to purchase high-value inputs (Pritchard, 2013).

In general, smallholder farm households' production and nutritious food accessibility, and availability in developing countries' context depend mainly on a range of social, economic, and environmental factors, especially the state of agroecosystems and ecosystem services interactions (MEA, 2005). Integrating all these dimensions in a set of decisions is complex. It is thus important to help these farmers and their governments to develop better-tailored tools to support decisions towards efficient farming practices.

The objective of this chapter is to propose a tool using economic valuation to analyze the benefits of free pollination services to smallholder farm household production, nutritious food consumption, and income generation. The economic valuation of the benefits of pollination services to the welfare of smallholder farm households is a tool among others that would help inform further decision-making taking into account the different aspects of these services in the holistic management of agroecosystems. Notably, as highlighted in Chapter 3, it is a means of raising individuals and collective awareness on threatened ecosystem services and the consequences of their degradation on social welfare.

Only a few studies have assessed the contribution of pollination services on well-being in developing economies context. Of those studies, IPBES (2016) estimated that the Insect Pollination Economic Value, for example, in Africa as a whole is worth US$11.9 billion that represents 8% of Africa's crop production value for human food. At the farm level, for example, in 2005 in Kenya, Nderitu et al. (2008) found that the value of pollination services was US$1,697.21 for sunflower production in Makueni District, accounting for 51% of the total value of sunflower in this district. Mushambanyi and Munyuli (2014) found that pollination services value, in Central Uganda, was about US$149.42 million from 0.401 million tons of coffee beans produced. In the case of Tanzania, Tibesigwa et al. (2019) estimated that the change in natural habitats of wild pollinators between 2008 and 2013 had reduced the mean of crop revenue by 29%.

Previous studies have barely addressed the consequences of pollinators decline at the household level. Yet, it is important to consider the impact of this decline on farm household welfare. Thus, the economic valuation of the benefits of pollination services at the household level, as well as their implications for the livelihoods of farm households, especially in developing economies context, is a concern. Cely Santos and Lu (ibid) is among few studies that assessed the contribution of pollination services to smallholder farmers' livelihood. Note that this study focuses on Colombia[27], an upper-middle-income economy. One of its conclusions is the following:

> "*Now their* [smallholder] *agricultural production is threatened by pollinators declines driven by agro-industrial practices, which are conducted by wealthier households who secure food access by purchasing foods that include fruits dependent on animal pollination formerly grown locally. These dynamics leave low-income farmers surrounded by simplified, chemical-laden landscapes inhospitable to the bees upon which their agricultural livelihoods depend; and faced with food insecurity, unable to afford or access culturally important foods they used to cultivate.*"

This chapter raises new questions and proposes a new analysis approach at the household level in Rwanda, a developing country with a low-income economy. The novelty is that we propose to assess 1) the vulnerability of food production and nutrient consumption of smallholder farm households on insect

[27] In the World Bank country classification, Colombia is a developing country and also an upper-middle income economy with 6,510 GNI per capita in 2019 (World Bank data, 2019).

pollination decline 2) in a particular context where both production and consumption are often interlinked relative to other farm households (e.g., Colombia, an upper-middle-income economy and a developing country). By vulnerability, we refer to farm households' exposure, sensitivity, and also the adaptive capacity of their food systems faced with a disruptive environmental change as it is defined in Turner et al. (2003). This study can stir up the literature on the economic valuation of ecosystem services at the farm household level in developing countries dominated by subsistence agriculture systems.

From an analytical and theoretical standpoint, we were inspired by the farm household theory first developed in economic models analyzing interdependence between utility and profit maximization decisions of farm households (e.g., Kuroda and Yotopoulos, 1978; Barnum and Squire, 1979; Dillon and Barrett, 2017; Chenoune et al., 2017). This theory postulates that the welfare of farm households in developing economies depends on jointed production and consumption decisions, given that their utility is subject to farm production and cash flow constraints (on and off-farm income). Due to these jointed production-consumption decisions, the decline of pollinators would impact simultaneously the farm household income and nutrition consumption. Analytically, we base our analysis on the production function approach (i.e. as described in Chapter 1) referring to Gallai et al. (2009) model that mobilizes the crop-pollinators dependence ratio method (i.e. as used in Chapter 2). For nutrition aspects, we base our analysis on nutrient ratios found in Chaplin-Kramer et al. (2014) (i.e. as in Chapter 2).

From the data collection standpoint, to identify the impacts of pollination services decline on smallholder farm households, a closer look at their food production, supply, and consumption is proposed in a case study. We conducted a questionnaire-based survey on a household scale. This survey took place in the Huye district in southern Rwanda. Based on a preliminary survey, which we carried out with local stakeholders from the private sector, public sector, University of Rwanda, and civil societies in November and December 2017, the current threats to ecosystems affect insect pollination services too. For instance, according to the Huye District chief agronomist, the degradation of honeybee pollinators in areas where crop farming interacts with beekeeping is at the origin of existing conflicts between local beekeepers and farmers in this area.

Thanks to this methodology, we estimate the vulnerability of food production and nutrient consumption to the insect pollination decline in the case of farm households in the Huye District focusing on their crop production quantity, their nutritional quality consumption, their supply income, and their food demand. First, we estimate the vulnerability of farm household production on insect pollination decline. Second, we estimate the vulnerability of income from supply of farm households on insect pollination decline. Third, we quantify the vulnerability of farm household nutrient consumption on insect pollination decline based on their total consumption, which include both self-supplied food and market demand for food.

This chapter shows that, in the studied area, insect pollination services contribute to the agricultural revenues and they participate especially to the nutritional quality of food produced by and for farm households, allowing thus these households to self-supplying essential nutrients contained in pollinator-dependent crops such as fruits, vegetables, and oilseeds. It shows, indeed, that if insect pollinators are completely extinct, more than half of the nutrients contained in the consumed fruits by these small farm households will be lost.

The rest of this chapter is divided into six sections and concluding remarks. The second section reviews the literature on determinants of farm households' production and consumption decisions, these households' dependence on ecosystem services for the production and nutritional quality consumption, and introduces the pollination service benefits in this reasoning. The third section describes our case study. The fourth section presents the methodological framework we use to assess the contribution of insect pollinators to farm households' production and consumption in this region. The fifth section sets out the main results obtained in details. The sixth section discusses the vulnerability ratios we found, the limits of the economic model used, and perspectives of possible changes under different scenarios of government interventions in the future. Finally, our concluding remarks are devoted to the implications of our findings in decision-making and future research perspectives.

4.2. Literature review on determinants of farm households' production and consumption decisions: How do the benefits of pollination services fit into this reasoning?

A farm household refers to a group of individuals who share the same living accommodation, consume certain types of goods and services collectively (e.g., food), and at least one member of the household is operating an agricultural land (OECD, 2002). The decisions of this farm household concerning farm production, consumption, and labor supply are taken altogether by the same economic unit, a household. A farm household decides, for example, the crops to produce, the farming practices to implement, the inputs to apply, when to plow, to seed, to harvest; how much to keep for consumption in the household and how much to sell to raise the cash necessary for other needs, or how much to store for future consumption or as seeds.

To extend the analysis of the impacts of pollination decline to the farm household well-being in a developing economies context, and more specifically, in a subsistence agriculture economy, we begin by setting the stage in four respects. First, we propose a review of the theoretical literature dedicated to the production, supply, and food consumption decisions of a farm household. Second, we highlight the dependence of the production and nutritional consumption of farm households on ecosystem services in a developing economy context. Then, we introduce insect pollination services in this reasoning. Last, we conclude this section by providing a synthesis of hypotheses that this literature review allows us to pose.

4.2.1. Farm household decisions from theoretical literature standpoints

In economic theories, determinants of production, supply, and consumption decisions in the case of farm households operating in developing countries have particularities compared to what usually happens in standard cases, mainly due to market conditions under which they operate. On the one hand, we review the differences in production and consumption decisions between this farm household and other economic agents. On the other hand, we review the theoretical implications of different market settings for farm household decisions.

1) The differences in production and consumption decisions between a farm household in developing countries context and other economic agents

One of the conclusions of major economic studies modeling the decisions of a farm household in developing countries (e.g., Barnum and Squire, 1979; de Janvry et al., 1991, 2020; Key et al.; 2000) is that this farm household makes production and consumption decisions jointly. This result sharply contrasts with standard approaches where a household makes independent production and consumption decisions as two separate economic agents would decide, either as a producer seeking to maximize its profit or as a consumer seeking to maximize its utility.

In other words, a farm household, as a standard producer, theoretically makes resource allocation decisions to different productions with the expectation to maximize farm profit. The standard supply decision considers the relationship between quantities produced and inputs factors used; the outcome of this decision-making affects the willingness and ability of a farm household as an economic agent to buy inputs and sell goods or services on the market. Specifically, a farm household can supply a share of its farm products and the time of its household members to the market. Theoretically, factors that influence the ability of a farm household to supply, as is the case for a standard producer, including the price and quantity of a good it plans to sell in the market and the related production costs.

On the other hand, a farm household, as a standard consumer, theoretically, makes the optimum decisions focusing only on the allocation of both his disposable income and time. These decisions imply the allocation of income gained from various activities for the consumption of goods and services and the decision on the amount of labor to allocate (or not) eventually to both on and off-farm activities to maximize their utility (Taylor et al., 2008). In theory, the demand decisions of a farm household, as those of a standard consumer, consider factors such as market prices of goods and services, its budget constraint, its preferences, market prices of substitute and complementary to its preferred goods and services, etc.

In contrast to a non-farmer economic agent, however, the production and consumption-related decisions of a farm household may also consider its farm and household socio-economic characteristics and its price band (Lopez, 1984; Benjamin, 1992). Price band refers to price margins between the lowest price at which a farm household could sell a commodity and the highest price at which it could buy that product on the market (Key et al., 2020). This band price is very important to underline here because it interferes with the decision of a farm household about how much of its produced goods to self-supply, and how much of these produced goods to offer on the market, as a net seller, as well as the amounts of crops to buy from the market, as a net buyer.

Indeed, as stated above, a distinction between decisions of farm household operating in developing countries context and other economic agents is importantly based on the market conditions in which this household operates.

2) Implications of market conditions on farm household decisions

According to Barnum and Squire's (1979) analytical model of the farm household, which is complemented by the work of various economists such as Sadoulet and de Janvry (1995, 2020), the optimal decisions of a farm household operating in a competitive market result in separable supply and demand functions, as in standard consumer or producer models. The supply (and demand) function represents the relationship between the quantity supplied (and demanded) of a product or service, its price, and other associated factors. Likewise, this model depicts that the optimal decisions of a farm household operating in a non-competitive market result in joint supply and demand functions. What does this model mean? What does it imply to our analysis?

From theoretical literature standpoints, the production-consumption relationships of a farm household and its supply (demand) relationships to market prices can be illustrated by both Figure 4.1 and Figure 4.2 below. Figure 4.1 describes the main determinants of a farm household’s production and consumption decisions in different market contexts. Figure 4.2 represents the relationship between the quantity of a product supplied (and demanded) by this household, the price this household assigns to its product, and the market price. Through these two figures, we elaborate further on the implications of different market contexts on farm household decisions including in theoretical extreme conditions where markets can be assumed to be perfect and in more realistic conditions where markets are imperfect or even absent for some particular goods or services.

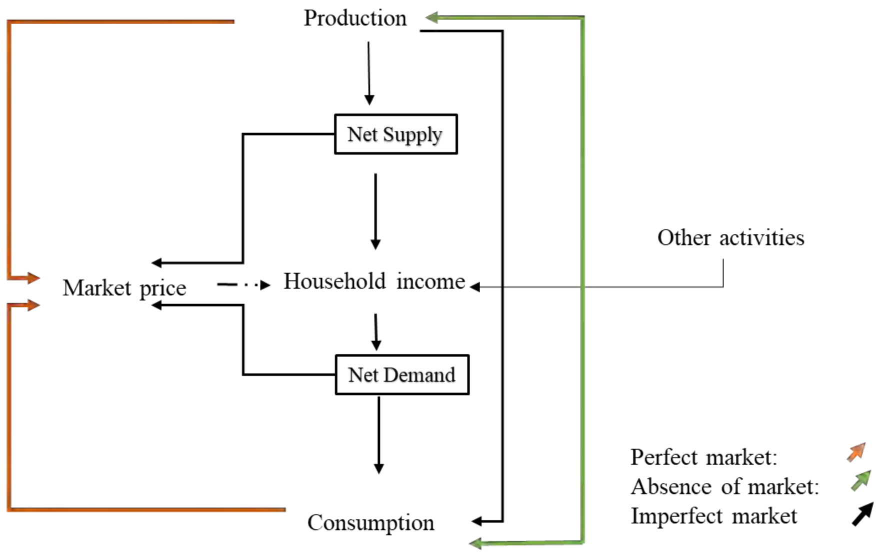


Figure 4. 1. Determinants of the decisions of farm household production and consumption in different market conditions

Source: Adapted from Sadoulet and de Janvry (1995)

a) The case of perfect markets

In theory, a perfect market refers to the existence of perfect competition. The existence of perfect competition is characterized by a large number of sellers selling identical products to a large number of buyers while both categories of agents have the same access to information regarding traded goods or services and are free to enter and exit any markets, by perfect mobility of factors of production and goods, and by the absence of price controls. In this case, all products and factors are tradable with no transaction costs (Key et al., 2000). Consequently, in perfect markets, household production, consumption, and work decisions models can be set in terms of market prices. For instance, a model of a farm household operating in an area where markets are competitive can show that this household is indifferent between consuming own-produced and market-purchased goods and can allocate indifferently production between consumption and market sales. In other words, production patterns do not affect consumption patterns and production is independent of household preferences. In this case, the farm household behaves as if production and consumption decisions are made sequentially (Sadoulet and de Janvry, 1995). It means that since farm profit is part of the household income on which consumption depends the production decisions of farm households can be analyzed before the consumption decisions (Sadoulet and de Janvry, 1995). In the theory of agricultural household, this makes more sense, but buyers of agricultural products may propose advances to the farmers through certain arrangements, such as contracts.

Also, in the case markets function perfectly for all goods and services, for a given household, theoretically, the production decision that maximizes the farm profit consists in allocating its resource according to its competitive advantage which would lead to more specialization by selecting few competitive crops on his farm. Along with production decisions, the theoretical model stipulates also that such a household would decide the number (in terms of variety) and quantity of the goods to supply to the market. On the other hand, subject to budget constraints, the household maximizes its utility by choosing the number of goods and services to buy from the market as well as labor time to offer (or not) in off-farm activities. Therefore, when markets function perfectly, the theory states that farm household supply and demand depends on market prices and its production and consumption decisions are independent of each other. As such, these decisions can be analyzed within the framework of the standard microeconomic theory of the producer, whose objective is to maximize profits, and the consumer, whose objective is maximizing utility. The utility of a farm household being a function of the number of goods and free or leisure time consumed.

However, in the framework of these models, empirical analyses of various economic studies (e.g., Sadoulet and de Janvry, 1995; Key et al., 2000) show that even if all markets work perfectly, some of farm household production is kept for home consumption. Indeed, based on the variety and quantity of crops produced, a farm household can behave either as a net seller or a net buyer for a share of its products relative to market prices, its preferences, and its internal prices (see Varian, 2010 (1987), 8th Edition, Chap 9, Figure 9.6). The internal price refers to a shadow price or a monetary value that this household assigns to its product out of market price. Each farm household's internal price may differ based on household resource endowment and the level of transaction costs.

What this case implies for our analysis is that a farmer operating under perfect market conditions can have a choice based on competitive advantage and decide to specialize in either pollinator-dependent or non-pollinator-dependent crops.

In reality, nevertheless, this farm household has to take into account the presence of market imperfections (e.g., transaction costs, asymmetry of information, price control power, etc.) and therefore adapts its demand and supply decisions accordingly; or it can face the absence of a market for some goods or services.

b) The case of imperfect markets

In theory, an imperfect market refers to a situation of imperfect competition in which the characteristics of an economic market do not meet all the necessary conditions of a perfectly competitive market, as mentioned above. For example, when agents acting in such a market have the power to influence the price of a good or service and thus raise the market price of this good or service above marginal costs; or when a farm household faces high transaction costs such as the cost of transporting agricultural commodities to major market centers (Stifel et al., 2003).

This imperfect market situation can have a significant impact not only on the economic performance but also on the behavior of a farm household operating in it, especially in the case of a shock in production as is the case with the decline of pollinators. See, for example, how differences in the level of transaction costs contrast the standard supply of farm households in a perfect market with the supply in an imperfect market in Figure 4.2 below. As this figure shows, in theory, the optimal solution for a farm household concerning his outputs utilization in the presence of transaction cost can be threefold:

1) A farm household may behave as an autarkic. In this case, the optimal solution for this household is to produce completely for self-consumption. As Figure 4.2a shows the presence of transaction costs τ for a farm household makes its marketed production not profitable within the price band (as defined above section 4.2.1.1.) between $P - \tau^s$ and $P + \tau^b$. $\boldsymbol{P}$ depicts market price, $P - \tau^s$ illustrates the low price at which a farm household could sell (s) a product, hence τ^s, and $P + \tau^b$ shows the high price at which it could buy (b) that product on the market, hence τ^b. As Figure 4.2b shows, this means that within this price band, household supply is inelastic to market price, till price change sufficiently to cover its transaction costs. This is the case for a household in an autarky with a supply curve S^* where the internal household equilibrium defines the internal price at $\boldsymbol{P}^*$.

2) A farm household may behave as a net seller when the demand and supply equilibrium internally within a farm household is established below the price band, as Figure 4.2a illustrates with the supply curve S^s. Thus, this household, as a seller, would effectively enjoy selling at the price $P - \tau^s$ which is greater than its internal price (green area on the supply curve, figure 4.2b).

3) A farm household can behave as a net buyer when the internal demand and supply equilibrium is established above the price band, as for the supply curve S^b on the figure 4.2b. Thus, this household, as a buyer, would effectively enjoy the price $P + \tau^s$ which is lesser than its internal price (orange area on the supply curve, figure 4.2b).

Therefore, in the framework of imperfect markets model, if the transaction costs are high for farm households, it is rational to produce their food entirely by themselves or to decrease the market share of their food supply and increase instead the share of their self-consumption to effectively meet their nutritional needs (Sadoulet and de Janvry, 1995).

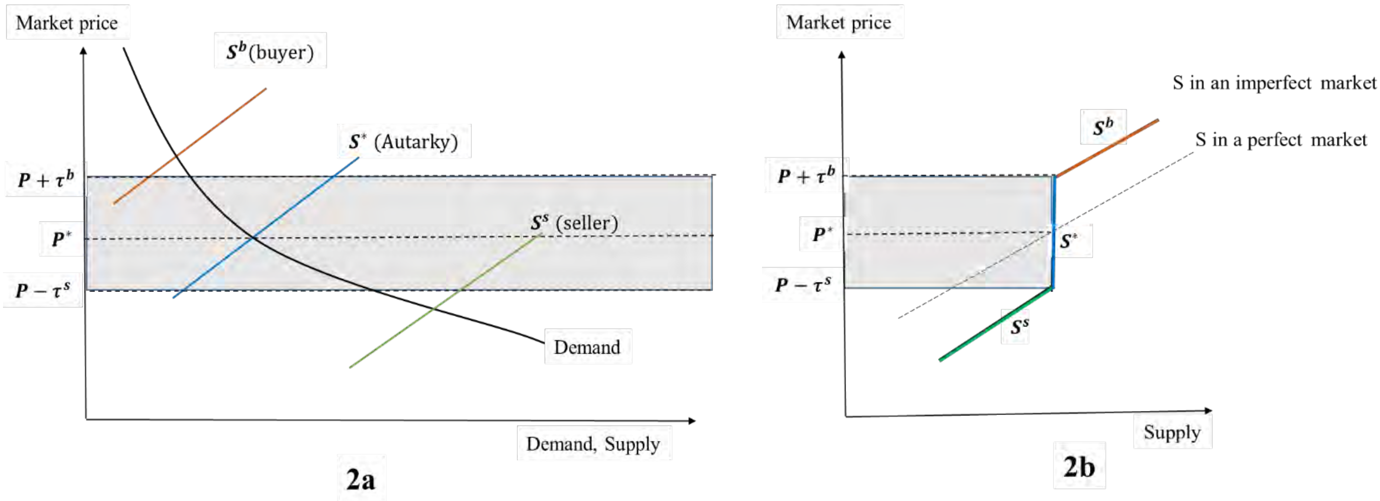


Figure 4. 2. Graphical representation of farm household supply and demand curve (2a) and farm household standard supply curve in a perfect market relative to supply in an imperfect market (2b)

Source: de Janvry et al. (2006) and Key et al. (2000)

Besides, as shown by figure 4.2, the decision-making of farm households is at odds with the standard law of supply and demand stipulating that an increase in market prices increases the quantity supplied on the market. Several empirical studies (see, e.g., Yotopoulos et al., 1974; Taylor et al., 2003) found that, on imperfect markets, an increase in market prices of staple crops results, to some extent, in a decrease of their marketed production share while it increases their self-consumption. Thus, in case of an increase of a staple price the farm household operates a transfer of quantity from the marketed production to its consumption.

What this case implies for our analysis is that in the context of rural areas in developing countries, where farm households operate under imperfect markets condition, to some extent, an increase in market prices may make the consumption of these households more dependent on their own production (as illustrated in Figure 4.2b above). Since the decline of pollinators induces an increase in marginal costs and thus market prices, it may lead to an increased need for farm households to produce pollinator-dependent crops for their own consumption.

Likewise, in the case of goods or services for which there is no market, the dependence of these households on their own production increases.

c) The case of absence of markets

In theory, the absence of a market refers to the fact that the market in which to exchange goods or services does not exist, while it is needed. This implies that a farm household can only consume some of the goods or services it produces if the market of such goods or services does not exist.

In reality, however, it may be related to many factors such as those noted above in other market contexts. For example, even though some goods or services may be abundant in an area, factors such as asymmetric information (e.g., a lack of understanding about who might demand these products) or the fact that these goods or services are isolated may prevent trade. Indeed, most rural economies fall somewhere between pure perfect and pure imperfect market situations (Holden et al., 1998). For example, villages can be isolated from external markets for some goods or services while they can still trade those goods between households within villages and self-supply them. This is especially likely in the case of subsistence agriculture that characterizes rural smallholder farm households in some developing economies where the distinction between produced and consumed crop species (or family labor and hired labor) is narrow. For instance, in Rwanda, where markets of some foods are isolated or missing, the main source of food for rural farm households is produced and self-supplied within the same household but is also sold outside to other households (Cantore, 2011; Yongabo, 2021). The consequence of the imperfection of markets is that it leads to adverse selection (Stiglitz, 1989).

Hence, the absence of markets may lead to unfavorable selection for goods or services for which markets are absent. That is to say, on the one hand, for the goods or services that a farm household cannot exchange due to the absent market, it can only consume them. On the other hand, this farm household cannot buy goods or services it prefers with the money it can get from selling its products if such goods or services are not sold. As such, this farm household cannot enjoy the various benefits that a functioning market offer, including, for example, specialization in competitive crops or economic activities, etc.

Therefore, the absence and the imperfection of markets can catalyze sub-optimal decisions that have detrimental effects on the human welfare (Barrett et al., 2020). Though, it is worth noting that sub-optimal supply and demand decisions of farm households towards demand and supply of goods or services in developing economies can be explained by many complex factors, including not only market factors as we discussed above, but also factors such as poverty, unreliable institutions, etc. For example, a lack of modern postharvest tools such as conservation machines, a lack of stable financial supports such as credit, a lack of off-farm economic activities to substitute with farming activities for farm household members, etc. result in adverse sub-optimal supply and demand decisions for these farm households. Indeed, a lack of conservation machines can lead to sub-optimal decisions such as selling goods at low prices in post-harvest seasons, while buying at a high price in off-peak seasons. Both of these factors are typical and often ubiquitous in rural economies in developing countries (Holden et al., 1998).

While the implications of the absence of markets for some goods or services to farm households can potentially be explored further, for the scope of this thesis, it is relevant to note that it is important for farm households operating in these market conditions to avoid pollinators decline. The reason being that this decline can increase farm households' marginal costs and thus reduce the benefits they obtain from pollinators, specifically on pollinator-dependent crops they may produce for their nutritional consumption.

In sum, the above theoretical results about farm household decisions in different market settings underscore the fact that private and public decision-makers should adapt their responses to pollinators decline to these different realities. Initiatives that may depend on collective actions between farm households or other stakeholders and public policies tailored to particular cases such as farm households operating in the context of developing countries can both help farmers make more effective decisions. In the absence of such efforts, the effects on the production of these farm households may have direct consequences not only on their income but also on their food consumption, with all that may entail.

Subsequently, we propose to focus on economic studies highlighting the role of local ecosystem services in the developing countries in farm production and, thence, in the consumption of nutritious food by farm households.

4.2.2. Farm household dependence on ecosystem services for production and nutritional quality consumption

As noted in Chapter 1, natural ecosystems are made up of communities of plants, animals, and other organisms that interact and provide a variety of services beneficial to human well-being, with or without deliberate management. The benefits of these ecosystem services for farm households are manifold (see, for example, Zhang et al., 2007). For instance, these benefits include those associated with direct economic uses that contribute to household income, protecting human health and mitigation of diseases and hazards. These natural ecosystems provide direct provision services to the farm households, through processes of farming or extraction of wild human food, forest products, feed for livestock, medicinal plants, etc. Ecosystem ensures provision, regulation, and cultural services (MEA, 2005) but it contributes particularly to smallholder farm households' production and nutrition in rural areas and cities of developing countries.

Concerning smallholder farm households' production, in fact, given the scarcity of financial and technical capital, the livelihood of these households is based on local natural resources (Chen and Ravallion, 2007). Thus, the production factors of these households are predominantly family labor, agricultural lands, and other natural services (Dixon et al., 2001). Although farming systems may differ depending on the farm type model applied, it is now widely recognized that ecosystem services improve the average, resilience, and stability of agricultural productivity in a sustainable manner (Garibaldi et al., 2011b). Ecosystem services regulate agricultural production, for example by regulating the processing and uptake of soil nutrients by crops, serving as a shelter for "farmer-friendly" insects that keep pests under control organically, or by providing habitat for pollinators which facilitate pollination among crops. Ecosystems services are especially important for the production systems of the non-staple crops (e.g., fruits and vegetables), wild or endogenous edible plants (Klein et al., 2007; Gemmil-Heren et al., 2014). Moreover, fruits and vegetables are categories of plants that have the most shares of essential nutrients (Chaplin-Kramer et al., 2014).

Concerning nutrition in rural areas and cities of developing countries, the agricultural production of smallholder farm households is used for both home consumption and to earn income by supplying nutritious food to the growing urban population. The diversity of food in local markets of developing economies is particularly indebted to smallholder farm households since they tend to grow more diverse crops than bigger-scale commercial farms (Jones, 2017; Cely-Santos and Lu, 2019).

Yet, while it may seem paradoxical, smallholder farmers make up a large proportion of the undernourished people worldwide (FAO, 2014). The food security and improved livelihood of these households remain still a major concern in developing countries. This can be translated into the fact that low-inputs-based production systems do not provide enough food to meet the needs of a growing population in developing economies, while these areas are typically characterized by both traditional farming practices that mobilize fewer inputs (e.g., polyculture) and poor market access. That is, people in these areas often live in institutional settings that are not conducive to alternative viable employment and off-farm income (Pender et al., 1999), which might improve the access of poor households to food diversity through the markets.

Therefore, improving productivity and complementing agricultural income from other sources of income is increasingly crucial to meet the nutritional quality consumption needs of rural farm households. Thus, the transformation of traditional farming systems towards more efficient farming systems seems to be the evident solution to improve the incomes of these households and, de facto, eradicate the problem of food insecurity.

Among solutions addressing the traditional farming limits are intensified monoculture systems that are economically and technically effective for producing staple crops (e.g., maize, rice) aimed at earning money which in turn can be used to meet the food demand of farm households (AGRA, 2016). However, as mentioned in the introduction section, these systems are subject to ongoing criticisms such as being unsustainable and threatening ecosystem services (see e.g., MEA, 2005).

In addition, while intensifying smallholding production is attractive in terms of improving market access and thus farm income, farmers with high transaction costs and limited access to financial support are less likely to participate. These observations are consistent with a variety of studies (e.g., MEA, 2005; Musahara and Huggins, 2005; Pritchard, 2013; Gassner et al., 2019). In short, it is crucial to bear in mind that an increase in income does not guarantee nutritious food consumption for low-income households and such changes may worsen their access to nutritious food such as fruits and vegetables (see e.g., Sadoulet and de Janvry, 1995).

Hence, efficient agricultural systems in developing countries should seek ways to meet food security (as defined by FAO) by increasing the quantity as well as the nutritional quality of production and consumption of farm households in a sustainable manner (Global Panel on Agriculture and Food Systems for Nutrition, 2016). This Global Panel on Agriculture and Food Systems for Nutrition (2016) suggests that establishing such efficient farming systems requires experimental research that could provide a reference to an optimal diversification at both farm and territorial scale and also recommend high-value inputs to be mobilized taking into account the benefits of ecosystem services on local farms.

So far, however, most of the literature on ecosystem services in developing countries, especially in Africa, focuses on the protected areas and their surroundings, notably national parks (Perfecto et al., 2019). The studies on the benefits of ecosystem services on agricultural lands in a country like Rwanda are quite a few − e.g., like that of Andrew and Masozera (2010); Dawson and Martin (2015); and Rukundo et al. (2018). Yet, understanding how ecosystem services dynamics generate and alter due to the trade-offs between these services and agriculture production is important to help national-level decision-makers to plan sustainable and rational agricultural land use for the benefit of all (i.e., de Groot et al., 2007; Long et al., 2012).

In brief, ecosystem services give the ability to people to farm and earn an income, access and use food effectively and contribute to food security. In the context of rural areas in developing economies, physical isolation and the absence of economic opportunities may make some communities highly dependent on ecosystem services, thereby reducing their access to alternative livelihoods (see for example Pomeroy et al., 2006). Even though monoculture practices can be seen as an alternative solution, they can nevertheless trigger both the destruction of ecosystem services and accelerate the loss of dietary diversity and nutritional collapse within the most vulnerable households. This can make rural households especially vulnerable to the degradation of ecosystem services. But, how do pollination services fit into this reasoning?

The following section highlights the vulnerability of production and nutritional consumption to the decline of insect pollination services in the case of farm households.

4.2.3. Vulnerability of farm household production and consumption to insect pollination service decline

The concept of vulnerability has been mobilized in several research fields (see Hufschmidt, 2011). In economics, for example, this concept has been used by Schröter et al. (2005) to assess the impacts of the decreasing supply of ecosystem services in Europe and by Gallai et al. (2009) to assess the impacts of pollinators decline on agriculture worldwide. Hufschmidt (2011) argues that the key factors of this concept are adaptation and adaptive capacity; which encompass human adaptation capacity to natural hazards, the social, economic, cultural, and political structures in which people live, and the constraints they face in their daily lives. Generally, the vulnerability of farm household production and consumption faced with the decline of pollinators can be expressed as a function of exposure, sensitivity, and adaptive capacity of these households to this decline (i.e., Gallai et al., 2009).

In this context, to understand this vulnerability, one has first to understand the dependence of crop production and nutritional consumption on insect pollination services. Insect pollinators and their pollination services are particularly important to the production of a large proportion of food with high nutritional value, like fruits, vegetables, edible oil crops, and other indigenous food crops (Gemmil-Heren et al., 2014). For some crops, insect pollination is not a strict requirement for fruit-bearing but it increases their yields (e.g., tomatoes or coffee) while insect pollination is strictly required for other crops (e.g., avocado) (Klein et al., 2007). In fact, in certain areas of the world, farmers have been renting or buying bee species to improve pollination services on their farms (e.g., California almond growers in the USA) (McGregor, 1976; Olmstead and Wooten, 1987; Gill, 1991; Dag et al., 2006; Klein et al., 2012). A rental market for honey bee colonies exists in developed countries, such as the United States of America (Sumner and Boriss, 2006), Europe (Carreck et al., 1997), etc. Hand pollination is another alternative to insect pollination, like for example in apple farms in Maoxian County in China (Partap and Ya, 2012).

However, it is necessary to highlight that the major staple crops, rich in macronutrients such as many cereals that provide calories (e.g., rice, wheat, maize, millet), can be produced without insect pollination. Many studies, yet, indicate that insect visits have a positive synergy to their production (Klein et al., 2007).

Table 4.1 below shows examples of some of those crops that necessitate pollinator visits to some extent for efficient mating. In addition, those crops are particularly rich in essential micronutrients such as Vitamin A, Vitamin C, Vitamin B6, Foliate, and Iron. Also, it turns out that the insect visits to the floral part of the plant trigger good fertilization, which contributes to a better plant nutrients supply (Chaplin-Kramer et al., 2014).

Table 4. 1. Examples of pollinator-dependent crops, their level of dependence on insect pollination services, and the share of nutrients containing 100g of their production

Crop	Dependence ratio	Nutrients ratio					
		Vitamin A	Vitamin C	Vitamin B6	Folate	Iron	Protein
	%	(IU per 100 g)	(mg per 100 g)	(mg per 100 g)	(mcg per 100 g)	(mg per 100 g)	(g per 100 g)
Onion & shallots	90-100	0	-	-	166	0	8,95
Mangoes	80-100	0	-	-	14	0	0,51
Sunflower	50-100	50	0	1,17	160	4,9	16,18
Cucumber and gherkins	50-90	105	2,8	0,04	7	0,28	0,65
Avocado	40-90	147	8,8	0,287	89	0,61	1,96
Guavas	40-90	0	-	-	14	0	0,51
Tomatoes	10-50	833	12,7	0,08	15	0,27	0,88
Coffee	20-40	0	-	-	2	0	0,12
Soybeans	10-40	180	29	0,065	165	3,55	12,95
Eggplants	10-40	0	-	-	22	0	1,01
Orange	10-30	225	53,2	0,06	30	0,1	0,94
Pigeon peas	0-10	28	0	0,283	456	5,23	21,7
Groundnuts	0-10	0	-	-	240	4,58	25,8
Red beans	0-10	0	-	-	421	0	22,343
Lemons and lime	0-10	36	41,05	0,0615	9,5	0,6	0,9
Papayas	0-10	1094	61,8	0,019	38	0,1	0,61

Source: Klein et al. (2007) and Chaplin-Kramer et al. (2014).
Note: The above numbers are average measures, however, insect pollination demand across crop species will depend on a number of factors, including varietal characteristics of each crop, techniques used, climatic factors, etc. (Eilers et al., 2011).

However, the dependence of crop pollination on pollinators has only been identified for globally known edible crops. The dependence of very local foods and some traditional food crops on insect pollination in rural areas of developing economies is not well understood. For example, according to Abukutsa-Onyango et al. (2010) and Gemmill-Herren et al. (2014), many indigenous crops are dependent on pollinators, especially on the African continent, such as many indigenous vegetables (e.g., amaranth, slender leaf) and many agroforestry fruit trees. These authors argue that the dependence on pollinators of other crops that are of vital importance in the daily consumption of rural households in Africa is not known or measured - for example, African eggplant (Solanum macrocarpon and Solanum gilo). Furthermore, even though the traditional or indigenous crops are essential for local food security and local food culture, their sustenance or even development have received poor attention from a variety of stakeholders including NGOs, scientists, and policy-makers in developing economies (Abukutsa-Onyango et al., 2010; Gemmill-Herren et al., 2014; Cely-Santos and Lu, 2019).

Yet, facing pollination crisis can be a disaster for the rural population in developing economies whose adaptive capacity to insect pollination service decline, via alternative pollination as those mentioned above, is limited. To mitigate such crisis risk, as the World Conference on Disaster Reduction held in Kobe in 2005 concluded, measuring the vulnerability is important to build resilience of nations and communities to disasters (UN, 2005). This conference's experts working group on measuring vulnerability goes further to assert that the development of tools to measure vulnerability is a prerequisite for effective preparedness strategies and sustainable resilience (Birkmann and Wisner, 2006).

The economic valuation tool addresses pollination crisis concerns. The economic valuation of the benefits of pollination services can help inform decision-makers about the impact of the degradation of pollination on the well-being of farm households in the longer term. This is particularly necessary for rural areas where low-income households depend mainly on natural resources for their livelihood and therefore more exposed and sensitive to a decreasing supply of insect pollination services. It should be pointed out that alternative pollination methods are expensive, whereas natural pollination costs nothing.

In the case of smallholder farm households in rural areas in developing economies, a variety of research questions can then be raised, including for example: How vulnerable might these households' production be to a decline in insect pollination? What is the vulnerability of their farm income on pollinators decline? And, thus, what could be the role of insect pollination services on both the availability and the access of smallholder farm households to the diversity and nutritious food consumption?

In what follows, we propose to address these questions by focusing on production, consumption, and supply aspects, following the production function approach (i.e., as defined in Chapter 1, Section 1.2.1). In doing so, we first present our hypotheses about the vulnerability of food production and nutrient consumption on pollinator decline in the case of smallholder farm households operating under the imperfect markets in the context of rural areas in developing countries.

4.2.4. Hypotheses

The above literature review, focusing on determinants of farm households' production and consumption decisions in rural areas of developing economies, shows that these decisions depend in particular on the market situation, which is often hindered by non-competitive market prices, high transaction costs, poor technologies, and poor access to financial means. This results in a relatively high dependence on free ecosystem services for these households' production and consumption of food. Also, with the example of insect pollination services (see Table 4.1), this review highlighted the fact that pollination services are essential to human nutrition both in quantitative and qualitative terms. Likewise, as noted in the general introduction, it emphasized the importance of considering factors such as the context of the analysis, the scale of the analysis, and questioning how an "economic agent" is defined as a unit of analysis.

As such, different hypotheses on the impacts of pollinators decline on food production and nutrient consumption can emerge depending on the specific characteristics of the areas and actors studied. In the case of smallholder farm households, operating in rural areas of developing economies under subsistence farming systems or supplying their agricultural products primarily to the local market, we can formulate three hypotheses focusing on their production, consumption, and market supply.

The first hypothesis, these smallholder farm households are more vulnerable to pollinators decline because the decrease in production quantities would reduce an already tight budget. Indeed, the production of smallholder farm households is more vulnerable to free pollination services decline, which pollinators offer, as the low levels of these households' income leave them little adaptation capacity to invest in alternative costly pollination services on their farms (e.g., hand or beehive rental pollination). As a result, the degradation of insect pollination may hurt the quantity of smallholder farm household crop production as the productivity of pollinator-dependent crops decrease. The following hypotheses derive from the first hypothesis since production is central to the consumption and income of these farm households.

The second hypothesis, the nutritional quality of smallholder farm households' consumption is more vulnerable to pollination services decline. Indeed, among other things, smallholder households' nutritional quality consumption and thus utility - as determined through their food consumption and purchased food - are likely to be negatively affected by the decline of pollinators. On the one hand, these households' low levels of income leave them little adaptation capacity to cope with the rise in food prices on markets resulting from this decline. On the other hand, these households' consumption of non-staples, such as pollinator-dependent crops, rich in essential nutrients depending primarily on self-consumption is threatened as marginal costs of their production increase. Thus, pollination decline may affect the nutritional quality of food available in the household, notably from own production, and thus household nutrition.

The third hypothesis, given that smallholder farmers produce a mix of crops on their farms to meet not only consumption but also cash needs, the decline of pollinators will decrease the farm income. Thus, the smallholder farm household supply income and profit are vulnerable to insects' pollination decline.

To quantify the vulnerability levels of quantity production, nutritional quality consumption, and income of smallholder farm households on the decline of insect pollination services, we will then develop a methodology. To do this, the estimates are based on a specific case study. We first present our case study below.

4.3. Case study description: the Huye district in Southern Rwanda

As Wong et al. (2005) indicates in the International Institute for Sustainable Development report, Rwanda is experiencing a loss of biodiversity in its agroecosystems throughout the country, particularly in swamps and valleys, where agricultural intensification is mainly taking place. Yet, as Andrew and Masozera (2010) points out, biodiversity degradation in this country hinders the maintenance of ecosystem services, which in turn impacts the provision of their benefits such as food and fiber, purification and regulation of water supply and fuel supply that are vital for the local population.

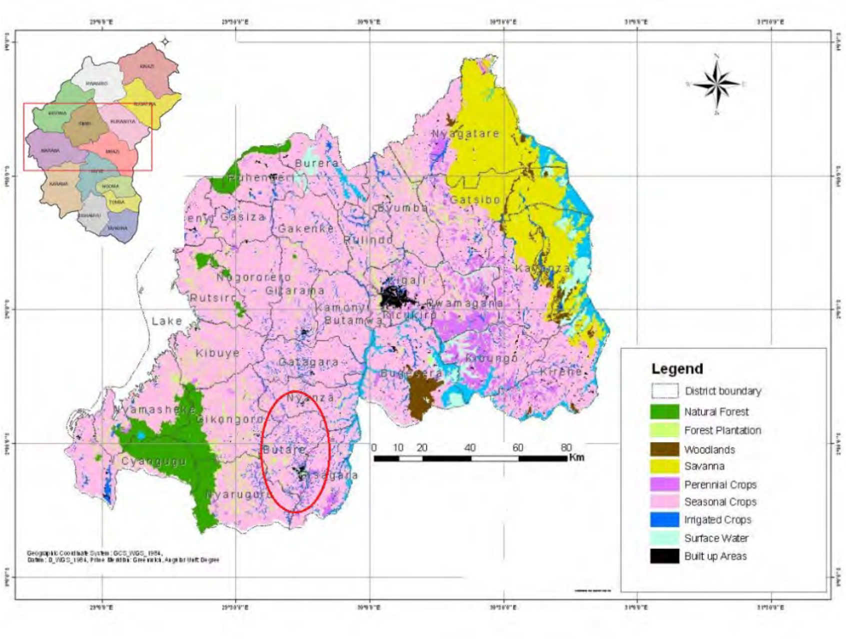
According to enquiries we conducted, the threats to ecosystems affect insect pollination services too. For the local stakeholders in the agriculture sector, the degradation of honeybee species, an insect pollinator, in some areas is at the origin of existing conflicts among local beekeepers and local coffee farmers; which is not an isolated case. These conflicts indicate that honeybee pollinators are under threat. Yet, bees are the most abundant and diverse pollinators, with over 20,000 species identified worldwide (Neff and Simpson, 1993; Klein et al., 2007; Michener, 2007). The local beekeepers and coffee farmers' conflicts are particularly strong in coffee production areas where intensive agricultural practices cohabit with beekeeping. Note that, in Rwanda, honeybees are traditionally produced in forest boundaries on hillsides, while Arabica coffee, a specialty of the region, is also preferably grown at high altitudes (NISR, 2019b). In developing country context, the same observation about a flawed cohabitation between intensification practices and bees has been made in Burkina Faso where traditional beekeepers noticed that their bees in hives situated near cotton fields (a cash crop) treated with pesticides were threatened (Gomgnimbou et al., 2010). In Rwanda, intensive farming practices are more encouraged in coffee farms as the coffee crop is the country's main agriculture export which contributes around 30% of Rwanda's total export revenue (Hakorimana and Akcaoz, 2017; NISR, 2019a). Thus, even if coffee crop is moderately dependent on insect pollination (Klein et al., 2003); pollinating insect decline could impair farmers income (Mushambanyi and Munyuli, 2014).

This can be the case in the Huye District, as coffee farming is a major income-generating crop in this area (NAEB, 2019b), where we conducted our survey. Agriculture is the main economic activity in the Huye District involving 76% of the active population (NISR, 2018). The Huye District is one of the eight districts in the Southern Province of Rwanda, which comprises 14 sectors, 77 cells as the smallest administrative units. The survey was carried out in the major coffee zones of this district: eight cells of

Simbi sector, one cell of Mbazi sector, and one cell of Maraba sector (see Rwanda and Simbi land cover maps, here below).

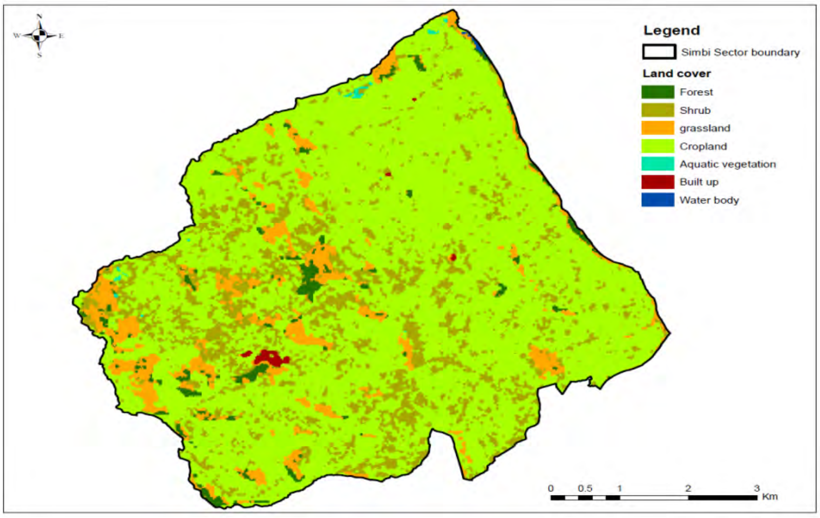
From an agronomic standpoint, apart from coffee and few edible crops (e.g., rice, maize) promoted in monoculture systems, other crops are grown in polyculture systems in this area including potatoes, sweet potatoes, bananas of several varieties, taro, cassava, squashes, peas, wheat, sugar cane, avocado, cabbage, and many others. Indeed, in Huye District, as in the rest of Rwanda, farming activity has been generally dominated by traditional practices of polyculture aimed at subsistence production (NISR, 2019b). Specifically, polyculture describes farming systems where many crop species are cultivated on the same plot of land across the year with the main goal to meet farmer households' food demand (Pritchard, 2013). The 2018 National Agriculture Survey reported that 95% of Rwandan farmers practiced traditional mixed farming on their farms and grew sixty different types of edible crops per year under different agricultural seasons shaped by weather conditions (NISR, 2019b). The climate in Rwanda has four distinct seasons: a long rain season (from mid-February to May), a long dry season (June to mid-September), a short rain season (mid-September to December), and a short dry season (January to mid-February). The Huye District encounters 1,200 mm average rainfall and 19 °C average temperature annually (NISR, 2015). In short, Rwandan agriculture is not mechanized, uses very low external inputs, is labor-intensive, and depends strongly on weather conditions (Cantore, 2011; GoR, 2012). As such, agricultural production in Rwanda depends greatly on the state of the agroecosystem and the interactions of ecosystem services.

From a socio-economic standpoint, in Rwanda, around 80% of the population relies on a smallholding of lesser than 0.7 ha on average as a source of livelihood (World Bank data, 2018), gross national income is around $780 per capita, and 62% of the population lives in poverty (i.e. as defined by the World Bank, 2020), around 70% of the total population are employed in the agriculture sector, of which 80.2% live in rural areas (NISR, 2019a). Moreover, around half of the population in Rwanda is malnourished like in many other countries in the region and there is alarming chronic malnutrition of 23% of children with ages between 12 months and 5 years (GoR nutrition, 2015).



Rwanda Map

The pink circle corresponds to the small map of the Huye (formerly Butare) region in southern Rwanda that is zoomed in at the top-left.



Simbi Land Cover Map

Figure 4. 3. Case study description: Huye district in Southern Rwanda

Data Source: FAO (2014) and RCMRD open database[28]

[28] http://www.fao.org/3/a-au280e.pdf and http://geoportal.rcmrd.org/layers/servir%3Arwanda_landcover_2015_scheme_ii

From a demographic standpoint, households comprise 4 to 5 members on average and the overall mean age of the population is 22.7 years old (NISR, 2018).

From a public policy standpoint, the government has implemented policies and strategies that aim to improve the livelihoods of people in various sectors, including agriculture. In the 2000s, it has put in place the Strategic Plan for the Transformation of Agriculture (SPTA) (MINAGRI 2009, 2011, 2013, 2018 a, b). Among SPTA strategies, the crop intensification and development of sustainable production systems were their absolute and urgent priority (GoR invest, 2014). In this transformation agenda, chemical and organic fertilizers, improved seeds, and "*land consolidation*" measures had utmost concern under the program called "Crop Intensification Program (CIP)" (see Uwingabire, 2012). This CIP program aims to raising agricultural productivity per hectare, as a means of achieving economic development, and weathering the current food and economic crises. *Land consolidation* is a policy that aims to organize small and fragmented farm parcels together to form one more practical and reachable farming unity (MINAGRI, 2018a). Since, it is more efficient to channel high-value inputs and extension services to grouped and homogenized farms. Though land consolidation is voluntary, it is a prerequisite to benefit from subsidized inputs provided under CIP programs (Kathiresan, 2012). Maize and rice have been readily adopted by households that have consolidated their lands compared to other crops in swamps and valleys, notably in Huye district (MINAGRI, 2018b).

However, traditional agriculture still dominates the study area as well as the rural Rwanda landscapes where the association of crops, crop rotation, and, to some extent, agroforestry,[29] are continuously practiced. Despite the dependence of these traditional farming systems on ecosystem services in general, and on pollination in particular, the conservation of these services in agricultural landscapes is not discussed openly between government and farmers. Consequently, there is neither a policy nor a measure that tackles the protection and preservation of pollinators and their ecosystem service in agricultural systems. Pollinator management practices are also not consciously implemented by farmers. As a result of the testimonies mentioned above during the surveys, although known hostile practices to pollinators are still thought to be rare in rural Rwanda in general, known causes of pollinators decline worldwide can be found in this area, like in other areas of the country. Such practices may include habitat transformation, loss of both diversity and abundance of floral resources, inappropriate use of pesticides, the spread of pests and diseases, and climate change (as explained in Cantore, 2011 about Rwanda; or generally in IPBES, 2016).

[29]Agroforestry, in Rwanda, is perceived as the presence of scattered trees on farm, planted trees along contour or erosion control ditches, boundaries of farm, or set as rotational woodlots or blocks (Ndayambaje et al., 2011).

Finally, the question arises as to how vulnerable the welfare of smallholder farm households might be to the decline of pollinating insects in the Huye District. To quantify this vulnerability, we will present the methodology we use in the next section.

4.4. Methodological framework for estimating the vulnerability of production and nutrient consumption on pollinator declines for farm households

In this section, we will develop a methodological framework to assess the vulnerability of production and nutrient consumption on the decline of insect pollination services in the case of low-income farm households located in the rural area of the Huye District in southern Rwanda. For that purpose, we collected detailed cross-sectional data on agricultural production, food consumption, and supply of crop at these farm households' scale based on the National Institute of Statistics of Rwanda (NISR, 2016b) farm household survey questionnaire[30]. In the first place, we will present how our sample was designed and how households were identified for data collection. In the second place, we will describe our valuation approach and develop economic model as well as indicators we use in our analysis.

4.4.1. Data collection: Households' sample design and identification

Pollinating insects and their ecosystem services, which have discrete but essential roles for food security and the good functioning of Nature, are still little-known by the general public. This is especially the case in our field of study in rural Rwanda. In addition to that, there is no academic literature on pollination services in Rwanda, thus, the household survey questionnaire used was adapted during a preliminary field study in this country, and both sample design and identification were set accordingly.

The preliminary field study went through three main steps:

The first step consisted of conducting interviews with local stakeholders to adapt our questions to local realities. This step was crucial to our study due to the lack of information about insect pollination services in Rwanda. It aimed at meeting key stakeholders to gather their opinions concerning the exposure of pollinators and effects of pollination services degradation on smallholder farms in Rwanda as well as the state and awareness of the decline of insect pollination services in the local context. Specifically, two main questions were addressed in these interviews. First, are local stakeholders aware of pollinator decline trends; and how are they addressing this decline if they address it? Second, to what

[30] We are indebted to Uwizeyimana Lambert, Forestry and Environmental Statistician at NISR, for his collaboration and involvement throughout the data collection process.

extent is local food production and local nutrient consumption of food can be affected by the decline of pollinators according to interviewed stakeholder perspectives?

We interviewed stakeholders from the private sector, public sector, University of Rwanda, and civil society, presented in table 4.2 below.

Table 4. 2. Local stakeholders interviewed for Rwanda case study

	Local agricultural stakeholders interviewed	Institute or company
1	Coffee farming specialists	Coffee exporter company(RWACOF)
2	Country manager of the coffee value chain	National Agriculture Export Board
3	Agronomist and technicians	Rwanda Agriculture Board
4	Officer in charge of forestry and environmental statistics and former coordinator of agricultural household surveys.	National Institute of Statistics of Rwanda
5	Project Director of agroforestry and food sustainability	FAO Rwanda
6	Agronomist and natural resources manager	Huye district
7	Director of the Center of excellence in biodiversity	University of Rwanda / CoEB
8	Beekeeping cooperative president	Cooperative of farmers

Thanks to these interviews, we gained valuable information that highlighted the context into which our project in Rwanda falls and the area on which we needed to concentrate. For instance, four out of eight interviewees during this step said that the conflicts among beekeepers and coffee farmers already exist in some areas. As stated earlier, the cause of these conflicts, according to them, is the use of pesticides in coffee farms that are prejudicial to bees. Consequently, areas with coffee farms associated with other crops become, for us, an interesting element to investigate the relationships between all crop production and insect pollination services in the agroecosystems.

The second step consisted of collecting statistics in collaboration with identified key stakeholders aimed at identifying a sample. Following on from the above, it was more relevant to discuss in an area where the decline of pollinators was sensed for this research centered on a less-discussed issue. We identified two regions in which different actors highlighted the problems of bees' mortality due to existing conflicts between beekeepers and coffee farmers. Those conflicts are mainly located in Coffee Zones in Southern (Huye District) and Western (Rutsiro District, etc.) provinces. These two areas were sampled, particularly, because they highlight the interactions between agriculture and pollination services, which is an important factor in our study. However, due to a lack of means, the study was conducted only in

Huye District. The choice to study the Huye District was especially motivated by the fact that, during step 1, we had met its local actors directly and claimed to be affected by such pollinators decline threats. In fact, according to the Huye district's agronomist, they have received complaints from local beekeepers, who are also farmers, about pesticides use that kills their bees. In addition, according to this district veterinarian, there were 5,553 known beehives in the Huye District during the time of this study and a plan to increase beehives in the future. However, most of these beehives, for either managed or wild bees providing honey are located in the forest areas, which is a common beekeeping practice in Rwanda.

The last step consisted of developing the survey design. During this step, a survey team was formed and trained[31]. The survey team composed of five enumerators (two students from the University of Rwanda, two former NISR survey officers, and my self). In this step, we developed a questionnaire in Kinyarwanda and tested it, adapted its terminologies to the local language, and tried to understand the existing dynamics of beekeeping activities and farming at the level of farmer households. This step was important for two reasons. On the one hand, it allowed us to test the relevancy of our questionnaire in the local context. On the other hand, it was a way to minimize errors by harmonizing the understanding of enumerators about the questionnaire and the study objectives. During this step, we visited a small group of farmers that own beehives in the Simbi sector in the Huye District. The group was composed of 16 farmers (six men and ten women), living in Simbi sector in this district. Beekeeping and mushroom production serve mainly as common activities in which these farmers socialize. Recently, the bees of this group of farmers surrounded by coffee fields died abundantly after the pesticides applications period, but those farmers did not understand clearly the mechanism, although, they cited pesticides applied in coffee farms as one of the reasons for the death of their bees. To resolve that issue, they are taking some of their hives in the forest area as an experiment[32]. Given the characteristics and daily practices of these farmers, they were willing to discuss the issue of pollinators decline and to contribute to the adaptation of the terminologies used in a questionnaire at the local level.

The average one-hour survey was conducted in 125 farm households at the beginning of the year 2018. Each interview was conducted in three phases after clarifying the main objectives of the study and assessing respondents' knowledge. Firstly, an enumerator assessed household crop production features

[31] Allow us to acknowledge the Center for Excellence in Biodiversity (CEOB) of the University of Rwanda, in particular its director Prof. Beth A. Kaplin (PhD), for hosting our team and the involvement of the CEOB team in organizing and participating in this training and survey. Under the auspices of CEOB, local government authorities approved our request to conduct interviews with their citizens in our convenient time frame.

[32] A biological or ecological study on this issue would provide more reliable data that could better inform the decisions of this group and local authorities, as well as the economic valuation of pollinators, thus improving the cohabitation of beekeeping activity and crop production; which can be mutually beneficial.

and farm characteristics. Secondly, household food consumption was assessed. Finally, information on the socio-economic characteristics of the household was collected (see the questionnaire in the appendix 4.4).

4.4.2. Data analysis: Indicators of the vulnerability of household on insect pollination

To analyze the vulnerability of production and nutrient consumption on pollinators decline for farm households in our case study, we were inspired by the farm household theory focusing on the particularities of farm households operating in imperfect markets in the context of rural areas in developing countries (as explained in Section 4.2.1). Analytically, we draw on two economic models consistent with the production function valuation approach (i.e. as described in Chapter 1). On the one hand, we refer to the model of Gallai et al. (2009) that mobilizes the crop-pollinator dependency ratio method (i.e. as used in Chapter 2) to estimate the vulnerability of world agriculture in the face of pollinators decline. On the other hand, we build on a static welfare economy model of a local economy incorporating insect pollination mobilized in Gallai and Salles (2016). For nutrition aspects, our analysis was based on nutrient ratios from Chaplin-Kramer et al. (2014) (i.e. as in Chapter 2). Such a combination allows us to develop economic indicators that quantify the vulnerability of farm households' welfare to insect pollination services in the context of rural areas in developing countries. In the first place, we describe our valuation approach and, in the second place, we develop economic model and indicators we use in our analysis.

i. Valuation approach

Our study is based on the assumption that the contribution of pollination services to the well-being of a farm household is related to the quantity and the nutritional quality of crops produced and consumed in household that depends on pollination by insects. Thus, households producing and consuming crops which fruit set require a certain level of insects' intervention is vulnerable to the decline of pollinators.

With this in mind, as noted above, we build our valuation approach on the production function approach defined in Chapter 1 (Section 1.2.3) and, in particular, the method that we developed in Chapter 2 following Gallai et al. (2009). As such, we construct indicators that allow us to quantify the vulnerability of smallholder farm households' nutrition and income on insect pollination based on the pollinator dependence ratio approach (as defined in Chapter 1). For the income vulnerability indicator, we consider the supply value of the overall quantity of crops that a household sold in the markets to earn an income one year before our survey. For the nutritional vulnerability indicator, we consider the levels of consumption of essential nutrients because deficiencies in these nutrients lead to serious public health problems in many developing countries (Black et al., 2008; Stein et al. al., 2008). By consumption, we refer to the overall amount of food that reached to a household for consumption in the year before our survey. The share of nutrients in crops was collected from essential nutrients including vitamin A, vitamin C, iron, folate, protein following Chaplin-Kramer et al. (2014).

However, these indicators may allow us to estimate the contribution of insect pollination services to farm household well-being in a static moment but it does not allow us to understand what might occur if a farm household integrate pollination degradation in their production and consumption decisions. Thus, the choice of the method is according to technical feasibility in our field of study and agro-ecological data constraints (e.g., pollinator threshold). However, these indicators may allow us to estimate the contribution of pollination services to farm household welfare in a static moment, but they do not allow us to convey what might happen if farm households were to integrate pollination degradation into its production and consumption decisions. Indeed, the choice of method is according to technical feasibility in our field of study and agro-ecological data constraints. A more in-depth and accurate analysis can eventually be done if, for example, more detailed data on the insect pollination threshold in the fields or the current trend of pollinators decline in our case study were available.

ii. Economic model and indicators

As in Chapter 2, we assume that the production of each crop c, where $c \in [1; C]$, benefits at some level from the visit of insect pollinators, which we represent with the dependence ratio D_c of crop c on insect pollinators, $D_c \in [0; 1]$ (values of D_c ratios can be found in Klein et al. (2007)). Thus, the level of the decline of insect pollinators, $\boldsymbol{\alpha_i} \in [0; 1]$, results in a variation from 100% of the total volume of output of crop c to $100 * (1 - \alpha D)$ % (Gallai et al., 2009; Gallai and Salles, 2016). Likewise, each crop c contains nutrient N_{cm}, where $m \in [1; M]$ (see Table 4.1, Section 4.2.3). N_{cm}, say nutrient ratio, stands for a portion of the amount of a nutrient (e.g., vitamin A, vitamin C, vitamin B6, iron, folate, protein, etc.) in a given volume of a crop in their respective units. For example, 100 g of apple fruit contains 4.6 mg of vitamin C and 54 international units (IU) of vitamin A, etc. Thus, the level of the decline of insect pollinators $\boldsymbol{\alpha_i} \in [0; 1]$, which may threaten crop production, may also reduce the nutrients intake. As such, the nutrients embedded in crop **c** consumption decrease to $100 * (1 - \alpha D) N_{cm}$ %. On this basis, in a first step, we introduce our economic model and in a second step, we develop a supply income indicator and a nutritional consumption indicator stemming from this model.

a) Economic model

To analyze the vulnerability of production and consumption of farm households' specific to pollinators decline, we build on an economic model of a local economy developed in Gallai and Salles (2016). This study links directly insect pollination to an economic model of welfare (i.e., utility plus profit) in the case of a local economy. Drawing on this model, we construct a static model that allows us to quantify the ratios of the vulnerability of farm households' welfare on the decline of pollinators. Our hypothesis is that pollinators decline will have a negative impact on farm household welfare (W).

As such, for each farm household h, where $h \in [1; H]$, economic welfare of each farm household (W_h) can be represented by utility (U_h), the expected farm profits (π_h), and any off-farm exogenous income (E_h). Due to jointed production and consumption decisions, as noted earlier (see Section 4.2.1), economic models focusing on farm households operating in the imperfect market in the developing economies context indicate that the utility function of these households can be particular. Specifically, several studies (see, for example, Singh et al.,1986; Dillon and Barrett, 2017; and Chenoune et al., 2017) show that the utility of these households is subject to farm production and on and off-farm income constraints, which emphasizes the relevance of E_h. Thus, for any annual production cycle, the welfare of farm household *h* can be written as follows:

$$W_h = U_h + \Pi_h + E_h \qquad (1)$$

Where, both the distribution rules within the household and the role of seasonality are ignored. Thus, the utility U_h and expected farm profit Π_h as well as off-farm income of each household *h* encompasses overall household members and the agricultural seasons. In that respect, for each farm household h, we identified the kilos of crop c produced (Q_{ch}), the total (T) number of kilos of crop c consumed at home ($C_{ch}{}^{T}$), including both the self-consumption ($C_{ch}{}^{a}$) and the quantity demanded on market ($C_{ch}{}^{d}$), the unit price of purchased crop c for own consumption ($P_c{}^{d}$) in Rwandan francs, the kilos of crop c sold on the market by each farm household ($Q_{ch} - C_{hc}{}^{a}$), and the unit price of own production of crop c sold in the market ($P_c{}^{a}$) in Rwandan francs.

With these points in mind, an economic model is formulated and indicators are proposed, the overall utility and expected profit of each farm household *h* can be formulated as follows:

The utility of each farm household $\boldsymbol{U_h}$ equals to the consumption of goods and leisure time. As noted earlier, leisure time consideration is especially crucial in analysis of fam household utility because this household maximizes its utility by choosing the goods and services to buy from the market as well as labor time to offer (or not) in farm (and off-farm) activities. Thus, the impact of the decline of insect pollinators (α) on the utility U_h can be calculated as follows:

$$U_h = (P_c{}^{a} C_{hc}{}^{a} + P_c{}^{d} C_{hc}{}^{d})(1 - \alpha D_c) + G_h + \omega C_{hL} \qquad (2)$$

Where, the different items consumed in each household h are composed of kilos of self-supplied food crops (${C_{hc}}^{a}$), kilos of purchased food crops (${C_{hc}}^{d}$), the value of non-food commodities purchased (G_h), and that of the hours household used in the form of leisure (C_{hL}) in Rwandan francs. As noted above, $(1 - \alpha D_c)$ depicts the impact of pollinators decline on food. The hours a household enjoys per day out of work and household chores is explicitly recorded and valued at the unitary market wage (ω) in Rwandan francs.

The expected profits $\boldsymbol{\Pi_{hc}}$ for each farm household h relate to the marketed output value minus purchased input costs. Assuming that technology is linear, Π_{hc} is as follows:

$$\Pi_h = \sum_{c=1}^{C} ({P_c}^{a}(Q_{hc} - {C_{hc}}^{a})(1 - \alpha D_c) - \omega {l_{hc}}^{H} - \sum {Z_c}^{j} {x_{hc}}^{j} - A_h) \qquad (3)$$

Where, the kilos of crop c produced (Q_{ch}), the kilos of self-consumption of crop c (${C_{ch}}^{a}$) and its price ${P_c}^{a}$ in Rwandan francs, purchased-input costs include hired labor working hours (${l_{hc}}^{H}$), quantities of high-value inputs (${x_{hc}}^{j}$) (e.g.; seeds, pesticides, and fertilizers) with ${Z_{hc}}^{j}$ as unitary cost of each input in Rwandan francs, and fixed costs (A_h). We assume that land and capital are fixed costs.

The off-farm exogenous income for each farm household $\boldsymbol{E_h}$ is equal to the value of the total stock of hours (T) minus the value of hours allocated to own household farming activities or household chores (${l_{hc}}^{F}$), and hours spent on leisure C_{hL} plus other income available in households (Y_h) (e.g. remittances and household members' income). For the sake of simplicity, we have recorded detailed information on the distribution of hours only based on the head of household and the unit market wage (ω) in the agriculture sector.

$$E_h = \omega(\mathrm{T} - {l_{hc}}^{F} - C_{hL}) + Y_h \qquad (4)$$

As pollinators decline, the measure of the farm household welfare variation (ΔW) is calculated as follows:

$$\Delta \mathrm{W} = W_{\alpha=0} - W_{\alpha=\mathrm{i}} \qquad (5)$$

The index alpha, $\boldsymbol{\alpha_i} \in [0; 1]$ represents the level of the decline of pollinators density compared to the baseline as an initial state (i.e. as in Chapter 2). In the case of this chapter, we consider the total extinction of pollinators, it means where α equals to 1 and the baseline as the current situation where α equals zero.

Therefore, if all things remain the same (e.g., time allocation, input costs, off-farm income, and non-food commodities consumption) in the case of farm household operating in imperfect markets in a developing economy context, the ΔW can be theoretically approximated as follows:

$$\Delta \mathrm{W} = ({P_c}^a Q_{hc} + {P_c}^d {C_{hc}}^d)(1 - \alpha D_c)$$ (See mathematical calculations in Appendix 4.2.) (6)

This solution of welfare variation (ΔW) highlights the fact that the vulnerability (i.e. Section 4.2.3) of smallholder farm household welfare to the decline in insect pollination is mainly a function of prices of both farm household own goods and purchased goods $P \in ({P_c}^a, {P_c}^d)$, and farm production $Q \in (Q_{ch})$, as well as food consumption $C \in (C_{ch})$ (see Eq. 6).

Following the above considerations, we propose to develop two indicators, a supply income indicator and a nutritional consumption indicator, to represent the vulnerability of farm households' consumption and output supply in the case of a decline in insect pollination services, which is new to our knowledge. Indicators refer to data elements that can be used to represent specific, observable and measurable characteristics of a subject under study (UNECE, 2000). The data elements needed to develop indicators of supply income and nutritional consumption for each farm household *h* can be identified based on the result of Eq. 6. The mathematical formulations of these indicators are as follows.

b) Supply income indicator

The value of each farm household supply (I) was approximated as follows:

$$I = \sum_{h=1}^{H} \sum_{c=1}^{C} ({P_{ch}}^a (Q_{ch} - {C_{hc}}^a))$$

Then, the economic value of insect pollination on farm household supply (IPI) is:

$$IPI = \sum_{h=1}^{H} \sum_{c=1}^{C} ({P_{ch}}^a (Q_{ch} - {C_{hc}}^a) D_c)$$

Following Gallai et al. (2009), the ratio of the vulnerability of smallholder farm household supply income (RVI) to insect pollination is a ratio of the economic value of insect pollination and farm income, which can be expressed as follow:

$$RVI = \frac{IPI}{I}\ \% \qquad (7)$$

If nothing is done to counterbalance the decline in pollinators, pollinator-dependent crops may decrease which may decrease the farm income I of each farm household. Yet, the dependence D_c of these crops to pollinating insects remains unchanged. In this sense, the RVI indicator estimates the level of increase in a farm household's vulnerability as insect pollination services decline.

c) Nutritional consumption indicator

Given that each crop c contains a ratio of nutrient N_{cm} with $m \in [1; M]$, the value of overall nutrient N_{cm} consumed by each farm household NV from crops can be expressed as follows:

$$\mathrm{NV} = \sum_{c=1}^{C} \sum_{m=1}^{M} ({C_{ch}}^{T} \cdot N_{cm}) \text{ ; (For } N_{cm} \text{ see appendix 2.2)}$$

Where the crop **c** consumption of farm household depends on both purchased ${C_{ch}}^{d}$ and own production ${C_{ch}}^{a}$, we assumed that the Total (T) farm household consumption ${C_{ch}}^{T}$ is as following:

$${C_{ch}}^{T} = {C_{ch}}^{a} + {C_{ch}}^{d}$$

Then, the value of nutrients in consumption of each farm household depending on insect pollination (IPNV) was calculated as follows:

$$\mathrm{IPNV} = \sum_{c=1}^{C} \sum_{i=1}^{M} ({C_{ch}}^{T} \cdot D_c \cdot N_{cm})$$

While D_c and N_{cm} for each crop *c* remain unchanged, the quantity of ${C_{ch}}^{T}$ consumed may decrease if pollinators decline is not curbed or if no alternative food sources is considered, which may increase vulnerability of nutrition intake for each farm household. As for income indicator above, the ratio of the vulnerability of nutrition for each farm household (RVN) to insect pollination can then be expressed as follow:

$$RVN = \frac{\mathrm{IPNV}}{NV} \tag{9}$$

To understand the role of self-consumption on nutrition for each farm household in our case study, we compared two major sources[33], market and own production, of farm household food consumption. Hence, we created an indicator of a farm household nutrition by consumption source NS for both pollinator-dependent crops and non-pollinator dependent crops:

$$NS = \frac{\sum_{c=1}^{C} \sum_{m=1}^{M} ({C_{ch}}^{a} \cdot N_{cm})}{\sum_{c=1}^{C} \sum_{m=1}^{M} ({C_{ch}}^{T} \cdot N_{cm})} \times 100 \tag{10}$$

With $0 < NS < 100$. If NS tend to 0 it means that a household consumes food products mostly from the market; while when NS tend to 100 it means that a household consumes food products mostly from its production.

[33] However, note that for a rural household in the study area, food sources include gifts, means of payment, etc.

In summary, the vulnerability of farms to pollinators decline is related to the dependence of their own production on pollinators and the ability of farmers to adapt to pollinator decline by purchasing food from the market and sustaining their own production. We used the data collected in our case study to calculate the vulnerability of own production, nutrients consumption and crop supply income to pollinator decline over all farm households.

4.5. Results

To address our research questions about the level of vulnerability of food production and nutrient consumption on pollinators decline in the case of smallholder farming households, our analysis is threefold. Based on the studied area, we first estimate the dependence of farm households' crop production and consumption on pollination services through the diversity of both crops they grow and purchase, and these crops dependence on pollinators. Second, we estimate the vulnerability of farm production and crop supply income of smallholder farm household on insect pollination decline. Third, we quantify the vulnerability of these households' nutritional consumption to pollinators decline based on farmer household's total consumption including their food consumption and purchased food. But before displaying our results, we report on socio-economic description of the studied sample.

4.5.1. Socio-economic description of the studied population

Out of 125 interviews within households, 110 were completed and thus analyzed. The total area of agricultural land owned by 50% of these 110 households was less than 0.5 ha, of which they produce about 46 different types of crops, and more than 50% of our sample reported producing coffee - a traditional cash crop - among other crops. The average value of total agricultural production, marketed production, and non-agricultural income was 50, 18, and 138 thousand Rwandan francs, respectively, in the year before the study. The household consists of five people on average, four of whom depend on the head of the household. Around 60% of our interviewees were the head of the household and 27% were their spouses. 70.5% of the head of the household in 110 households have primary school level, 70% are men and 30% are women, with 47 years old on average. The main socio-characteristics of the surveyed households are summarized in Table 4.3 below.

Table 4. 3. Household social-economic characteristics

Variable	characteristics	Percent
Respondent	Head of household	60
	HHH partner	27
	HH member	13
HH farmland total Size	<0.5 ha	50
	0 .5 to 1 ha	29
	1 to 5 ha	21
Livestock	Households owning livestock	75
Main livestock	Cow	37
	Pork	10
Beehives	HH owning beehives	12
	HH average beehives	9
Head of household profile	Solely farmer	91
	Cooperative leader	7
	Local agricultural officer	2
Gender of Head of household	Male	70
	Female	30
Marital status	Single	3.5
	Married	70
	Widower	23
Head of household Education	Primary	70.5
	High school	4
	University	3
	None	1.5
HHH farming activity	Different crops, coffee and beekeeping	48
	Different crops and beekeeping	47
	Different crops and coffee	40
	Different crops only	

Variable	Mean	Std. Dev.	Min	Max
Age of HHH	47	12.8	25	84
HH members	5	1.9	1	12
Number of dependents	4	2.0	0	12
HHH Farming time a day	6	1.9	0	12
Hours HHH spent on Non-farm activities a day	3	3.8	0	18
HHH Free time hour/ day	2	1.1	0	5
Total HH Nonfarm Revenue	138,824	332,889	0	2,040
HHH Non-farm revenue	103,613	302,402	0	1,800
Total farming revenue	50,240	40,129.07	1,5	1,950

HH : Household
HHH : Head of household

Generally speaking, the studied smallholder farm households mobilize traditional farming practices. For instance, 89% of interviewed households state to rotate their crops within a year (in different agricultural seasons) and 80% of them mix crops on the same plot. 89% of farmers affirm to leave or plant some buffer, strips, shrubs, fruit trees, or other trees on their farms. However, the main reason they have these pollinator habitats is not for pollinators or pollination services. These practices are rather for their other ecosystem services, particularly, erosion protection for 70% and animal feed for 90%. About 35% of households own parcels in consolidated lands and use pesticides on their farms. In practice, only 15% of crops are treated with pesticides. Pesticides are mostly used on vegetables, cereals, and coffee crops. Households spend 67% of their production costs on labor wages, while spending on pesticides covers only 2% of the total costs. However, the government provides pesticide and fertilizer as subsidies for the coffee crop, and fertilizer in vouchers format to support the Crop Intensification Program (CIP). The CIP targeted crops include maize, rice, and bean crops in Huye. 56% of pesticide spending is destined to be used on vegetables and a 23% share of total pesticide costs is allocated to cereals.

4.5.2. Diversity of crops grown and demanded and their dependence on pollinators

Of the crops grown and consumed throughout the year in the smallholder farm households interviewed, 37% depend on pollinators at different levels, 22% do not necessitate pollinators for their pollination, and for the remaining 41%, and their level of dependency on pollinators is not yet known. The major crops produced were traditional foodstuffs such as sweet potatoes, red beans, and sorghum. 56 out of 110 households produce coffee (Arabica) and consider it only as an income-generating or cash crop. Most households consume more categories of crops than they produce (Figure 4.4a).

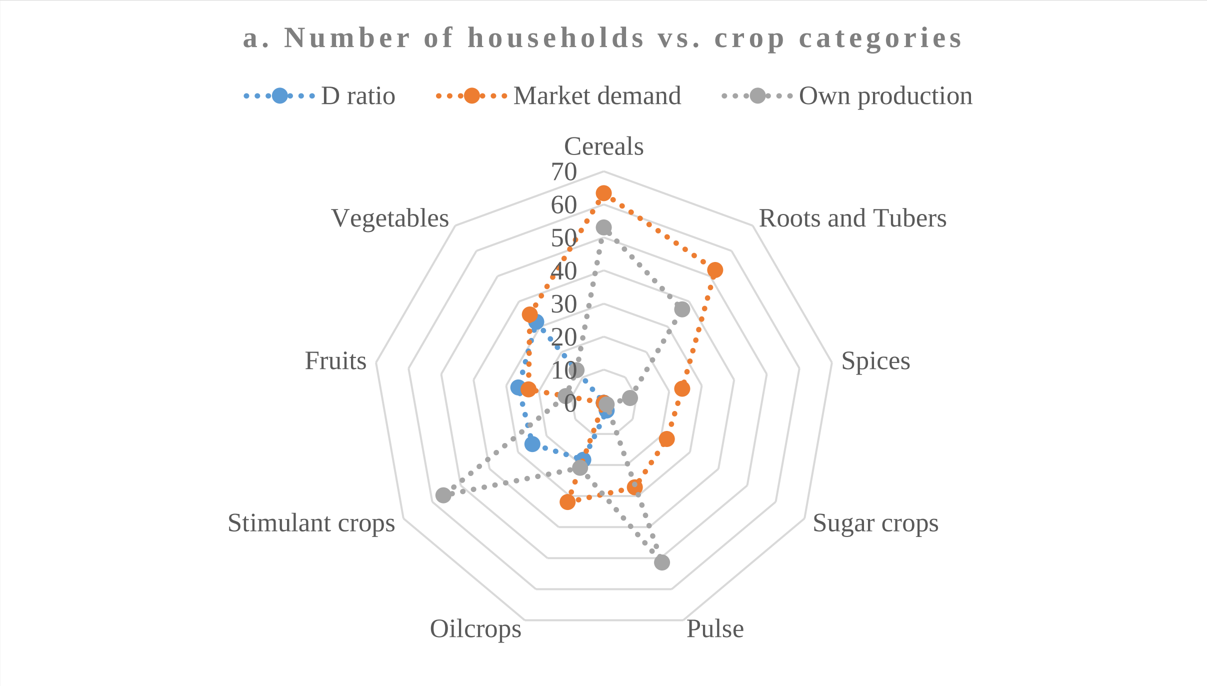


Figure 4.4. Diversity of crops grown and demanded by farm households and their dependence on pollinators

Many households produced and consumed not only staple crops such as rice, potatoes, and maize (non-pollinator-dependent crops) but also non-staple crops like tomatoes and eggplants (pollinator-dependent crops) (Figure 4.4b). 41.4% of interviewed households affirmed that they would continue to produce the same crops even if half of their production decreased by half due to any shock in production. Some of the reasons given (their frequency in %) were the fact that those crops are cultural and traditional food. 72% of households said that they can continue to produce the same crops because they are the basic and traditional food crops for their consumption. 14% of households said that they produce what others produce. 14% of households believes that responsible officers would find for them a suitable variety for replacement.

Crop	Own production	Market demand	D ratio
Maize	72	84	0
Sorghum	70	29	0
Spinarch & basil	7	19	0
Peas dry	23	17	0
Taro (cocoyam)	24	54	0
Rice paddy	17	77	0
Lentils	10	20	0
Pepper (piper spp.)	8	24	0
Sugar cane	1	22	0
Bananas, fruit	29	25	0
Bananas, platain	19	40	0
Bananas, beer	12	18	0
beans dry, short	89	53	5
beans dry, long	84	19	5
chillli	12	19	5
Oranges	8	25	5
Papayas	7	23	5
Groundnuts with shell	7	47	5
Lemons and limes	6	21	5
Tomatoes	17	70	5
beans green	16	30	5
Coffee green	56	0	25
Soybeans	40	24	25
Eggplants (aubergines)	27	68	25
Sunflower seed	16	25	25
Eggplants, big	3	21	25
Avocados	31	33	65
Guavas	10	21	65
Mangoes mangosteens guavas	14	24	65
Onoin	22	62	95
Onoin, white and long	4	20	95
Sweet potatoes	66	39	-
Cassava	47	54	-
Potatoes	28	75	-
Carrots and turnips	24	47	-
Cabbages and other brassicas	15	51	-
Garlic	11	21	-
Beetroot	9	20	-
Squash, Zuchinni	9	18	-
Celery leaves	4	21	-
passion fruits	5	20	-
Tree tomato fruit	4	20	-
Pineapples	3	25	-

Figure 4. 4b. Number of households vs. crops

Diversity of crops grown and demanded by households in comparison to their dependence on pollinators (D), the blue bar represents the number of households produced and demanded each crop out of 110 interviewed

Besides, farm households in the studied area cannot totally fulfill their food needs throughout the year with their production. To complete their food needs they rely on the local markets. The value of purchased non-pollinator-dependent crops with D = 0 is greater than the value of their production (see Figure 4.5 below). By contrast, for crops with D ratio equals to 0.25, which includes coffee crop that is produced as a cash crop, the production value exceeds the consumption value. This is also the case for crops with D ratio equals to 0.65 as they are mainly non-staple crops and households mainly consumed them from their production.

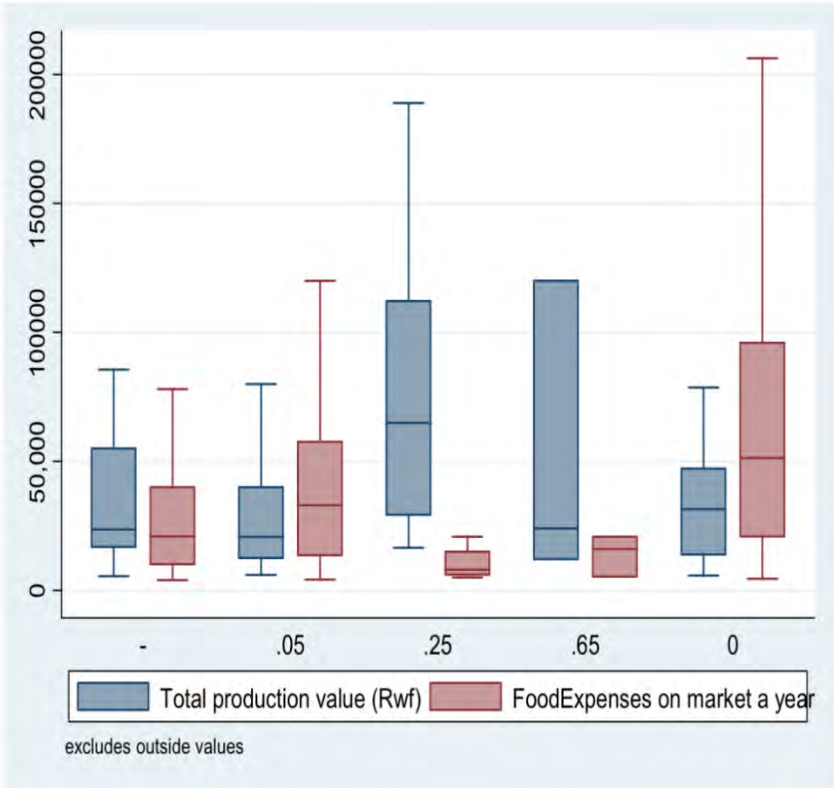


Figure 4. 5. Comparison of production value and food expenses (in Rwandan franc) within a year per pollinator dependence ratio

Figure 4.6 below highlights households' dependency on pollinators per crop categories. The value of households' expenses for cereals (with D=0) is greater than the value of their production for cereals. As for stimulant crops (coffee in this area), fruits and vegetables, the production value exceeds the purchased value per household in the studied areas. The oil crops produced in this area are mainly nuts, soybeans, and sunflower. Roots and tubers are important in rural households' diet but their dependence ratios to pollination are not yet known. Ultimately, this result shows that crops other than staple crops - for example, fruits, vegetables, and oilseeds -are particularly available to these farm households when they are self-supplied.

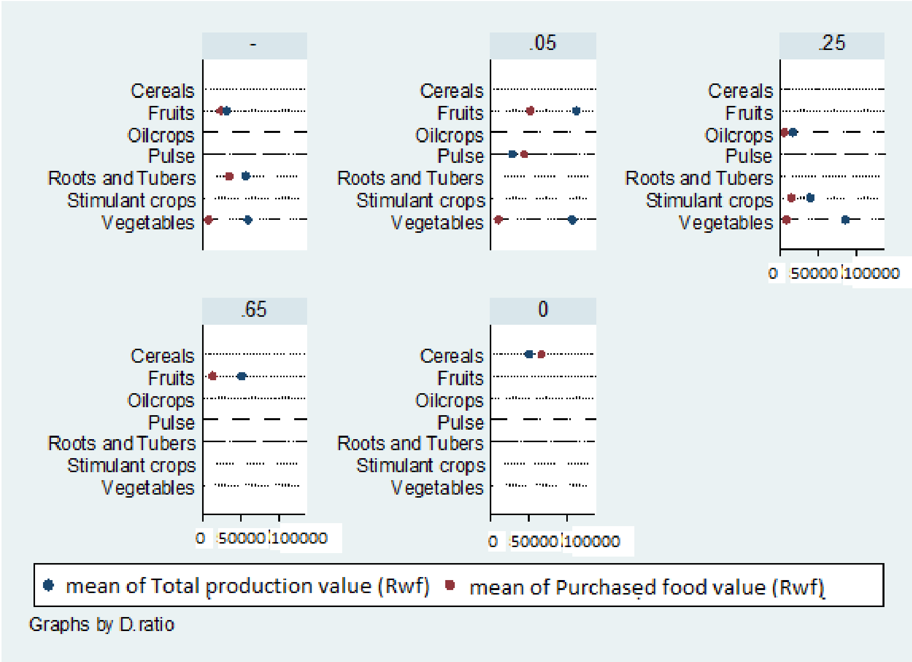


Figure 4. 6. Contribution of pollinators to crop categories grown and consumed by households

4.5.3. Vulnerability of smallholder farm household's production and consumption to insect pollination

In the studied households, the ratio of vulnerability on insect pollination for expected farm profit is 20%; utility is 0.5%, and welfare is 1%. This is because these farm households' off-farm income is more than twice greater than farm income (see Table 4.4a). The ratio of the vulnerability of farm household marketed production is 13 %; self-supplied crops are 9.5%; while that of purchased food is 4%. These figures are summarized in the table below.

Table 4. 4. The ratios of vulnerability of household production and consumption values to insect pollination

Variables	Mean value (1000 x Rwandan franc)	Ratios of vulnerability (%)
Self-consumption	32	9,5
Marketed production	18	13
Farm income (Self-consumption and marketed production)	50	11
Purchased food	28	4
Farm profit	-13	20
Utility	432,5	0,5
Total Off-Farm income	138	-
Welfare	588,5	1,0

Note: Ratio of vulnerability of each of above mentioned variables to insect pollination equals the economic value of insect pollination to each variable ($\sum Quantity * Price * D_c$) divided by the value of each variable ($\sum Quantity * Price$) (i.e., Gallai et al., 2009).

Most pollinator-dependent crops produced in the study area are the stimulant crops (coffee), which 25% of production, on average, depends on insect pollination; oil edible crops, which 24% of production depends on insect pollination; and fruits, which 23% of production depends on insect pollination. Moreover, insect pollination contributed about 6% to the total smallholder farm households' consumption. Pollinator-dependent crops consumed by households were fruits 25%, oil edible crops 13% and 6% for vegetables and pulses 5%. This highlights the fact that the share of pollinator-dependent crops in own food consumption is greater than in market food demand in studied farm households. As for production, the share of none-pollinator dependent crops, tubers, and cereals is about 42% of total farm income and thus the other share is for crops that depend on pollinators at different levels (see Table 2.b).

Table 4.4b. The ratios of vulnerability of crop production and consumption values to insect pollination

	Distribution of total values per crop categories			Ratios of vulnerability to pollinators	
Crop category	**Farm income**	**Self-consumption**	**Purchased food**	**Total consumption**	**Marketed production**
Roots and Tubers	**23%**	28%	**20%**	0%	0%
Cereals	**19%**	19%	**49%**	0%	0%
Pulse	16%	**22%**	8%	5%	5%
Stimulant crops	16%	0%	0%	0%	**25%**
Vegetables	13%	7%	**13%**	6%	7%
Fruits	11%	**12%**	5%	**25%**	**23%**
Oilcrops	2%	2%	4%	**13%**	**24%**
Spices	0%	0%	0%	0%	0%
Sugar crops	0%	0%	0%	0%	0%

4.5.4. Vulnerability of smallholder farm household nutritional quality consumption on insect pollination

The ratio of vulnerability of essential nutrients consumption to pollinators in studied households is about 28% for vitamin C, 20% for folate, 15% for Vitamin B6, 14% for vitamin A, and 5% for both iron and crop-protein. An important part of nutrients consumed by smallholder farm households is relatively self-supplied as the SN indicators show, here in table 4.5 below.

Table 4. 5. Vulnerability of smallholder farm household nutrients consumption on insect pollination

Nutrients	The ratio of vulnerability (RVN, %)	Consumption source indicator (SN, %)
Vitamin C	28	49
Folate	20	42
Vitamin B6	15	45
Vitamin A	14	51
Iron	5	47
Crop-protein	5	45

Fruits and oil edible crops are the main providers of these nutrients in the households' diets. If pollinators extinct totally, more than 60% of iron, folate, and crop protein, 51% of Vitamin A, and 37 % of Vitamin C consumed from fruits by smallholder farm households will be lost. In that case, also, about 25% and 5% of these essential nutrients consumed from oil edible crops and vegetables, respectively, will be lost in the studied household diet.

Yet, interviewed households declare to spend only occasionally on animal source food (e.g., on Christmas) as described in table 4.6 below.

Table 4. 6. Interviewed households expenditure on animal source food

Purchased (in Rwandan Francs/ year)	Min	Max	Mean	Number of households
Beef meat	0	400 000	23 439	73
Chicken	0	60 000	909	2
Eggs	0	60 000	1 728	9
Fish (*Indagara*)	0	40 000	13 44	11

Finally, our results show that the availability of foods providing richer nutrients in smallholder farm households depends to a large extent on plant-based foods. Also, an important part of nutrients consumed by smallholder farm households is relatively self-supplied.

4.6. Discussion of smallholder farm households' vulnerability to pollinators: Limits and perspectives

The economic analysis of the benefits of insect pollination services through crop production, farm income, and nutritious food consumption highlights the direct impacts of these services' degradation on human welfare, particularly in the case of smallholder farm households in a rural context of a developing country. The first section discusses our results. The second section highlights the limits of the economic model developed in this study. The third section sets the perspective of changes in the future if pollinators decline.

4.6.1. The discussion on smallholder farm households' vulnerability to pollinators decline

The estimated ratios of the vulnerability of the farm household well-being to pollination decline were based only on worldwide known food crops, thus the contribution of pollinators to the animal fodder, local or traditional plants, floristic industry, etc. is not considered. With that in mind, let us discuss three of our results.

First, insofar as nothing changes, our findings show that 11% of total farm income (50 thousand Rwandan francs on average; i.e. approximately €50[34]) and 20% of marketed production share (18 thousand Rwandan francs on average; i.e approximately €18) of the farm households can be lost in the case of total extinction of insect pollination. This tendency of farm income decrease is supported by tremendous literature on the economic valuation of pollination services (see Chapter 1). Besides, in our field of study, this percentage includes only around seventeen crops, already known to be pollinator-dependent species worldwide, out of forty-six different types of crops produced. Yet, in the study are, like the rest of the African continent, there are indigenous crops that are pollinator-dependent but their dependence ratio is still unknown and thus the contribution of insect pollination on the yields of such crops in our sample is not evaluated. Consequently, the decline of pollinators will further affect the welfare of farm households.

Also, any shock in production, which increases market prices, as is the case with pollination decline, has a bold negative impact on low-income farmers. The decline in pollination services risks worsening agricultural production for these households, if nothing changes, and thus increases the risk to widen price band magnitude. Faced with a wide price band, households may be better off choosing self-provision in that good if the price which equates to its supply and demand (its shadow price) falls inside

[34]Based on the average indicative exchange rate of the National Bank of Rwanda in 2020, one euro is roughly equivalent to 1,000 Rwandan francs (RWF).

the band. According to Sadoulet and de Janvry (1995), the magnitude of the price band may be increased by various factors, including transaction costs, shallow local markets, price risks, and risk aversion. In this situation, household decisions to adapt to pollinators decline shock in their production could not be influenced by market prices (as explained in section 4.2.1). Instead, household characteristics will play a key role in the adaptation, which will reduce, for instance, farmers' free time to compensate for pollination through management practices of pollinators or increase off-farm activities to compensate for the loss of farm income and thus weaken general welfare.

Second, current farm household food consumption risks losing about 6.7% if insect pollination services totally extinct. Indeed, staple crops are an important share of their daily food consumption and thus their share of food demanded on the market is important (Table 3.b). Moreover, staple crops are an important quantity produced and the main source of farm income. Those crops include beans, roots, tubers, whose pollinator dependence and nutrient ratios are mostly unknown, and maize, which is not dependent on insect pollination services and fewer nutrient providers. In food bought on the market, the shares of fruits and vegetables in total expenses are 5% and 13% respectively; as for their self-production, the shares of fruits and vegetables are 12% and 7%, thus, own production for micronutrient providing crops is crucial for these households. These results are important knowing that the level of malnutrition in the territory is already alarming as more than 50% of the population is malnourished (GoR nutrition, 2015). These results highlight concerns raised in various studies on the impacts of monoculture systems on the food security of smallholder farmers (Pritchard, 2013; Cely-Santos and Lu, 2019). Also, this is echoed in academic debates about the magnitude of the income elasticity of nutrient intake compared with the income elasticity of food expenditures in poor households (see e.g., Behrman and Deolalikar, 1990; Gassner et al., 2019). The problem of malnutrition cannot be resolved, efficiently, if the production of these non-staple crops is not supported on a large scale.

Last, our findings show that the practices of smallholder farms in the studied area can be conducive for the preservation of pollinators and pollination services. Smallholdings characteristics might allow more precision in the application of pesticides and the application of pollination management practices in general. The farming practices identified can be conducive to boost pollination services and many other ecosystem services on the farm if they are well supported. As the benefits of pollinators density for crop yield are greater for small-scale farms than for larger farms (Garibaldi et al., 2016). The use of external inputs such as pesticides, which can have a trade-off with pollination services, is still mediocre even if it is encouraged via subsidies policy (Cantore, 2011). The pesticides are used only on 15% of the crop produced and are used only by 35% of farmer households. Agriculture is still labor-intensive in the area studied as well as in Rwanda in general. On the contrary, as stated by Cantore (2011), these practices are extremely counterproductive, and external inputs that are extremely low are of bad quality and misused in Rwanda. For example, the conflicts raised by beekeepers against practices in coffee plantations indicate a possible trade-off between insect pollination services and pesticide use existing currently in the studied area and other similar areas in the country.

Finally, agricultural policies that aim to transform subsistence agriculture focusing on sustainable crop intensification by promoting external inputs use and monoculture development on consolidated farm parcels to increase land factors can be re-evaluated. However, despite the progress made to adopt crop intensification program patterns in Rwanda, in the studied area is still low. Farm production is positively and significantly influenced by labor, land size, and fertilizers as highlighted in studies evaluating crop intensification programs at the country level (GoR, 2010). The major reasons can be explained by the relatively low expenditure on other inputs (Cantore, 2011).

4.6.2. Our economic model limits

Our model allows us to estimate the ratios of vulnerability of farm household production and consumption on insect pollination decline, despite the limitations of the technical feasibility and agro-ecological data constraint (e.g., pollinator threshold) of new research questions in our case study. However, it has no-negligible limits to reflect the reality.

Among other limits, our model does not allow us to estimate the changes that the decline of insect pollination can generate as farmers adapt to pollinators decline. Farmers may, for example, adapt to this change by adopting intensification practices, specializing thus in non-pollinator dependent crops; or by adopting pollinator-friendly practices, reinforcing thus productivity of their overall produce mix. Three major limitations specific to our case should be highlighted. First, our model does not predict the changes that might occur in a farm household production and self-consumption decisions integrating the pollination factor. Second, the variation in quantities and quality of farm household goods and services that will be exchanged as pollinators decline (at the new equilibrium) cannot be estimated with our model. Third, non-human food crops and wild food are not included in our analysis (e.g., farm household animal fodder, local or traditional plants, honey or floristic production income, medicinal plants), although their contribution to the welfare of rural households, as pollinator-dependent crops decline, could be important.

Yet, pollinators decline will change prices (${P_c}^a, {P_c}^d$) and production costs as farm households will have to allocate their resources differently ($\text{e.g.}, \ pesticides\ A,\ {l_{hc}}^F, C_{hL}$) to adapt and/or to mitigate this decline. For instance, as we have seen in Chapter 2, the total extinction of pollinators may result in a 186% increase in the world price of crops. Also, the degradation of pollinators and their pollination services can change individual WTP, given their preferences, towards the benefits of pollinators as, for example, it was expressed in our study in Southwestern France, in the Comminges territory, where individuals are willing to pay about five hundred euros per household a year to avoid pollinators decline (see Chapter 3).

Although there is little literature on pollination at the farm household level, following the above considerations, in line with several economic studies on economic valuation of pollination services (e.g., Klein et al., 2007; Gallai et al., 2009; Breeze et al., 2015; Gallai and Salles, 2016; Bauer and Wing, 2016, IPBES, 2016; Cely-Santos and Lu, 2019), reasoning centered on farm households facing pollinators decline can emerge. Indeed, farm households confronted with pollination declines will have to adapt their consumption and production under the constraints of local consumption structures and the level of liquidity available in households. Moreover, the government may intervene to mitigate and halt the consequences of pollinators decline.

As indicated, this thesis proposes to support public policy needs to halt this decline. The following section discusses different government intervention scenarios.

4.6.3. Perspective of changes in the future relative to pollinators benefits

Currently, in the studied area, the adoption of land-use consolidation and crop intensification technologies is very low as is the case across the country (Cantore, 2011). Future consequences of pollinators decline on the welfare of farm households in this area can be discussed relative to technological changes, following three prospective scenarios adaptable from the IPCC SRES Scenarios (IPCC 2000) - current trends scenario (as a baseline), conventional-intensification scenario (referring to characteristics of the Agriculture Market Liberalization scenario), and sustainable-intensification scenario (referring to characteristics of the Green Agriculture scenario) – over the time frame of twenty years. With a focus on agricultural/food production policies concerning both productivity and sustainability (as illustrated in Figure 4.7 below), we discuss the perspective of future changes in the production and consumption attributes in the studied area relative to the thresholds of pollinators (see table 4.7 below). The vulnerability of these attributes to the declines of pollinators as analyzed in this chapter offers a narrative of possible outcomes in the studied area if the agricultural transformation measures are keenly adopted by farmers.

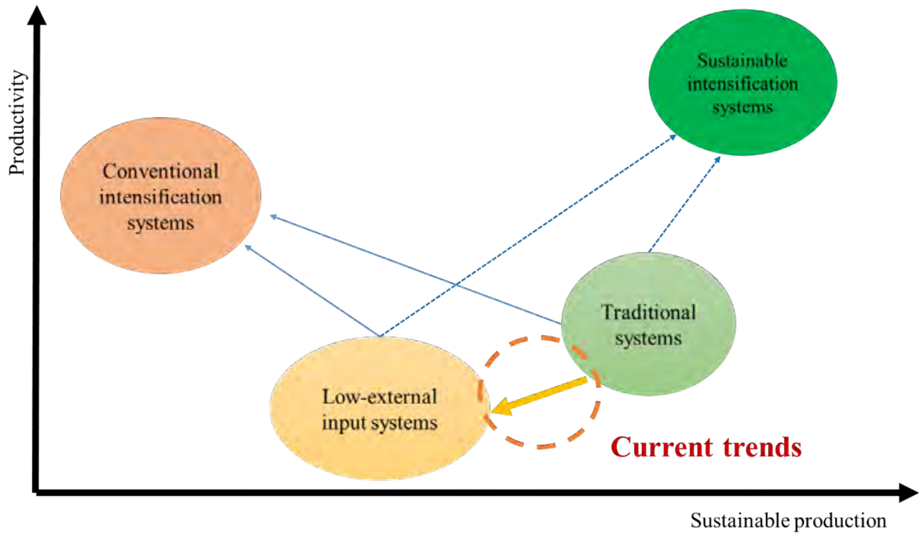


Figure 4. 7. Possible outcome scenarios depicting consequences relative to agricultural policies concerning both productivity and sustainability of agricultural production

In the current trends scenario, farm households are in a situation where no action is concretely mobilized as a solution to pollination decline. In this case, future patterns of activity assume that there will be no significant change in people's attitudes and priorities, or no major changes in technology, economics, or policies so that normal circumstances towards pollinators can be expected to continue unchanged. As a consequence, the production of local pollinator-dependent crops may decrease while their production costs, as well as their local prices, may increase as the services of pollinating insects decrease. For rural farm households in developing economies, the quantity and nutritional quality of consumption and farm income will be negatively impacted.

In a conventional-intensification scenario, farm households can be in a situation where intensive and monoculture practices are encouraged as solutions to offset pollinator decline effects. As noted before, conventional intensification systems are linked to the introduction of monoculture systems that include the use of high-value external inputs, including synthetic fertilizers, pesticides, herbicides, and others (Perfecto et al., 2019). In this situation, farmers might move from traditional and low-external input systems to conventional-intensification systems, specializing thus in non-pollinator-dependent crops. Traditional systems refer to the peasant's farming systems that do not mobilize synthetic inputs. In this scenario, the services of pollinating insects would not be a strict requirement. This may result in the substitution of production of pollinator-dependent crops with non-pollinators dependent crops. This would mean modifying both the production utilization and the local consumption structure. For farm households in developing countries like Rwanda, this change would have a positive impact on income in the short term (Uwingabire, 2012) and a negative consequence of nutrient consumption (see for example Sadoulet and de Janvry, 1995).

To resolve the concerns listed previously, we propose to apply the sustainable-intensification scenario.

In the sustainable-intensification scenario, farm households can be in a situation where actions mobilized are about the reinforcement of the efficiency of environmental patterns on agricultural lands as solutions to the decline of pollinators. For sustainable intensification systems we refer to a system where agricultural yields are increased without adverse environmental consequences (Pretty et al., 2014), and systems that take into account the human condition, nutrition, and social equity (i.e., as in Smith et al., 2017). In this scenario, farmers would be incited to adopting ecological innovations and technologies that are pollinator-friendly practices, reinforcing thus productivity of their overall products mix. This will result either in enhancing or maintaining local consumption structure while increasing productivity. In this scenario, farmers will conserve insect pollination services on their farms along with other ecosystem services. This change would have positive consequences in the longer term on both farm resilience and nutrient consumption of farm households in developing countries by improving access to diverse nutrients.

Table 4. 7. Change perspective of attributes with impacts on welfare indicators for smallholder farm households

Attributes	Vulnerability ratio obtained	Current trends scenario	Conventional-Intensification scenario	Sustainable-Intensification scenario
Changes in technology	-	No	Intensive and monoculture practices	Ecological-innovations and technology improvement
Public measures	-	No change	Subsidize only staple crops	Reinforcement of the environmental patterns on agricultural lands (e.g., PES)
Production	11%	Decrease	Increase few crop species productivity	Reinforce a mix of crop species productivity
Costs	-	Maintain	Increase	Decrease
Local food prices	-	Increase	Decrease for some crops	Sustain
Supply income	13%	Decrease	Increase	Improve
Farm profit	20%	Decrease	Positive in shorter-term Negative in longer-term	No change in the shorter-term Positive in longer-term
Consumption	6.7%	Maintain	Decrease	Increase
Nutritional intake quality	5% to 28%	Negative	Maintain or Negative	Positive
Self-consumption	9.5%	Decrease	Modify or decrease	Increase
Local consumption structure	-	No significant change	Modify	Enhance or maintain

In conclusion, we highlight the implications of our findings for decision-making and future research prospects.

4.7. Concluding remarks

This chapter analyzed the vulnerability of agricultural production, farm income, and nutritional quality consumption on the decline of insect pollination services in the case of smallholder farm households operating under imperfect market conditions in a developing country with a low-income economy, Rwanda. It showed that these households stand to lose about 20% of their already negative farm profits and 11% of their farm income (especially from pollinator-dependent crops - e.g., coffee sales) if pollinators totally extinct. In addition, the food consumption of farm households in the study area includes a significant share of self-supply of micronutrient-providing crops, which are particularly vulnerable to pollinators decline, including fruits, edible oilseeds and vegetables. While insect pollination services make only a small contribution to the production of staple crops in this region (e.g., about 5% for pulses, 0% for tubers and cereals), their contribution to nutritional quality consumption - which is critical at the moment - is nonegligeable. Thus, if the trend of pollinator decline continues, the state of nutritional quality consumption may get worse.

These results imply that policies that focus only on a limited number of staple crops, particularly non-pollinator-dependent crops, may fail to improve the quality of life in the study area. This is supported by the literature (see Section 4.2), which has shown that such efforts can be undermined because low-income farmers operating in a context of market imperfections are reluctant to adopt monoculture farming systems. Two major reasons have been noted. First, the livelihood of many farm households rely primarily on small farms (< 0.5 ha) and natural ecosystem services, thus more vulnerable to the degradation of such services. Moreover, the main concern for most smallholder farm households with low-income in developing countries remains survival at present (Gassner et al., 2019). In this case, food security measures should be a priority. The food security of smallholder farmers relies on the diversities of indigenous legumes, cereals, roots and tubers, fruits and vegetables, spices, and medicinal plants, and their cohort of auxiliary fauna, flora, and microorganisms (MEA, 2005), which they can self-supply. Second, effective crop intensification, which focuses on increasing production of a small number of crops, involves expensive technologies using external inputs that low-income farmers cannot afford and knowledge that is beyond their reach. Also, in the absence of sufficient disposable income to meet the basic food needs of smallholder farming households, they may remain risk averse – to adopt conventional intensification agriculture - by mobilizing mixed cropping systems.

Therefore, is not it more efficient to improve traditional cropping systems currently practiced by farmers to develop sustainable intensive agriculture in Rwanda, as well as in countries dominated by small-scale farm holdings? For example, promoting free ecosystem services within agroecosystems, rather than promoting solely purchased off-farm inputs that may compromise social equity (i.e. as in Loos et al., 2014). Could not there be a solution to invest in technologies on how to intensively grow more diverse and better-adapted crops that would address local food and nutrition security and, later on, give more economic opportunities to smallholder farmers, at local and regional level contexts?

Public policies can promote the transformation towards sustainable intensification systems by stressing on combining the characteristics of smallholdings to complement external inputs use which might be mutually beneficial to pollinators and to the ecosystem service they provide to food supply (see Garibaldi et al., 2016, Smith et al., 2017).

In future research, there is a necessity to analyze how to efficiently combine the potential of smallholding characteristics to improved and accessible technologies, which might be mutually beneficial to pollinators and the ecosystem service they provide to food supply for smallholder farm households in developing economies context. There is also a necessity to analyze public policies that can incentivize not only the production but also the provision of insect pollination as well as other ecosystem services in agroecosystems (e.g., Payments of Ecosystem Services) to safeguard, in the longer term, the benefits of these services for society.

General Conclusion

The objective of this thesis was to address these questions:

i) What would be the consequences of the decline of pollinators on the quantity and nutritional quality of edible crops produced and consumed worldwide given international trade mechanisms?

ii) What could be the public willingness to protect pollinators?

iii) What could be the impacts of pollination services decline on food production and nutrient consumption in the case of farm households in a developing country context?

To respond to these questions, from an economic point of view, we measured the economic value of marketed and non-marketed benefits that pollinators can generate to human well-being through three indicators: the quantity and nutritional quality characteristics of food, landscape characteristics, and farm household patterns.

In this light, as Table 5.1 below summarizes, this thesis conducted economic valuation at the global, territorial, and farm household scales through distinct case studies set in different contexts. The economic and nutritional impacts of pollinators decline on human well-being were assessed using the production function approach, which integrated the crop production dependence ratio on pollinators (i.e., as defined in Chapter 1) and nutrient ratios in crops found in Chaplin-Kramer et al. (2014) (see Chapter 2, Chapter 4). To assess the general public willingness to protect pollinators, we used the stated preferences approach (Chapter 3) and estimated willingness to pay for various benefits of pollinators.

Table 5. 1. Summary of the case studies addressed in this thesis

Spatial scales Case study contexts	**Scope of economic concepts covered**			**Economic valuation method**
	Pollinators benefits	**Unit of analysis**	**Variable**	
Global International trade context	Food quantity and nutritional quality on the market	Countries aggregated in sub-regions	Producer profit & Supply, Consumer surplus & Demand, Nutrient consumption	Crop production dependence ratio on pollinators
Territorial Comminges in Southwestern France Developed & High-income economy (with GNI > US$40000/capita/year)	Food quality and varieties, wild flowers, and the existence of pollinators in the local landscape	Individuals in the general public	Willingness to pay (WTP)	Stated preferences
Farm household Huye district in SouthernRwanda Developing & Low-income economy (with GNI ~ US$800/capita/year)	Food quantity and nutritional quality in farm households	Smallholder farm household	Production, Income, Consumption, Self-supply	Crop production dependence ratio on pollinators

Based on this methodology, we showed that the decline of insect pollinators could have significant consequences on human well-being at local and global scales. As we have pointed out in Chapter 1, there is the interdependence of ecological and socio-economic phenomena concerning pollinators benefits (Chapter 1, Section 1.3.2), various values at play (Chapter 1, Section 1.2.3), and multiple actors involved in their use (Chapter 1, Section 1.4.1). As such, in this thesis, we argued that it is essential to consider responses to the decline of pollinators not only from locally-focused public policies but also from national and international coordination, as well as general public initiatives.

As closing remarks, we articulate our main results, highlight the implications of this thesis on responses to the decline of pollinators at each scale in the contexts studied, the specific contribution of this thesis to the literature, the limitations of our analysis, and provide perspectives for future research.

1) Results of the economic analysis

i) The consequences of the pollinators decline on the quantity and nutritional quality of edible crops produced and consumed worldwide

Our results showed that all countries are impacted by the pollination crisis through international trade mechanisms, either as net producers or net consumers of pollinator-dependent crops (e.g., fruits and vegetables) (Chapter 2). In other words, if pollinators decline, countries may lose in terms of crop production quantity, sources of nutrients, which may induce an increase in prices of pollinator-dependent crops. As a result, there may be a decrease in consumer surplus and producer profit and a loss of nutrients consumption, thus an overall loss of human welfare. Therefore, this thesis argued that the vulnerability of countries to the decline of pollinators depends not only on their production specialization, as exporters of pollinator-dependent crops, but also on their demand, as importers of agricultural products in the context of declining global nutrient supply.

Eventhough pollinators decline is a global concern, in the same line with previous studies, our results underline that the vulnerability of countries to this decline is heterogeneous across regions of the world due to, among other things, differences in their initial endowments. For example, some countries have relatively specialized in pollinator-dependent crops (e.g., cacao for Ivory Coast), and malnutrition is prevalent in some countries. Therefore, this decline will exacerbate malnutrition in those already affected and hamper the productivity of some countries. Thus, the consequences of the pollination crisis across countries can be perceived differently, which may reflect the different willingness, sensibility, or awareness of countries and, thus, the importance (value) they place on the benefits of pollinators. In analyzing the international market, we could not consider all such effects and specificities. As such, our analysis on a global scale reflects only a partial set of facts.

We have thus supplemented our economic analysis with more local assessments (in chapters 3 and 4). Thanks to the opportunities we have had during this Ph.D. project, we assessed the economic value of the benefits of pollinators in two case studies, as Table 5.1 above shows. On the one hand, we undertook the economic valuation of various benefits of pollinators in the Comminges territory of the Southwestern France, a developed country with high-income economy. On the other hand, we proposed an analysis in the smallholder farming households in the Huye region in the Southern Rwanda, a developing country with low-income economy. Using the economic literature and consultation with panels of local experts, we explored what the decline of pollinators might imply for the well-being of local actors in the studied areas. Two main questions were of our concern: are local stakeholders aware of current trends of pollinators decline? If yes, are they willing to participate in combating this decline? To what extent is local food production, local consumption of nutritious food, local biodiversity, and thus local actors' well-being affected by this decline of pollinators?

ii) The public willingness to protect pollinators: The case of the Comminges territory in the South-West of France

On the territory studied in France, there is a better knowledge, a growing awareness, and sensitivity to this pollinators decline issue at the level of producers and consumers. From a production perspective, this awareness is echoed in some public policies. For example, France has launched an action plan, "France, Terre de Pollinisateurs 2017-2020," aimed at preserving wild bees, which stems from the

"European Pollinator Initiative" of the EU's 2014-2020 rural development program. Similarly, the panel of local experts was aware of the consequences of the decline of pollinators in their area. However, from a consumer perspective, the benefits of pollinators and their values remain understudied.

Therefore, this thesis proposed studying the general public's willingness to participate in the conservation of pollinators at a territorial scale in French context (in Chapter 3). Through the stated preferences, respondents from the general public in the study area were significantly willing to pay (€516/household/year) for the existence of pollinators, the quality and variety of local fruits and vegetables they eat, and the local wildflowers they enjoy in their neighborhood. This analysis provided information about individuals preferences, awareness, understanding, responsibility, etc. - all of which go hand in hand - toward the issue of pollinators decline in the Comminges and thus the importance they place on them.

iii) The impacts of pollination services decline on food production and nutrient consumption: The case of smallholder farm households in Huye District in Southern Rwanda

In the international model, we showed that countries like Rwanda will be severely impacted by the decline of pollinators. However, the macro analysis does not show how local actors can take up this issue and especially how they will be impacted on both economic and nutritional aspects. It was therefore interesting to focus on the context of developing countries to complete our study, which we did focusing on smallholder farm households in Huye District in Southern Rwanda. In Rwanda, as in many developing countries, economic studies or policy reports on the issues of pollinators decline are still rare. As for panels of local experts in the studied area, concerns about pollinators decline are relatively untapped. Therefore, from both a production and consumption perspective, there are considerable gaps in the actions of local actors on the issue of pollinators decline.

In this case, economic valuation can only be relevant to actors whose welfare is directly linked to the benefits of pollinators, such as farmers. A farmer is one of the actors' well-being directly affected by pollinators decline and likely to mobilize practices to preserve pollinators effectively. Moreover, in theory, farm households in a developing country context are unique. As described in Chapter 4, farm households in developing countries are both producers and consumers of crops and, consequently, the imperfection of markets in which they operate makes their production and consumption decisions often interdependent. Thus, any shock affecting the production of this type of farm households has direct effects not only on their income but also on the quantity and quality of their food consumption. Thus, the arbitration between the development of economic activities and the protection of insect pollination can be through these households, which are consumers and producers.

This thesis proposed thus an analysis at farm household scale (in Chapter 4), arguing that this scale has to be considered in its own right because the types of coordination are different in developing countries context, and so might be the types of pollinators protection responses. By stressing that public policymakers have to look at things more broadly through, for example, the different uses but also the different centers of interest or conflicts of interest that may exist.

Our results showed that pollinators decline could particularly affect incomes and nutrients consumption in the case of low-income smallholder farm households studied. Notably, our results showed that these households often self-supply essential nutrients contained in pollinator-dependent crops, such as fruits, vegetables, and oilseeds.

2) Implications of our results in terms of public policy and initiatives

The implications of our results at each scale studied are threefold.

First, considering pollinator protection measures through international trade processes is crucial because a large part of the relations between countries are organized through international market rules (for example, the WTO rules). Although, our economic valuation at the global scale was limited to the marketed benefits of pollinators (e.g., the quantity of production and nutritional quality of food consumption); it can provide channels for anticipating responses at this international level. Among other possible measures, the coordination of states can help homologate pollinator protection rules at the country level. Such an effort can effectively provide oversight or monitoring and management of, for example, specialization trends that may threaten global benefits of pollinators (e.g., food pollination by insects, insects as biodiversity). That coordination could ensure that the countries contributing to international trade mechanisms, which continue to produce pollinator-dependent products, protect pollinators to maintain the global food balance and biodiversity. In addition, this coordination can be structured to encourage these goods to become increasingly accessible to all through trade (e.g., by reducing trade tariffs as an incentive for good pollinator management), which can also help combat malnutrition. However, as noted above, the heterogeneity of the pollination crisis across countries may reflect their different economic, social, and ecological contexts and thus the varying willingness, sensibility, or ability of the countries to consistently implement public policies and initiatives that address pollinators decline.

Second, our results can be used if there is a public policies need to apply more localized and inclusive measures or actions by considering the preferences of the actors in a territory, which can be more effective. Also, our analysis may allow for the consideration of cost-benefit analysis and payments for pollination ecosystem services in future local stakeholder coordination. Indeed, it may allow local public authorities to facilitate arbitration within local actors. Although the results of such an assessment could vary depending on the context in which the study is conducted, our results imply a need to define pathways that can guide individual choices and decisions in actions concerning the protection of pollinators.

And third, public policies aiming at improving food security in the context of smallholdings and low-income households whose primary consumption of nutritious food comes from the self-supply should consider protecting insect pollination services. In that sense, this thesis argued that public policies should seek to promote affordable innovations and technologies towards sustainable intensification systems focusing on the potential of smallholding characteristics (e.g., see Chapter 4). For instance, such policies can significantly improve the livelihoods of the most vulnerable households by targeting external high-yield inputs that are beneficial to pollinators and thus to the ecosystem service they provide to the food supply.

As such, the implications of this thesis in terms of public policy and initiatives imply that to protect the benefits of pollinators requires setting complementary responses that may include decisions, interventions, and the coordination of actors operating at different scales. A variety of actors noted as part of the pollinators protection efforts, included states, international organizations, the general public encompassing consumers and producers. First, states can intervene through public policies supporting the management of pollinators. Second, coordination of international organizations through various initiatives is essential to overcome the geographic limitations of states. Third, the decision of the general public to participate in the preservation of pollinators is critical to the effectiveness of public policies and to safeguard pollinators and their various benefits. And finally, the decision of producers (farmers) to adopt public policies and adapt their actions to practices beneficial to pollinators. Particularly, the findings of this research may effectively contribute towards the improvement of the current and ongoing policy measures in, for example, Rwanda (e.g., agriculture transformation policies) and in the Occitanie Region (ecological transition policies) towards the provision of pollination services.

Coming back to our analysis, public policy must encompass more things than those that the economic valuation tool (in Chapter 1, section 1.2) can highlight because decision-makers must take political decisions, i.e., integrating thus more precautions by considering a set of interests of the population living today and in the future. Given that public policy may play an arbitration role, in particular in the allocation of a limited budget to various and varied problems, economic valuations can support its choices. For instance, ignoring the nutritional problem relative to economic problem that results from insect pollination degradation can devalue the problem of child health and malnutrition in several countries. The economic value will allow putting in place political instruments through different mechanisms such as incentives, subsidies, sanctions, etc. Note that without there being any need to make a budgetary arbitration for political decision-makers between different concerns, certain public policies concerning pollination can be internalized transversally in other political agendas which would aim, for example, to do evolve behavior towards pollinators such as education.

3) What does the analysis at different scales really bring?

Each level of analysis was crucial to understanding the different aspects of the problem of pollination crisis due to pollinators decline, as well as the complexity of possible political responses to it. Economic values depend on the scales of analysis, the definition of the problem, and, in particular, the actors concerned since the people's perceptions and uses of pollinators and pollination services may differ.

The consistency of the implications of our findings in decision-making, while focusing on different spatial scales and case studies, bounces back to the necessity of complementary responses to the decline of pollinators from a variety of actors operating at different scales (Chapter 1). While it was not the intent of this thesis to address interdependencies of economic phenomena analyzed, measures taken at the international trade level can affect agricultural practices at local scales, which, in turn, can reshape landscapes and their characteristics, notably in rural areas.

Similarly to economic valuation, public policies are essential but ultimately depend on the definition of the problem, the actors targeted, the scales considered, and all of these go hand in hand. Some public policies are possible in one area and not in another context. On the one hand, depending on the scale, some public policies are possible because there is a respected authority, whereas others have no administrative authority with coercion. On the other hand, there are places where coercive policies are not needed because they are not effective and would be very costly, while collective initiatives might work better.

But, what is the added value of this thesis in the literature?

4) This thesis-specific novelty

The contribution of this thesis to the economic literature concerns the enrichment of the economic valuation of the benefits of pollinators by examining economic and nutritional aspects at the global scale and local scales in different contexts. Table 5.2 below briefly summarizes these contributions.

Table 5. 2. The specific contribution of this thesis to the literature

SCALE \ VALUE	Use-Value		Non-Use Value	Details in thesis:
	Marketed-benefit	Non-marketed benefit	Non-marketed benefit	
Global - food scarcity	Quantity of food crops (Bauer and Wing, 2016)	**Nutritional quality of food crops**		Chapter 2
Territorial - landscape characteristics	**Quality and Varieties of local fruits and vegetables**	Wild flowering plants (Breeze et al., 2015)	**Pollinators existence**	Chapter 3
Farm household - livelihood	Quantity of food crops (Cely Santos and Lu, 2019)	**Quantity and nutritional quality of self-supplied food**		Chapter 4

Note: Our contribution to the literature of economic valuation of various benefits of pollinators is in bold. In parentheses are the economic studies investigating the benefits of pollinators in each of the scales and contexts this thesis covered.

Indeed, an empirical study that considers international trade mechanisms to analyze the overall impacts of pollinators decline on producer profit, consumer surplus, and nutrient consumption is new to our knowledge. The existence value of pollinators had also not been assessed before. It also contributes to the economic literature by suggesting a new approach to analysis quantifying the effects of pollinators decline from the farm household perspective in a particular context where production and consumption are often linked.

Besides our contribution, there are still some limitations that should be considered.

5) The limits of our analyses

As more specific limitations are highlighted in the chapters, the crosscutting limitations of our analyses can be approached in two respects.

On the one hand, we did not consider in our analysis the fact that pollinators depend on ecosystems and are natural elements that function in interactions with other ecosystem services to which they are linked. Also, we considered pollinators as a whole, rarely differentiated managed pollinators to wild pollinators, whereas managed pollinators can be considered non-endangered species. Hence, our analyses lack insights regarding how other natural elements (e.g., managed honeybees) would compensate the decline of pollinators in ecosystem and thus foster adaptation of crops and wild plants to the lack of insect pollinators, which might be endangered, in agroecosystems or other landscapes.

On the other hand, our economic valuation was primarily based on the perspective of individual welfare. Both our analytical and theoretical models, rooted in individual rationality, and our experimental designs could not consider some of the complexities of the real world and all aspects of the benefits of pollinators. Considering the interdependencies of a variety of actors benefiting from pollinators is essential for comprehending different adaptations to this decline and, thus, its economic consequences. Also, our analytical approach did not allow us to estimate the changes that this decline of insect pollination may generate for actors who adapt to it through, for example, substitution mechanisms. Indeed, there may be substitution within the same crop category (e.g., a pollinator-dependent crop versus a non-pollinator-dependent crop), switching to other means of pollination, etc. Such substitutions are likely to occur when the prices of pollinator-dependent crops increase or when pollinators, as a factor of production, decrease. Indeed, pollination market already exists in some countries (e.g., US, France, Australia, etc.) (See Chapter 1, Section 1.2.3).

Finally, the results and limitations of this thesis may provide ideas for future work that would be important for a better understanding of ecosystem service networks and appropriate actions to address their potential degradation based on social rationality.

6) Future research perspectives

There are at least two potential areas of development in future research concerning the framework for analysis of ecosystem services and the development of public policy instruments related to them.

First, it is worth considering the economic and health aspects of the benefits that other ecosystem services generate for society in order to strengthen public policies and practices aimed at conserving pollinators as well as other components of Nature, as their functions are often linked in Nature. Also, given that the decline of pollinators may decrease productivity and increase prices, low-income farm households operating small farms primarily for livelihoods are more likely to adapt to this decline by diversifying its farm to self-supply nutritious food crops (see Chapter 4, Section 4.2.1). Such adaptation is essential for these households' self-sufficiency in food, and thus public policies should be developed to support such efforts. In this regard, future research can analyze both the feasibility and potential of combining smallholder farm characteristics with improved, high-yielding input technology beneficial to pollinators and other ecosystem services essential to the food supply of smallholder farm households in the developing country context.

Second, research will be needed to translate the economic values, such as those we obtained and the preferences we recorded in this study, into local public policy measures and local collective actions. In other words, given the interdependence of these services, the multiple stakeholders concerned, and the numerous environmental values at play, in future research, mobilization of complex thinking and implementing social rationality may be useful to meet the democratic requirement of public decision-making (Fleury, 2010). Indeed, it might be interesting to complement our economic valuation in the Comminges with deliberative monetary valuation.

In the context of developing economies, there is also a need to analyze public policies that can encourage not only crop production but also the provision of ecosystem services in agro-ecosystems to sustain the long-term benefits of these services for society, especially for low-income rural farm households; - e.g., payment for ecosystem services for non-agricultural purposes, the introduction of beekeeping on farms, support to beekeepers, etc.

Finally, analysis of the interdependencies of responses from different scales in the management of pollinators may also be useful - for example, how does the E.U. ban of the use of neonicotinoids affect pesticide markets and farming practices within and beyond the E.U member countries? Or, how can the WTO facilitate the flow of the economic and nutritional benefits of pollination ecosystem services among countries?

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Appendix 2. 1. FAO classification of world sub-regions

Region	Sub-region Acronym	Sub-region	Country
Africa	eaf	Eastern Africa	British Indian Ocean Territory, Burundi, Comoros, Ethiopia PDR, Djibouti, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Eritrea, Zimbabwe, Réunion, Rwanda, Seychelles, Somalia, United Republic of Tanzania, Uganda, Ethiopia, Zambia, Mayotte, South Sudan.
	maf	Middle Africa	Cameroon, Central African Republic, Chad, Congo, Equatorial Guinea, Gabon, Sao Tome and Principe, Democratic Republic of the Congo.
	naf	Northern Africa	Egypt, Libya, Morocco, Western Sahara, Sudan (former), Tunisia, Sudan.
	saf	Southern Africa	Lesotho, Namibia, South Africa, Swaziland.
	waf	Western Africa	Benin, Gambia, Ghana, Guinea, Cote d'Ivoire, Liberia, Mali, Mauritania, Niger, Nigeria, Guinea-Bissau, Saint Helena, Ascension and Tristan da Cunha, Senegal, Sierra Leone, Togo, Burkina Faso.
Asia	cas	Central Asia	Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan.
	eas	Eastern Asia	China- Hong Kong SAR, Japan, Democratic People's Republic of Korea, Republic of Korea, China- Macao SAR, Mongolia, China- Taiwan Province, China.
	sas	Southern Asia	Afghanistan, Bangladesh, Bhutan, Sri Lanka, India, Iran (Islamic Republic of), Maldives, Nepal, Pakistan.
	seas	South-Eastern Asia	Brunei Darussalam, Myanmar, Indonesia, Cambodia, Lao People's Democratic Republic, Malaysia, Philippine, Timor-Leste, Singapore, Thailand, Viet Nam.
	was	Western Asia	Armenia, Bahrain, Cyprus, Azerbaijan, Georgia, Iraq, Israel, Jordan, Kuwait, Lebanon, Qatar, Saudi Arabia, Syrian Arab Republic, Oman, Turkey, United Arab Emirates, Yemen, Occupied Palestinian Territory.
America	nam	Northern America	Bermuda, Canada, Greenland, Saint Pierre and Miquelon, United States of America
	cam	Central America	Belize, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama.
	car	Caribbean	Antigua and Barbuda, Bahamas, Barbados, Aruba, Cayman Islands, Cuba, Dominica, Dominican Republic, Guadeloupe, Haiti, Jamaica, Martinique, Montserrat, Netherlands Antilles, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Trinidad and Tobago, Turks and Caicos Islands, British Virgin Islands, United States Virgin Islands, Anguilla, Curaçao, Saint Maarten (Dutch Part).
	sam	South America	Argentina, Bolivia (Plurinational State of), Brazil, Chile, Colombia, Ecuador, Falkland Islands (Malvinas), French Guiana, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela (Bolivarian Republic of).
Europe	eeu	Eastern Europe	Bulgaria, Czechoslovakia, Belarus, Hungary, Republic of Moldova, Czech Republic, Poland, Romania, Russian Federation, Slovakia, Ukraine.
	neu	Northern Europe	Denmark, Estonia, Faroe Islands, Finland, Iceland, Ireland, Latvia, Lithuania, Norway, Sweden, United Kingdom, Channel Islands, Svalbard and Jan Mayen Islands, Isle of Man

	seu	Southern Europe	Albania, Andorra, Bosnia and Herzegovina, Gibraltar, Greece, Holy see, Croatia, Italy, Malta, The former Yugoslav Republic of Macedonia, Portugal, Serbia and Montenegro, San Marino, Slovenia, Spain, Yugoslav SFR, Serbia, Montenegro.
	weu	Western Europe	Austria, Belgium-Luxembourg, France, Germany, Liechtenstein, Monaco, Netherland, Switzerland, Belgium, Luxembourg.
Oceania	Aus&newz	Australia & New Zealand	Australia, Christmas Island, Cocos (Keeling) Islands, New Zealand, Norfolk Island.
	mela	Melanesia	Solomon Islands, Fiji, New Caledonia, Vanuatu, Papua New Guinea.
	mic	Micronesia	Kiribati, Guam, Marshall Islands, Micronesia (Federated States of), Nauru, Northern Mariana Islands, Pacific Islands Trust Territory, Palau.
	poly	Polynesia	American Samoa, Cook Islands, French Polynesia, Niue, Pitcairn Islands, Tokelau, Tonga, Tuvalu, Wake Island, Wallis and Futuna Islands, Samoa.

Appendix 2. 2. Mathematical details for an international agricultural trade model simulating the impacts of pollinators decline on social welfare

We first maximize producer profit by performing a derivation of:

$$\Pi_{ij} = p_{\,ij} * \left(1 - \alpha D_j\right) Q_{ij} - \frac{a_{ij} Q_{ij}^2}{2} - Fixed\ costs \text{ , over production, Q.} \quad (1)$$

To maximize $\pi'_{ij} = 0$

$p_{\,ij} * \left(1 - \alpha_i D_j\right) - a_{ij} Q_{ij} = 0$

That results in the equation (2), the inverse domestic supply:

$$p_{ij} = \frac{a_{ij} Q_{ij}}{1 - \alpha_i D_j} \quad (2)$$

The domestic supply becomes; $Q_{ij} = (1 - \alpha_i D_j)\frac{p_{ij}}{a_{ij}}$

For the world crop, j, supply, Q_{wj^*} an aggregate of the sub-regional productions for the crop j^* is approximated as $Q_{wj^*}(p, a) = \sum_1^N Q_{i^* j^*}(p, a)$ where domestic price equal the world producer price, p_{ij^*}=p_{wsj^*}.

As for consumers, we optimize utility function presented by equation (3) subject to a budget allocated to foodstuffs, R_i, denoted as follows;

$$R_i = \sum_1^k p_{i,j} X_{i,j}. \quad (4)$$

The optimization problem results in the following:

$$X_{i^* j^*}(p, R) = \frac{R_{i^*}}{k_{i^*} p_{ij^*}} \quad (5)$$

The inverse demand function becomes:

$$p_{i^* j^*}(X, R) = \frac{R_{i^*}}{ki{*}X_{i^* j^*}} \quad (6)$$

For the world demand, X_{wj^*} an aggregate of the sub-regional demands for the crop j^* is simply $X_{wj^*}(p, R) = \sum_1^N X_{i^* j^*}(p, R)$. Where p_{ij^*}= p_{wdj^*}.

From these regional market, the model simulate a World market price of crop, j, at the world equilibrium (Pwj) (see Figure 2.3). The equilibrium of the economy is the combination between interior market, exterior market and the international market for the same product. Prices and quantities exchanged at the equilibrium are determined when supply for the product *j* equalized the demand for the same product (see Figure 2.3).

The domestic demand equilibrium is when $Q_{ij} = X_{i^*j^*}(p, R)$ and $p_{ij*s} = p_{i^*j^*d}(X, R)$:

- when considering supply and demand:

$$(1 - \alpha_i D_j)\frac{p_{ij}}{a_{ij}} = \frac{R_{i^*}}{k_{i^*}p_{ij^*}}$$

$$Hence, p'_{ij}(D, R, \alpha) = \sqrt{\frac{\frac{R_{i^*}}{k_{i^*}}}{(1-\alpha_i D_j)\frac{1}{a_{ij^*}}}} \quad (7)$$

- when considering inverse supply and inverse demand

$$\frac{a_{ij}Q_{ij}}{1-\alpha_i D_j} = \frac{R_{i^*}}{ki{*}X_{i^*j^*}}$$

$$Hence, X'_{ij}(D, R, \alpha) = \sqrt{\frac{\frac{R_{i^*}}{k_{i^*}}*(1-\alpha_i D_j)}{a_{ij^*}}} \quad (8)$$

The index *a* is calculated using the Eq. (2) and Eq. (6) and we assume that $aij = aij;_{\alpha=0}$= constant, thus the expression $(1 - \alpha_i D_j) = 1\ where\ \alpha_i = 0$, so a is approximated as the following:

$$aij(R, Q, D) = \frac{R_i}{ki{*}Q_{ij}^{*\,2}}\text{, with } Q_{ij}^* = X_{ij}^* \text{ at the equilibrium} \quad (9)$$

At the world equilibrium p_{wsj^*}=p_{wdj^*}=p_{wj}. The World price, p_{wj} is approximated as following;

$$P_{w,j},(D, R, \alpha) = \sqrt{\frac{\Sigma\frac{R_{i^*}}{N}}{(1-\alpha_i D_j)\sum_{j=1}^{J}\frac{1}{a_{ij^*}}}}\text{, with N= the number of all crops} \quad (10)$$

To simulate the impacts of pollinator declines, we used scenario assuming different level of pollinators decline in the world. As a result the supply curve shift inward (see Figure 2.4). Consequently, the nutrients intake, the producer surplus (PS) and profit, consumer surplus (CS) and social welfare (SW) change accordingly. The *SW* is the sum of *PS* and *CS*. The Figure 2.4 represents the ΔSW *i.e.* the difference between the initial supply function and the new one due to the decrease of pollinators' availability. The new supply curve is a linear function.

The social welfare variation can be approximated using the following formula:

$$\Delta SW_{ij} = \Delta CS_{ij} + \Delta PS_{ij} \quad (11)$$

The surpluses are approximated by the formulas illustrated in the Figure 2.4:

- The Consumer surplus variation area, -A-B, is defined as;

$$\Delta CS_{ij}(Pw) = \int_{X=X_{ij}^{\alpha=0}}^{X=X_{ij}^{\prime,\alpha=1}} \frac{R_{i^*}}{ki{*}X_{i^*j^*}}\,dx + P'_w X'_w - P_w X_w \quad (12)$$

- The Producer surplus variation area, A-D, at World price, is defined;

$$\Delta PS_{ij} = \frac{(P'_w * Q'_w - P_w Q_w)}{2}$$

Appendix 2. 3. Data of crops dependence ratios and nutrients ratios in crops used (Source : Chaplin-Kramer et al. (2014))

Crop	D ratio Mean	Vitamin A	Vitamin C	Vitamin B6	Folate	Iron	Protein
		(IU)	(mg per 100g)	(mg per 100g)	(mcg per 100g)	(mg per 100g)	(g per 100g)
CEREALS							
Barley	0	22	0	0,26	23	2,5	9,91
Cereals nes	-	0	-	-	0	0	0
Fonio	0	0	-	-	0	0	0
Hops	0	0	-	-	0	0	0
Maize	0	214	0	0,622	19	2,71	9,42
Maize green	0	104,5	-	-	46	0,52	3,22
Millet	0	0	0	0,384	85	3,01	11,02
Oats	0	0	0	0,119	56	4,72	16,89
Rice paddy	0	0	-	-	20	1,635	7,72
Rye	0	11	0	0,294	60	2,67	14,76
Sorghum	0	0	0	0	0	4,4	11,3
Triticale	-	0	0	0,138	73	2,57	13,05
Wheat	0	5,4	0	6,5236	40,2	3,97	11,728
FRUITS							
Almonds with shell	0,65	1	-	-	50	3,72	21,22
Anise badian fennel coriander	0	0	-	-	10	0	17,6
Apples	0,65	54	4,6	0,041	3	0,12	0,26
Apricots	0,65	1926	10	0,054	9	0,39	1,4
Avocados	0,65	147	8,8	0,287	89	0,61	1,96
Bananas	-	0	-	-	20	0	1,09
Berries Nes	0,65	0	-	-	0	0	0
Blueberries	0,65	54	9,7	0,052	6	0,28	0,74
Cashewapple	0,65	0	-	-	0	0	0
Cherries	0,65	64	7	0,049	4	0,36	1,06
Cranberries	0,65	60	13,3	0,057	1	0,25	0,39
Currants	0,25	136	111	0,068	4	1,27	1,4
Dates	0	149	0	0,249	15	0,9	1,81
Figs	0,25	142	2	0,113	6	0,37	0,75
Gooseberries	0,25	0	-	-	6	0	0,88
Grapefruit (inc. pomelos)	0,05	0	-	-	10	0	0,645
Grapes	0	66	10,8	0,086	2	0,36	0,72
Kiwi fruit	0,95	87	92,7	0,063	25	0,31	1,14
Lemons and limes	0,05	36	41,05	0,0615	9,5	0,6	0,9
Mangoes mangosteens guavas	0,65	0	-	-	14	0	0,51
Melons other (inc.cantaloupes)	0,95	0	-	-	0	0	0
Oranges	0,05	225	53,2	0,06	30	0,1	0,94
Papayas	0,05	1094	61,8	0,019	38	0,1	0,61
Peaches and nectarines	0,65	329	6	0,025	4,5	26,5	0,985

Pears	0,65	23	4,2	0,028	7	0,17	0,38
Persimmons	0,05	1627	7,5	0,1	8	0,15	0,58
Pineapples	-	0	-	-	18	0	0,54
Plums and sloes	0,65	345	9,5	0,029	5	0,17	0,7
Quinces	0,65	0	-	-	3	0	0,4
Raspberries	0,65	0	-	-	21	0	1,2
Strawberries	0,25	12	58,8	0,047	24	0,41	0,67
Tangerines mandarins clementines satsumas	0,05	681	-	-	20	0,145	0,83
OILCROPS							
Coconuts	0,25	0	3,3	0,054	26	2,43	3,33
Groundnuts with shell	0,05	0	-	-	240	4,58	25,8
Karite nuts (sheanuts)	0,25	0	-	-	0	0	0
Linseed	0,05	0	-	-	0	0	0
Mustard seed	0,25	62	-	-	0	9,98	0
Oilseeds Nes	-	0	-	-	0	0	0
Olives	0	403	0,9	0,009	0	3,3	0,84
Poppy seed	-	0	-	-	0	0	0
Rapeseed	0,25	0	-	-	0	0	0
Safflower seed	0,05	50	0	1,17	160	4,9	16,18
Soybeans	0,25	180	29	0,065	165	3,55	12,95
Sunflower seed	0,25	50	-	-	227	5,25	20,78
PULSE							
Beans dry	0,05	0	-	-	421	0	22,343
Broad beans horse beans dry	0,25	0	-	-	423	0	26,12
Chick peas	0	0	-	-	557	0	19,3
Cow peas dry	0	50	-	-	633	8,27	23,52
Lentils	0	39	4,4	0,54	479	7,54	25,8
Lupines	0	0	-	-	355	0	36,17
Peas dry	0	149	-	-	274	4,43	24,55
Pigeon peas	0,05	28	0	0,283	456	5,23	21,7
String beans	0,05						
Potatoes	0	0	-	-	16	0	2,02
ROOTS AND TUBERS NES							
Cassava	-	0	-	-	27	0	1,36
Sweet potatoes	-	0	-	-	11	0	1,57
Taro (cocoyam)	0	0	-	-	22	0	1,5
Yams	-	0	-	-	23	0	1,53
SPICES							
Chilies and peppers dry	0,05	26488	-	-	0	6,04	0

Cloves	-	0	-	-	25	0	5,97
Ginger	-	0	-	-	11	0	1,82
Nutmeg, mace and cardamoms	-	0	-	-	0	0	0
Pepper (Piper spp.)	0	0	-	-	17	0	10,39
Peppermint	0	0	-	-	114	0	3,75
Spices nes	-	0	-	-	0	0	0
Vanilla	0,95	0	-	-	0	0	0,06
STIMULANT CROPS							
Cocoa beans	0,95	0	-	-	0	0	0
Coffee green	0,25	0	-	-	2	0	0,12
Kola nuts	0,65	0	-	-	0	0	0
Maté	0	0	-	-	0	0	0
Tea	0	0	-	-	0	0	0
SUGAR BEET	0	0	-	-	0	0	0
TREENUTS							
Areca nuts	0,05	0	-	-	0	0	0
Brazil nuts with shell	0,95	0	-	-	22	0	14,32
Cashew nuts with shell	0,65	0	-	-	25	6,68	18,22
Chestnut	0,25	0	-	-	68	0	4,2
Hazelnuts with shell	0	20	-	-	113	4,7	14,95
Nuts nes	0	-	-	-	-	-	-
Pistachios	0	553	5	1,7	51	4,15	20,61
Walnuts with shell	0	0	-	-	98	0	15,23
VEGETABLES							
Artichokes	-	0	-	-	68	0	3,27
Asparagus	-	0	-	-	52	0	2,2
Beans green	0,05	0	-	-	23	0	1,295
Buckwheat	0,65	0	0	0,21	30	2,2	13,25
Cabbages and other brassicas	-		-	-	57	-	1,21
Carrots and turnips	-	0	-	-	19	0	0,93
Cauliflowers and broccoli	-	0	-	-	57	0	2,95
Chillies and peppers green	0,05	0	-	-	23	0	2
Cucumbers and gherkins	0,65	105	2,8	0,04	7	0,28	0,65
Eggplants (aubergines)	0,25	0	-	-	22	0	1,01
Garlic	-	0	-	-	3	0	6,36
Lettuce and chicory	-	0	-	-	136	0	1,23
Melonseed	0,95	0	0	0,089	58	7,28	28,33
Mushrooms and truffles	0	0	-	-	17	0	3,09

Okra	0,25	375	21,1	0,215	88	0,8	2
Onions dry	-	0	-	-	166	0	8,95
Onions shallots green	-	0	-	-	19	0	1,1
Peas green	0	765	-	-	65	1,47	5,42
Pumpkins squash and gourds	0,95	0	-	-	23	0	1,053
Quinoa	0	14	0	0,487	184	4,57	14,12
Spinach	0	9377	28,1	0,195	194	2,71	2,86
Tomatoes	0,05	833	12,7	0,08	15	0,27	0,88
Vegetables fresh nes	0	-	-	-	-	-	-
Watermelons	0,95	569	8,1	0,045	3	0,24	0,61

Appendix 3. 1. List of local expert panels

Structure	Type d'acteurs	Localisation
Décideur public	Maire	Eoux (rural profond) St André (rural profond) Esparon (rural profond) Peyrissas (rural profond) Aurignac (un peu plus ville)
	DRAAF DREAL ADEME	
Association environnementale / consommateur	Nature Comminges	31800 SAINT-GAUDENS
	Arbre et paysage d'autan	31450 AYGUESVIVES
	LPO 31 et 32 (Ligue pour la protection des oiseaux)	
	Vivre en comminges http://www.vivreencomminges.org/	President de l'Association
	Val de Gascogne	Pôle communication avec Fabienne Pôle innovation avec Denis Mousteau
Organisation professionnelle	ACVA (association cantonale de vulgarisation agricole)	Animé par la chamber d'agriculture
	Synergie (Coop bovine)	Pamiers et centre d'allaitement à Casagnabere
	Erables 31 Gabb 32 FD Civam Terres Inovia	
	Pierre Pujos	Trophée agriculteur DD et apiculteur
	Syndicat d'apiculture de Midi-Pyrénées	Représentante

Appendix 3. 2. Interview guide with local expert panels in the Comminges

Protocole de l'entretien collectif avec les acteurs

L'objectif de l'entretien est de faire valider les hypothèses que nous avons pour le questionnaire. Le but final de l'étude est une gestion collective des pollinisateurs sauvages donc durant cet entretien collectif, il serait intéressant d'avoir des élues, des agriculteurs ou représentants de la profession et des représentants de la société civile (association de protection pour l'environnement).

Comme nous n'avons aucune idée du niveau de connaissances de chacun des individus dans le domaine, la première partie est consacrée à s'assurer que chacun ait le même niveau de connaissances pour la suite des discussions (première étape).

Ensuite, nous faisons valider les attributs et leurs niveaux (étape 2) par rapport au contexte local, de même pour le consentement à payer des individus (étape 3) et enfin nous déterminerons la zone d'étude optimale (étape 4).

a) *Première étape : amener la discussion sur les attributs de l'enquête*

1) **Selon vous, qu'est ce qu'un service écosystémique ?**

La notion de service écosystémique a été développée pour répondre au besoin de mieux comprendre l'interdépendance entre les écosystèmes et la société. Les services écosystémiques sont définis comme les bénéfices que les êtres humains tirent des écosystèmes. Par exemple, les feuilles et les racines des arbres qui retiennent l'érosion limitent la perte de diversité et maintiennent la bonne qualité des eaux de rivière, en diminuant les coûts de traitement de l'eau. (CIRAD, février 2013)

Naturellement, l'objectif de cette approche par les services écosystémiques n'est pas de restreindre la nature à un rôle de support pour l'humanité. Au contraire, l'approche par les services écosystémiques permet de développer une approche interdisciplinaire où les aspects liés à la gouvernance socio-économique et à la connaissance des processus biophysiques sont pris en compte de façon articulée, permettant de mettre en œuvre des stratégies au niveau national, régional et local, et ceci pour tout type d'acteurs. (CIRAD, février 2013)

2) **Dans le cadre du projet SEBIOREF, nous nous intéressons plus particulièrement à la pollinisation sauvage. Dans quelle mesure la pollinisation sauvage peut elle être considérée comme un service écosystémique ? Plus simplement, quelles sont les bénéfices que peuvent tirer les sociétés humaines des pollinisateurs sauvages ?**

C'est grâce aux caractéristiques propres aux pollinisateurs : taille et diversité des pollinisateurs, additivité des populations… ainsi que les caractéristiques des symbiotes et de l'interaction qu'ils ont avec les insectes que les sociétés humaines peuvent en tirer des bénéfices.

Les pollinisateurs, grâce à la pollinisation, augmentent la production des cultures dépendantes de ces insectes. Cela permet aussi d'augmenter le brassage génétique chez les espèces florales améliorant ainsi leurs adaptations aux conditions nouvelles de l'environnement. D'un point de vue qualitatif, les pollinisateurs peuvent indirectement améliorer l'apport en nutriment des fruits et légumes ayant ainsi un impact sur la sécurité nutritionnelle. Ils peuvent aussi influencer positivement la forme et l'aspect des fruits.

Grâce à la pollinisation des fleurs sauvages, les pollinisateurs sont un des moteurs de la conservation de la biodiversité et permet aussi, particulièrement en période de floraison, de contribuer à l'esthétisme des paysages.

Enfin, les pollinisateurs peuvent avoir des bénéfices culturels en apportant des services de récréation, d’éducation et d’activité.

b) Faire valider les attributs, leurs niveaux et les confronter aux contextes locales

Bénéfice	Attribut	Echelle
Augmentation de la quantité de la production	1) Disponibilité des fruits et légumes sur les marchés locaux	Faible ; Moyenne ; Forte 0 ; -10% ; -20% ; -30%
Amélioration de la biodiversité	2) Biodiversité esthétique de la faune et de la flore	0 ; -10% ; -20% ; -30%
Amélioration de la biodiversité	3) Degré de connectivité des habitats naturels	
Amélioration de l’esthétique	4) Esthétique de la faune et de la flore/ des campagnes / des paysages	Faible ; Forte
	5) Quantité de pollinisateurs domestiques	
	Attribut sur la valeur d’existence 6) Le nombre d’espèces menacées	0 ; +20% ; +50%
	7) Consentement à payer	
	8) Autres : …	

3) En identifiant les bénéfices de la pollinisation sauvage, nous avons pu déterminer des attributs (variables que l’on étudie dans notre questionnaire) à utiliser dans le questionnaire. Nous rappelons que ce dernier tente de déterminer la perception des citoyens par rapport aux bénéfices de la pollinisation. Les attributs sont les suivants : la production des fruits et des légumes disponible sur les marchés locaux, la biodiversité esthétique de la faune et de la flore, la quantité des pollinisateurs domestiques, le degré de connectivité des habitats naturels et le nombre d’espèces de pollinisateurs en danger.
Comment comprenez vous ces attributs et est ce qu’ils sont difficiles à se représenter ?
Est ce que ces attributs sont adaptés au contexte local ? Si non, comment pourraient-ils être adaptés au contexte local ?

Production des fruits et légumes disponibles sur les marchés locaux : quelles sont les principaux produits agricoles vendues ? Connaissez-vous les tendances actuelles quant à la diversification des produits sur le marché ?

Biodiversité esthétique locale : qu’est ce qui caractérise la biodiversité floristique locale ? Avez-vous des exemples d’espèces ? D’espèces en danger/protégées ? De références pour retrouver les recherches qui ont été menées la dessus ? Bis pour l’aspect faunistique : biodiversité des pollinisateurs sauvages. Quelles sont les espèces en danger et vulnérables sur le territoire ? Avez-vous des connaissances sur les tendances à venir ?

Quantité de pollinisateurs domestiques : est-elle difficile à évaluer ? Est-on dans un espace où l’apiculture est développée ? A-t-elle subit des évolutions importantes au cours des 50 dernières années ? Quelle est la tendance actuelle ?

Le degré de connectivité des habitats naturelles : Quels sont les différents types de paysages existant dans la zone ? Quelles sont leurs dynamiques ?

4) **Suivant le contexte local, chacun de ces attributs peut avoir plusieurs niveaux. Par rapport à la situation actuelle et aux échelles que l'on vous propose qu'elle serait le niveau des attributs suivants ? Par rapport aux différents scénarios possibles (en prenant en compte les plus positif en terme d'environnement et les plus négatifs) comment pourraient évoluer le niveau de ces attributs ? Est-ce que le choix que l'on a fait est judicieux, pertinent et réaliste dans le cadre local ?**

c) *Mise en place de l'attribut du consentement à payer et adaptation au contexte local*

5) **Enfin, à travers ce questionnaire nous cherchons à déterminer combien les individus seraient près à payer pour conserver les pollinisateurs sauvages. Selon vous, qui doit recevoir cet argent ? Qui doit payer ? En sachant que l'objectif est une conservation avec l'ensemble des acteurs du terrain.**

6) **Or, nous pouvons envisager plusieurs types de payement : les taxes environnementales, une redistribution des taxes locales, une contribution volontaire à un fond pour financer la conservation, une charge réservée obligatoire ou bien des frais sur le tourisme paysager. Lesquelles pourraient être envisageable selon vous par rapport au contexte local ?**

d) *Délimitation du terrain d'étude*

La limite du terrain d'étude pour le questionnaire est donnée par la délimitation des carrées noir sur la carte ci-dessous au niveau des vallées et coteaux de Gascogne.

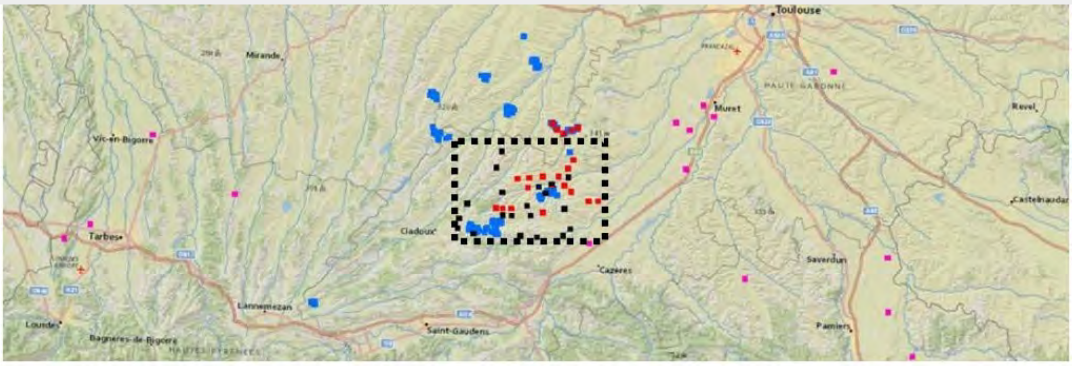


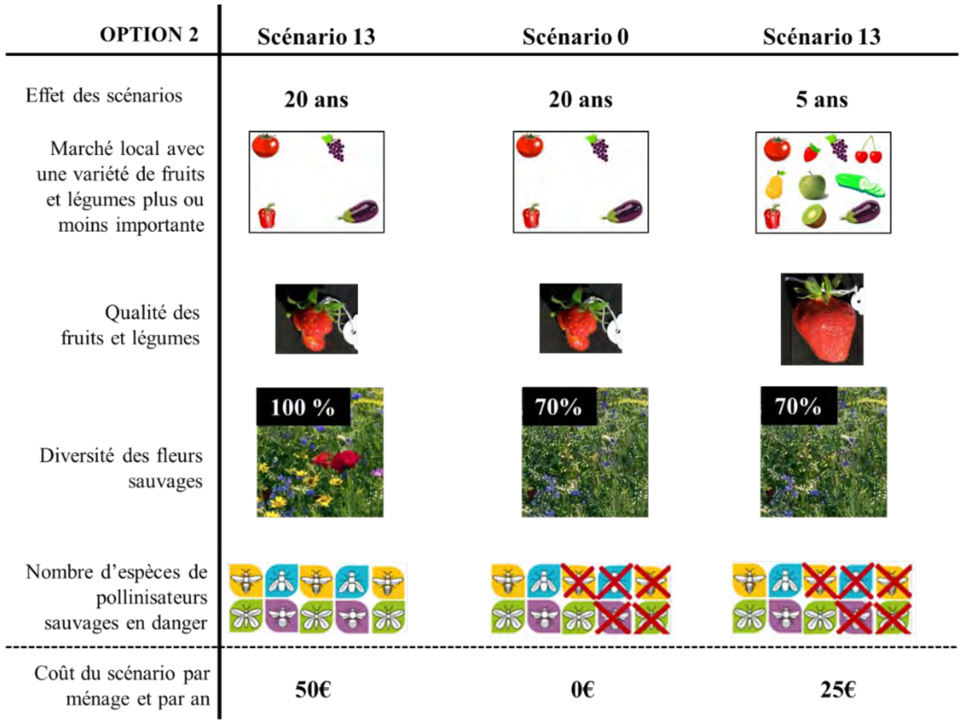
Figure 3 : *Dispositifs de recherche sur la biodiversité agricole et les services écosystémiques associés en Midi-Pyrénées (**Ecophyto-ENI**; **UE-Biobio**; **Farmland 2013**; **Farmland 2014 & Sebiopag-Phyto**). Le rectangle en pointillé noir indique l'étendue du site d'étude à long terme Vallées et Coteaux de Gascogne.*

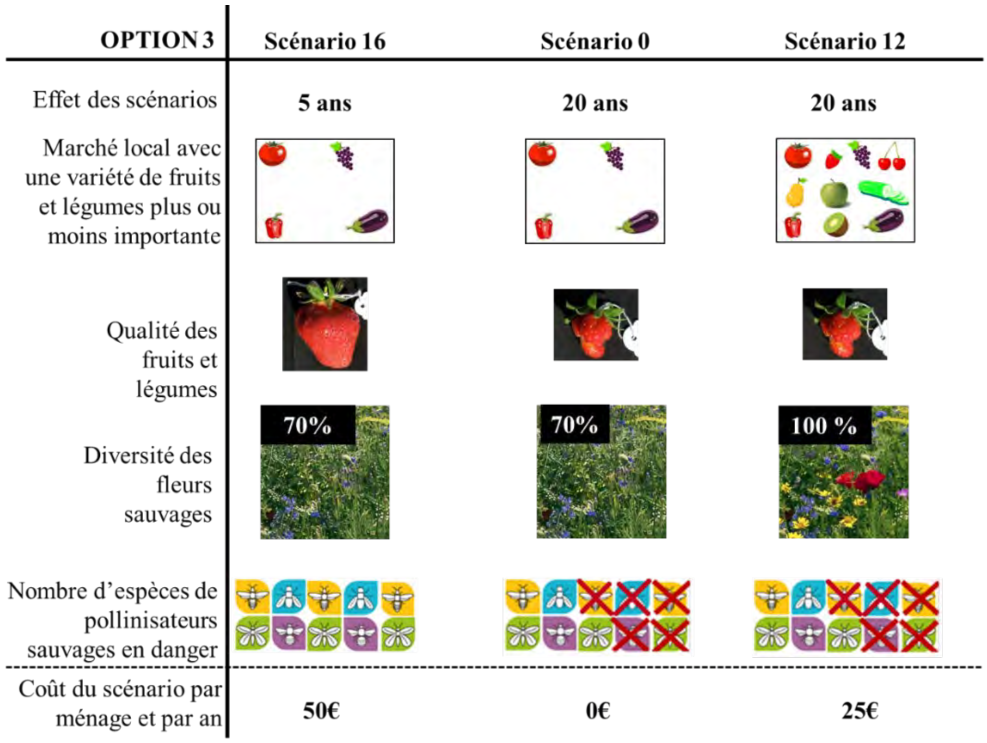
Source : SEBIOREF

7) **Pensez-vous que cette délimitation géographique est pertinente ? Est-elle trop étendue/restreinte ? Comment faudrait-elle la modifier ?**

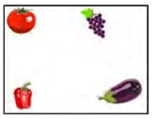
Appendix 3. 3. The "Fractional Factorial Design" code using R and Choice sets

```
> rotation.design(attribute.names = list(Variety=1:2,quality=1:2,flowers=1:2,time=1
:2, pollspecies=1:2,cout=1:4),nalternatives = 2,nblocks = 1,row.renames = FALSE,rand
omize = TRUE)
```





OPTION 4	Scénario 2	Scénario 0	Scénario 11
Effet des scénarios	**20 ans**	**20 ans**	**5 ans**
Marché local avec une variété de fruits et légumes plus ou moins importante			
Qualité des fruits et légumes			
Diversité des fleurs sauvages			
Nombre d'espèces de pollinisateurs sauvages en danger			
Coût du scénario par ménage et par an	**25€**	**0€**	**100€**

OPTION 5	Scénario 11	Scénario 0	Scénario 1
Effet des scénarios	**5 ans**	**20 ans**	**20 ans**
Marché local avec une variété de fruits et légumes plus ou moins importante			
Qualité des fruits et légumes			
Diversité des fleurs sauvages			
Nombre d'espèces de pollinisateurs sauvages en danger			
Coût du scénario par ménage et par an	**25€**	**0€**	**100€**

OPTION 7	Scénario 9	Scénario 0	Scénario 7
Effet des scénarios	**5 ans**	**20 ans**	**20 ans**
Marché local avec une variété de fruits et légumes plus ou moins importante			
Qualité des fruits et légumes			
Diversité des fleurs sauvages			
Nombre d'espèces de pollinisateurs sauvages en danger			
Coût du scénario par ménage et par an	**100€**	**0€**	**100€**

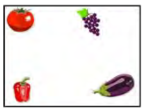
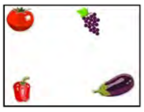
OPTION 8	Scénario 6	Scénario 0	Scénario 14
Effet des scénarios	**20 ans**	**20 ans**	**5 ans**
Marché local avec une variété de fruits et légumes plus ou moins importante			
Qualité des fruits et légumes			
Diversité des fleurs sauvages			
Nombre d'espèces de pollinisateurs sauvages en danger			
Coût du scénario par ménage et par an	**50€**	**0€**	**25€**

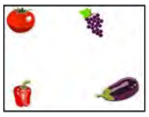
OPTION 9	**Scénario 14**	**Scénario 0**	**Scénario 15**
Effet des scénarios	**20 ans**	**20 ans**	**5 ans**
Marché local avec une variété de fruits et légumes plus ou moins importante			
Qualité des fruits et légumes			
Diversité des fleurs sauvages			
Nombre d'espèces de pollinisateurs sauvages en danger			
Coût du scénario par ménage et par an	**100€**	**0€**	**50€**

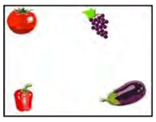
OPTION 10	**Scénario 7**	**Scénario 0**	**Scénario 8**
Effet des scénarios	**20 ans**	**20 ans**	**5 ans**
Marché local avec une variété de fruits et légumes plus ou moins importante			
Qualité des fruits et légumes			
Diversité des fleurs sauvages			
Nombre d'espèces de pollinisateurs sauvages en danger			
Coût du scénario par ménage et par an	**100€**	**0€**	**50€**

OPTION 11	Scénario 12	Scénario 0	Scénario 8
Effet des scénarios	5 ans	20 ans	20 ans
Marché local avec une variété de fruits et légumes plus ou moins importante			
Qualité des fruits et légumes			
Diversité des fleurs sauvages			
Nombre d'espèces de pollinisateurs sauvages en danger			
Coût du scénario par ménage et par an	25€	0€	100€

OPTION 12	Scénario 10	Scénario 0	Scénario 4
Effet des scénarios	5 ans	20 ans	20 ans
Marché local avec une variété de fruits et légumes plus ou moins importante			
Qualité des fruits et légumes			
Diversité des fleurs sauvages			
Nombre d'espèces de pollinisateurs sauvages en danger			
Coût du scénario par ménage et par an	50€	0€	25€

OPTION 13	Scénario 8	Scénario 0	Scénario 4
Effet des scénarios	5 ans	20 ans	20 ans
Marché local avec une variété de fruits et légumes plus ou moins importante			
Qualité des fruits et légumes			
Diversité des fleurs sauvages			
Nombre d'espèces de pollinisateurs sauvages en danger			
Coût du scénario par ménage et par an	100€	0€	50€

OPTION 14	Scénario 5	Scénario 0	Scénario 16
Effet des scénarios	5 ans	20 ans	20 ans
Marché local avec une variété de fruits et légumes plus ou moins importante			
Qualité des fruits et légumes			
Diversité des fleurs sauvages			
Nombre d'espèces de pollinisateurs sauvages en danger			
Coût du scénario par ménage et par an	100€	0€	50€

OPTION 15	Scénario 4	Scénario 0	Scénario 9
Effet des scénarios	**20 ans**	**20 ans**	**5 ans**
Marché local avec une variété de fruits et légumes plus ou moins importante			
Qualité des fruits et légumes			
Diversité des fleurs sauvages			
Nombre d'espèces de pollinisateurs sauvages en danger			
Coût du scénario par ménage et par an	**25€**	**0€**	**25€**

OPTION 16	Scénario 1	Scénario 0	Scénario 6
Effet des scénarios	**5 ans**	**20 ans**	**20 ans**
Marché local avec une variété de fruits et légumes plus ou moins importante			
Qualité des fruits et légumes			
Diversité des fleurs sauvages			
Nombre d'espèces de pollinisateurs sauvages en danger			
Coût du scénario par ménage et par an	**25€**	**0€**	**50€**

Appendix 3. 4. The Choice Experiment Questionnaire

Nom de l'enquêteur : | Date :

Heure :

Lieu de l'enquête : | Numéro de questionnaire :

Enquête pollinisateurs sauvages SEBIOREF [35]

Bonjour, je m'appelle... et je suis étudiante en ……. À l'université... Pourriez-vous me consacrer un peu de votre temps (30 mn environ) pour répondre à un questionnaire portant sur les insectes pollinisateurs sauvages.

Différents travaux scientifiques montrent que ces insectes sont mal connus bien qu'ils assurent pourtant une fonction cruciale dans la pollinisation des cultures agricoles, le maintien de la diversité alimentaire et au-delà la préservation de la biodiversité. Ces mêmes travaux montrent également que ces insectes sont en voie de déclin. C'est dans ce contexte que notre étude conduite en partenariat avec la Région Occitanie vise à mieux comprendre comment les différents acteurs de ce territoire (agriculteurs, élus, membres d'association, et plus généralement habitants du territoire) perçoivent le rôle de ces pollinisateurs sauvages et sont prêts à les protéger. Nous allons enquêter auprès de 250 personnes. Je vous précise par ailleurs que les résultats de notre enquête seront rendus publics et présentés à la population. Ils sont notamment destinés à éclairer la prise de décision des acteurs locaux dans le domaine de la protection des milieux naturels. C'est donc dans ce cadre que nous souhaiterions recueillir votre avis. Celui-ci nous sera très précieux. Je vous précise bien sûr que votre anonymat sera garanti.

Partie 1 : Connaissances sur les pollinisateurs et leurs environnements

Nous allons commencer ce questionnaire par des questions générales portant sur votre rapport avec l'environnement naturel.

Question 1 Habitez-vous dans le territoire ?
- o Oui
- o Non

Question 2 Que diriez-vous de ce territoire ?

Question 3 Comment vous sentez-vous ici ?

Question 4 Que diriez-vous de la qualité principale de l'environnemental naturel dans lequel vous vivez ?

Question 5 Comment classeriez-vous ce territoire ?
- Territoire plutôt urbain
- Territoire plutôt péri-urbain
- Territoire plutôt rural

Question 6 Pensez-vous que ce territoire est plutôt : … *Hiérarchisez les réponses*.
- o Un espace récréatif (lieu de détente et de loisir)

[35] Enquête coordonnée par l'INRA et l'ENSFEA et menée en collaboration avec la coopérative Val de Gascogne.

- Un espace valorisé économiquement (par exemple à travers le développement de l’activité touristique ou agricole
- Un espace naturel préservé
- Un espace représentatif du patrimoine culturel du territoire
- Autres :______________________

Question 7 Avez-vous une certaine connaissance de la diversité de la flore et la faune présente dans le milieu naturel environnant ?

Question 8 Parmi cette faune, y-a-t-il des insectes que vous connaissez?

Question 9 Savez-vous que parmi ces insectes, il y a des insectes pollinisateurs ?

Question 10 Savez-vous qu’est-ce qu’un pollinisateur ?

- Oui
- Je crois que oui
- Je crois que non
- Non

Question 11 Sur l’affiche suivante, pourriez-vous m’indiquer les pollinisateurs que vous reconnaissez.

[Photo pollinisateurs]

Question 12 Savez-vous dans quel habitat vivent les pollinisateurs sauvages ?

- Oui
- Je crois que oui
- Je crois que non
- Non

[Photo habitats]

Question 13 Pour vous, quel est le rôle des pollinisateurs non-élevés par l’homme / sauvages ?

- Amélioration des rendements des productions agricoles
- Amélioration de la qualité des produits agricoles (apports de nutriments, meilleure conformité des fruits et légumes : forme et aspect)
- Augmentation de la biodiversité
- Amélioration de l’aspect esthétique du paysage
- Production de miel
- Piquer les randonneurs
- Aucun

Nous venons d'en finir avec la partie générale. Nous allons maintenant vous posez des questions plus précises sur votre rapport avec le milieu naturel et plus particulièrement avec les insectes pollinisateurs qu'il abrite.

Partie 2 : Votre perception des pollinisateurs sauvages et autres

Question 14 Possédez-vous des ruches ?

- o Oui
- o Non

Question 15 Faites-vous partie d'une association dont les actions ont un quelconque rapport avec l'environnement naturel et sa préservation ?

- o Oui
- o Non

Question 16 Habituellement (d'avril à août), avez-vous l'habitude de cultiver des fruits et légumes chez vous ou dans un jardin partagé ?

- o Oui
- o Non→ 19

Si oui lesquels ?

Pour quelles raisons cultivez-vous des fruits et légumes ? (plusieurs réponses)

- o Pour le plaisir
- o Parce que les fruits et légumes que je produits sont de qualité et goûteux
- o Parce que je peux planter ce que je veux
- o Par principe
- o Parce que cela est bon pour la santé
- o Parce que je connais les produits (engrais, produits phytosanitaires) que j'utilise.
- o Parce que c'est un moyen pour moi de renouer un lien avec la terre
- o Parce que mes parents le faisaient, c'est traditionnel
- o Autres : ____

Question 17 Habituellement d'avril à août, avez-vous l'habitude d'acheter des fruits et légumes locaux ?

Plus d'une fois par semaine	Une fois par semaine	Une fois toutes les deux semaines	Moins d'une fois par mois	Je ne sais pas

Quels sont les principaux fruits et légumes locaux que vous achetez ?

Pour quelles raisons achetez-vous ces fruits et légumes locaux ? (plusieurs réponses)

- o Parce que les prix sont attractifs
- o Parce que les produits sont de qualité et goûteux
- o Parce que les produits sont beaux, attirants, bien conformés, …
- o Parce que les produits proposés sont très variés
- o Par principe
- o Par ce que cela est bon pour la santé
- o Parce que cela participe à la préservation des milieux naturels
- o Parce que cela permet de soutenir l'économie locale
- o Autres : ____

Question 18 Visitez-vous fréquemment des espaces naturels comme les espaces verts, les forêts ou bois et les parcs naturels environnants ?

Tous les jours	*Toutes semaines*	*lesTous les mois*	*Moins d'une par mois*	*foisJamais*	*Je ne sais pas*

Pourquoi ?

____

Question 19 Pourriez-vous me dire jusqu'à quel point vous êtes en accord ou en désaccord avec chacune de ces 3 affirmations ?

Pour répondre vous utiliserez une échelle allant de 1 à 4. Ainsi vous répondrez 1 si vous êtes fortement en désaccord avec l'affirmation et 4 si vous êtes tout à fait d'accord avec cette affirmation.

Fortement en désaccord → Tout à fait d'accord

Dans les espaces naturels du territoire, vous appréciez l'abondance des fleurs présentes	1	2	3	4
Dans les espaces naturels du territoire, vous appréciez la diversité des fleurs présentes	1	2	3	4
L'état actuel des fleurs et de la flore dans les espaces naturels du territoire sont pour vous préoccupant.	1	2	3	4
L'état futur des fleurs et de la flore dans les espaces naturels du territoire sont pour vous préoccupant.	1	2	3	4

Question 20 Ces dernières années, avez-vous constaté une ou des évolutions du paysage environnant ?

- Oui
- Non
- Je ne sais pas

Si oui, laquelle ou lesquelles?

Question 21 Pour vous, léguer un cadre environnemental de qualité aux générations futures est-il une préoccupation essentielle ?

- Oui
- Non
- Je ne sais pas

Question 22 Est-ce que vous légueriez cet environnement dans son état actuel ?

- Oui
- Non
- Je ne sais pas

Si, non pourquoi ?

Question 23 Savez-vous que la population des insectes pollinisateurs sauvages est très dépendante de l'état de santé du milieu naturel et des paysages ?

- Oui
- Je crois que oui
- Je crois que non
- Non

Si oui, comment avez-vous eu cette information ?

- Médias
- Internet
- Formation
- Observation

Question 24 Savez-vous que les pollinisateurs sauvages sont en déclin ?

- Oui
- Je crois que oui
- Je crois que non
- Non

Si oui, par quel biais avez-vous eu l'information ?

- Médias
- Internet
- Formation
- Observation

Question 25 Pensez-vous que l'on puisse compenser ce déclin en recourant davantage aux pollinisateurs domestiques comme par exemple les abeilles élevées dans des ruches ?

- Oui
- Non
- Je ne sais pas

[Apporter des connaissances]

Les insectes pollinisateurs en général et les sauvages en particulier sont en déclin dans le monde. Nous sommes ici pour comprendre les conséquences de ce déclin sur notre société. C'est pour cela que, dans la prochaine étape, nous allons vous présenter différents scénarios retraçant plusieurs évolutions possibles de l'état du milieu naturel. Nous allons vous demander de comparer ces différents scénarios et de choisir le scénario que vous préférez.

Partie 3 : Les cartes de choix

Pour chaque option, la question suivante sera posée :

Question 26 Sur une échelle allant de 0 à 10, quel est votre degré de certitude du scénario que vous avez choisi ? (Autrement dit jusqu'à quel point êtes-vous convaincu par votre choix et décidé de ne pas en changer)

0 correspondant à Absolument incertain et 10 à Absolument certain

0 1 2 3 4 5 6 7 8 9 10

Numéro de l'option	**Quel scénario choisiriez-vous ?**	**Degré de certitude (entre 0 et 10)**	**Vous avez coché un paiement supplémentaire par an égal à 0€. Pourquoi avez-vous effectué ce choix ?**
Option ☐	Je ne sais pas ☐ Scénario 1 ☐ Scénario 2 ☐ Scénario 3 ☐		
Option ☐	Je ne sais pas ☐ Scénario 1 ☐ Scénario 2 ☐ Scénario 3 ☐		
Option ☐	Je ne sais pas ☐ Scénario 1 ☐ Scénario 2 ☐ Scénario 3 ☐		
Option ☐	Je ne sais pas ☐ Scénario 1 ☐ Scénario 2 ☐ Scénario 3 ☐		
Option ☐	Je ne sais pas ☐ Scénario 1 ☐ Scénario 2 ☐ Scénario 3 ☐		

Sur l'ensemble de vos choix, considérez-vous avoir pris en compte tous les éléments contenus dans les cartes de choix ? Je vous rappelle ces éléments : variété des fruits et légumes disponible sur les marchés locaux, qualité des fruits et légumes, diversité de la faune et de la flore, proportion des espèces de pollinisateurs sauvage en danger, le temps d'apparition des bénéfices d'un scénario, paiement supplémentaire obligatoire annuel.

- Oui
- Non

Question 27 Si non, lesquels avez-vous omis ?

- Variété des fruits et légumes disponible sur les marchés locaux
- Qualité des fruits et légumes
- Diversité de la faune et de la flore
- Proportion des espèces de pollinisateurs sauvage en danger
- Le temps d'apparition des bénéfices d'un scénario

- o Paiement supplémentaire obligatoire annuel

Je souhaiterai à présent vous poser quelques questions sur les actions qui, selon vous, seraient les plus adaptées pour protéger le milieu naturel et les insectes pollinisateurs sauvages qu'il abrite.

Question 28 Parmi les vues aériennes suivantes du territoire, laquelle préférez-vous ? (Voir ci-dessous)

Vue Aérienne A Vue Aérienne B Vue Aérienne C Je ne sais pas

Question 29 Selon vous, parmi ces vues aériennes, laquelle favorise le plus le maintien ou le développement des pollinisateurs sauvages ?

Vue Aérienne A Vue Aérienne B Vue Aérienne C Je ne sais pas

Question 30 Pourriez-vous m'indiquer jusqu'à quel point vous êtes en accord ou en désaccord avec chacune de ces 3 affirmations ?

Pour répondre vous utiliserez une échelle allant de 1 à 4. Ainsi vous répondrez 1 si vous êtes fortement en désaccord avec l'affirmation et 4 si vous êtes tout à fait d'accord avec cette affirmation.

Fortement en désaccord → Tout à fait d'accord

Il est important de protéger le milieu naturel.	1	2	3	4
Il est important de réagir contre le déclin des pollinisateurs sauvages.	1	2	3	4
La protection de l'environnement et des pollinisateurs sauvages est un enjeu d'intérêt public.	1	2	3	4

Question 31 Seriez-vous prêt à vous investir personnellement pour la protection des pollinisateurs sauvages ?

- o Oui
- o Non
- o Je ne sais pas

Question 32 Si oui, comment :

- o En apportant une contribution financière (contribution au financement d'une association qui participe à la préservation des pollinisateurs sauvages, …)
- o En apportant mon expertise, mes connaissances (je suis apiculteur, agriculteur et j'ai fait des études en écologie, …)
- o En apportant une aide volontaire (participation à une association de protection des insectes pollinisateurs sauvages, implication sur le terrain,…)
- o En modifiant mes pratiques quotidiennes (moindre utilisation de produits chimiques, respect des habitats naturels des insectes pollinisateurs,…)
- o Autres : ____

Question 33 Selon vous, quelles seraient les trois mesures propres à assurer une meilleure protection des pollinisateurs sauvages ?

Mesures	
▪ Intégrer la sauvegarde des pollinisateurs sauvages dans la gestion des espaces verts par les communes.	☐
▪ Encourager les habitants à mettre en place des hôtels à insectes dans leurs jardins.	☐
▪ Réduire l'usage des produits chimiques : pesticides, fongicides, insecticides et herbicides.	☐
▪ Maîtriser l'urbanisation et favoriser l'habitat regroupé.	☐
▪ Conserver et développer les habitats naturels des insectes pollinisateurs sauvages : prairies, haies bocagères, jachères fleuries…	☐
▪ Implanter les ruches tout en prenant en considération les milieux de vie des pollinisateurs sauvages.	☐
▪ Favoriser un changement de pratiques agricoles en allant dans le sens d'une plus grande diversification des cultures…	☐
▪ Autres (précisez) :	☐

Uniquement pour les agriculteurs : Sinon, passer à la question 36

Description de votre exploitation agricole

Question 34 Quelle est la taille de votre exploitation ?

- o - de 10 ha
- o 10 à 25 ha
- o 25 à 50 ha
- o 50 à 100 ha
- o 100 à 200 ha
- o Plus de 200 ha

Question 35 Quelle est l'orientation principale de l'exploitation ?

- o Bovins lait
- o Bovin viande
- o Bovin Mixte
- o Arboricultures
- o Grandes cultures
- o Horticulture, maraîchage
- o Ovins, autres herbivores
- o Polyculture – élevage
- o Porcins, volailles

- Viticulture

Question 36 Quelle est la variété ou la race la plus cultivée ou élevée ?

____

Question 37 Est-ce que l'une de vos productions est labélisée ?

Question 38 Si oui, sous quel(s) label(s) vos produits sont-ils commercialisés ?

- AOC/AOP
- IGP
- Label Rouge
- Spécialité Traditionnelle Garantie (STG)
- Agriculture Biologique
- Autres : ______________________________

Question 39 Quel est le principal mode de commercialisation de vos produits ?

- Vente directe auprès du consommateur
- Circuit court
- Circuit long

Question 40 Pourriez vous nous dire :

- votre chiffre d'affaire annuel moyen en Euro per an :………………………………….
- Votre cout de production moyen en euro par an :……………………………………….

Question 41 Dans votre exploitation, avez-vous contractualisé une Mesure Agro-environnementale et Climatique (MAEC)/ aides vertes ?

- Oui
- Non

Question 42 Combien cela vous coûte-t-il environ par hectare pour mettre en oeuvre les pratiques environnementales associées à la MAEC contractualisée ?

Question 43 Pensez-vous que cette MAEC a des impacts positifs et/ou négatifs sur les insectes pollinisateurs sauvages ?

Question 44 Si oui, lesquels ?

Question 45 Parmi les types de pratiques listés sur le tableau suivante, pouvez-vous me précisez, les pratiques auxquelles vous avez effectivement recours ?

Question 46 Indiquez-moi celles qui, selon vous, ont un impact positif, négatif ou nul sur :

a. La densité des insectes pollinisateurs sauvages.
b. La diversité des insectes pollinisateurs sauvages

Question 47 Si oui, pouvez-vous préciser vos réponses ?

Dans la table ci-dessous, sont résumées un certain nombre des pratiques agricoles.

Types de pratiques agricoles	**Question 44 – pratiques effectivement mises en œuvre :**	**a- Impact sur la densité des insectes pollinisateurs sauvages**	**b – Impact sur la diversité des insectes pollinisateurs sauvages**
Assolement (Diversification)	Nombre de cultures sur l'exploitation ? Sont-elles associées ?		
Rotation	Rotation entre les différentes cultures Oui / Non Sur combien d'années la rotation est-elle conçue ?		
Gestion des produits phytosanitaires	Utilisation de produits phytosanitaires Oui / Non Quantité utilisée par an et par hectares par type de produits		
Maintien des infrastructures agro-écologiques	Existent-ils des infrastructures agro-écologiques (expliquer) sur votre exploitation ? Oui / Non Quelle proportion, ces infrastructures représentent-elles approximativement sur votre SAU ? **0** **500m** **0** **50%**		
Travail du sol	Quel type de travail du sol pratiquez-vous ? Labour/semi-labour/travail superficiel/0 labour		
Fertilisant chimique	Quel type de fertilisation utilisez-vous ? Fertilisation minérale/ fertilisation organique /Les deux Si vous utilisez de la fertilisation chimique, quels sont les quantités apportées par an et par hectare ?		

Question 48 Si vous recourez au moins à l'une des pratiques agro-environnementales évoquées précédemment (rotation de cultures, plan d'assolement, réduction des intrants, simplification du travail du sol…), pourriez-vous me précisez vos principales raisons ?

- o Agronomiques (amélioration de la fertilité des sols, lutte contre l'érosion…)
- o Économiques (réduction des charges en intrants et gain lié aux subventions…)
- o Environnementales (contribution à la préservation du milieu naturel)
- o Professionnelle (plus grande autonomie de décision, revalorisation de l'image de mon métier…)
- o Autres : ___________________________________

Question 49 Si vous ne recourez à aucune des pratiques agro-environnementaux évoquées précédemment (rotation de cultures, plan d'assolement, réduction des intrants, simplification du travail du sol…), pourriez-vous me précisez vos principales raisons ?

- o Manque de temps
- o Coût financier
- o Risques de pertes de récolte et de qualité des produits
- o Manque de connaissances et d'encadrement technique
- o Contrainte administrative
- o Autres : ___________________________________

Question 50 Quelles seraient les conditions requises pour que vous adoptiez ces pratiques ?
____

Question 51 Votre exploitation se différencie-t-elle par des pratiques innovantes ou singulières ?
Si oui, quelles sont ces pratiques ?

Je souhaiterai terminer l'entretien en vous posant quelques questions plus personnelles. Bien sûr votre anonymat sera garanti. Les informations recueillies nous serviront avant tout dans le traitement de nos données et dans l'analyse de nos résultats. Je vous rappelle que nous enquêtons auprès de 250 personnes

Partie 5 : Informations personnelles

Question 52 Sexe

- o Femme
- o Homme

Question 53 Quel est votre âge ?

16 à 29 ans	30 à 44 ans	45 à 59 ans	60 à 74 ans	75 ans et plus

Question 54 Quelle est votre situation personnelle ?

- o Célibataire
- o En concubinage
- o Pacsé(e)
- o Marié(e)
- o Autres :

Question 55 Combien avez-vous d'enfant(s) à charge ?

0	*1*	*2*	*3*	*Plus de 3*

Question 56 Dans quel secteur d'activité travaillez-vous ?

- o Agriculture et agroalimentaire
- o Industrie et énergie
- o Service (commerce, tourisme, assurance, banque,…)

Question 57 Quelle est votre profession?

- o Agriculteur exploitant
- o Apiculteur
- o Artisan, commerçant et chef d'entreprise
- o Cadre et professions intellectuelles supérieures (Professions libérales, Cadres de la fonction publique, Ingénieurs et cadres techniques d'entreprise…)

- Profession intermédiaire (Professeurs des écoles, instituteurs et assimilés, Techniciens, Contremaîtres, …)
- Employé
- Ouvrier
- Retraité
- Sans activité professionnelle

Question 58 Lieu d'habitation :

Résident permanent ☐ Résident secondaire ☐

Code Postal : _________________ Commune : ____

Question 59 Où avez-vous passé la majorité de votre enfance ? (de 0 à 16 ans)

- Dans une ville importante, dans le centre-ville
- Dans une banlieue ou en périphérie urbaine
- En zone rurale

Question 60 Quel est votre niveau d'études ?

- BAC + 5 et plus
- BAC + 3 et plus
- BAC, BTS, DUT ou équivalent
- Niveau BAC ou inférieur

Question 61 Quel est votre revenu annuel ?

Inférieur à 9000€	*10.000 à 18.000€*	*19.000€ à 28.000€*	*29.000€ à 40.000€*	*41.000€ à 55.000€*	*Supérieur à 56.000€*

Question 62 Si vous êtes en couple quel est le revenu annuel de votre partenaire ?

Inférieur à 9000€	*10.000 à 18.000€*	*19.000€ à 28.000€*	*29.000€ à 40.000€*	*41.000€ à 55.000€*	*Supérieur à 56.000€*

Nous arrivons au terme de notre enquête. Je vous remercie vivement de votre participation.

Question 63 Souhaiteriez-vous être informé des résultats de cet enquête ?

- Oui, je suis intéressé. Contact (Email, Tél): ________________________________
- Non, je ne suis pas intéressé

Question 64 Auriez-vous éventuellement d'autres informations à partager avec nous ? D'autres avis à formuler ?
____
____

Appendix 3. 5. Summary and descriptive statistics of respondent in the Comminges territory

1. Do you own beehives?

0 = No
1 = Yes

(oui =1, non=0)	Freq.	Percent	Cum.
0	219	85.88	85.88
1	36	14.12	100.00
Total	255	100.00	

2. Do you belong to an association whose actions are related to the natural environment and its preservation?
0 = No
1 = Yes

(oui=1, non=0)	Freq.	Percent	Cum.
0	185	72.55	72.55
1	70	27.45	100.00
Total	255	100.00	

3. In recent years, have you noticed any changes in the surrounding landscape?

1 = Yes
2 = No
3 = Do not know

(oui=1,non=2,j.s.pas=3)	Freq.	Percent	Cum.
1	160	62.75	62.75
2	69	27.06	89.80
3	26	10.20	100.00
Total	255	100.00	

4. Is passing on a quality environmental framework to future generations a key concern for you?
1 = Yes
2 = No
3 = Do not know

(oui=1,non=2,j.s.pas=3)	Freq.	Percent	Cum.
1	237	92.94	92.94
2	13	5.10	98.04
3	5	1.96	100.00
Total	255	100.00	

5. Would you bequeath this environment in its current state?

1 = Yes
2 = No
3 = Do not know

(oui=1,non=2,j.s.pas=3)	Freq.	Percent	Cum.
1	134	52.55	52.55
2	112	43.92	96.47
3	9	3.53	100.00
Total	255	100.00	

6. Did you know that the population of wild pollinating insects is highly dependent on the health of the natural environment and landscape?

1 = Yes
2 = I think so
3 = I do not think so
4 = No

(oui=1,je crois que oui.oui=2,je crois que non=3,non=4)	Freq.	Percent	Cum.
1	200	78.43	78.43
2	42	16.47	94.90
3	1	0.39	95.29
4	12	4.71	100.00
Total	255	100.00	

7. Did you know that wild pollinators are in decline?

1 = Yes
2 = I think so
3 = I do not think so
4 = No

(oui=1,je crois que oui .oui=2,je crois que non=3,non=4)	Freq.	Percent	Cum.
1	171	67.06	67.06
2	37	14.51	81.57
3	3	1.18	82.75
4	44	17.25	100.00
Total	255	100.00	

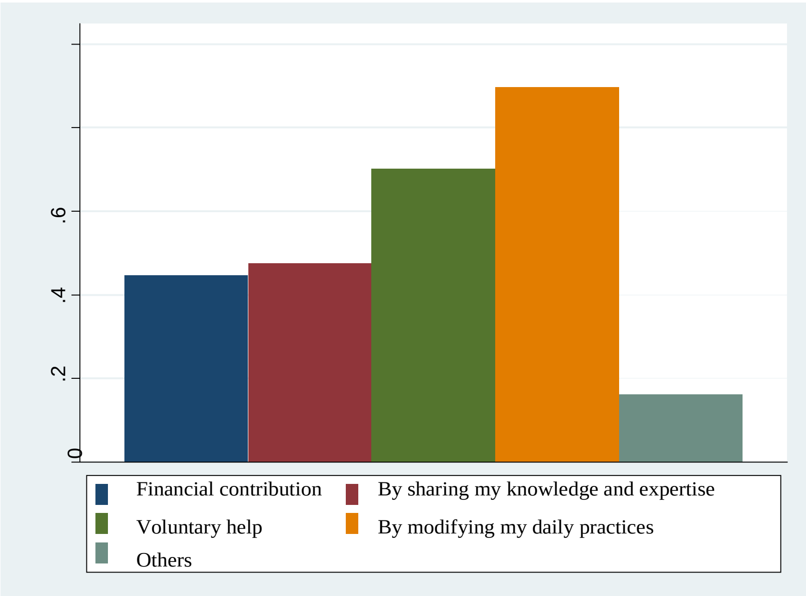
8. Do you think that this decline can be compensated for by making greater use of domesticated pollinators such as bees kept in hives?
1 = Yes
2 = No
3 = Do not know

(oui=1,non=2,j.s.pas=3)	Freq.	Percent	Cum.
1	64	25.10	25.10
2	135	52.94	78.04
3	56	21.96	100.00
Total	255	100.00	

9. Would you be willing to get personally involved in protecting wild pollinators?
1 = Yes
2 = No
3 = Do not know

(oui=1,non=2,j.s.pas=3)	Freq.	Percent	Cum.
1	204	80.00	80.00
2	21	8.24	88.24
3	30	11.76	100.00
Total	255	100.00	

10. How would do you like to contribute to the protection of pollinators? (204 observations)



11. Farm sizes of interviewed farmers (i.e., 71 respondents)

	Freq.	Percent	Cum.
lesser than 10 ha	22	38,60	38,60
10 to 25 ha	5	8,77	47,37
25 to 50 ha	8	14,04	61,40
50 to 100 ha	11	19,30	80,70
100 to 200 ha	9	15,79	96,49
More than 200 ha	2	3,51	100
Total	57	100	

12. The main type of operation of the farm owned by interviewed farmers

	Freq.	Percent	Cum.
Dairy cattle	4	7,02	7,0
Beef cattle	5	8,77	15,79
Mixed Cattle	2	3,51	19,30
Arboriculture	9	15,79	35,09
Crop production	15	26,32	61,40
Market gardening	10	17,54	78,95
Sheep, other herbivores	6	10,53	89,47
Polyculture & livestock	3	5,26	94,74
Pigs, poultry	2	3,51	98,25
Viticulture	1	1,75	100,00
Total	57	100,00	

Appendix 3. 6. STATA Codes

*Dataset overview

```
list id n_id choice_n time variety quality diversity pollspecies WTP agriculteur in 1/30, sepby( id)
```

	id	n_id	choice_n	time	variety	quality	divers~y	pollsp~s	WTP	agricu~r
1.	1	1	1	0	1	1	1	0	50	0
2.	1	1	0	0	0	0	0	0	0	0
3.	1	1	0	1	0	0	0	1	25	0
4.	2	1	1	0	1	0	0	1	100	0
5.	2	1	0	0	0	0	0	0	0	0
6.	2	1	0	1	0	1	1	0	50	0
7.	3	1	0	0	0	1	0	0	100	0
8.	3	1	0	0	0	0	0	0	0	0
9.	3	1	1	1	1	0	1	1	50	0
10.	4	1	0	1	1	1	1	0	25	0
11.	4	1	0	0	0	0	0	0	0	0
12.	4	1	1	0	1	0	1	1	100	0
13.	5	1	1	1	1	0	0	0	50	0
14.	5	1	0	0	0	0	0	0	0	0
15.	5	1	0	0	0	1	1	1	25	0
16.	6	2	1	0	0	0	1	1	50	0
17.	6	2	0	0	0	0	0	0	0	0
18.	6	2	0	1	1	1	0	0	25	0
19.	7	2	1	1	0	1	0	1	50	0
20.	7	2	0	0	0	0	0	0	0	0
21.	7	2	0	0	1	0	1	0	25	0
22.	8	2	0	0	0	0	1	0	25	0
23.	8	2	0	0	0	0	0	0	0	0
24.	8	2	1	1	1	1	0	1	100	0
25.	9	2	0	1	0	1	0	0	25	0
26.	9	2	0	0	0	0	0	0	0	0
27.	9	2	1	0	1	0	1	1	100	0
28.	10	2	1	1	1	0	0	1	100	0
29.	10	2	0	0	0	0	0	0	0	0
30.	10	2	0	0	0	1	1	0	100	0

```
summarize id n_id choice_n time variety quality diversity pollspecies WTP
```

```
    Variable |       Obs        Mean    Std. Dev.       Min        Max
-------------+---------------------------------------------------------

          id |      3825    637.9179    368.2069          1       1275

        n_id |      3825         128    73.62122          1        255

    choice_n |      3771    .3306815    .4705209          0          1

        time |      3825    .3351634    .4721093          0          1

     variety |      3825    .3566013    .4790583          0          1

     quality |      3825    .3328105    .4712809          0          1

   diversity |      3825    .3563399    .4789799          0          1

 pollspecies |      3825    .3330719    .4713736          0          1

         WTP |      3825    37.93464    36.99338          0        100
-----------------------------------------------------------------------
```

* Discrete-choice models
* The classical multinomial logit (MNL)

```
clogit choice_n time variety quality diversity pollspecies WTP, group(id)
```

* Mixed logit model
* Estimate mixed logit model with normally distributed intercept

```
mixlogit choice_n, group(id) id(n_id) rand(time variety quality diversity
pollspecies WTP)
estimates store mixlogit
estimates table mixlogit, star(0.05 0.01 0.001)
```

Appendix 3. 7. Estimated results of Mixed logit model relative to the Classical multinomial logit

	Multinomial logit			**Mixed logit model**		
Attributes	**Coefficient**	**z**	**significance**	**Coefficient**	z	significance
Time	0,15	2,16		0,36 (1,06)	1,69	
Variety of local fruits et vegetables	0,90	10,49	***	2,79 (-2,85)	6,05	***
Quality of local fruits et vegetables	0,58	8,09	***	1,40 (-2,33)	4,96	***
Wild flowers diversity	0,61	8,15	***	1,43 (-2,58)	4,52	***
Endangered insect pollinator species	1,61	17, 9	***	4,96 (4,48)	7,57	***
WTP	-0,003	-1,95		-0.02 (-0,01)	-3,87	*
Number of obs	3741				3741	
LR chi2 (6)	1037.32				594.13	
Prob > chi2	0.0000				0.0000	
Log likelihood	-851.07206				-554.0067	
Pseudo R^2	0.3787				0.4971	

*** p<.05; ** p<.01; *** p<.001**
NB: Figures in parentheses are standard deviations

In first place, we performed the Hausman test for independence of irrelevant alternatives for MNL. This test rejected assumptions regarding the independence of irrelevant alternative with MNL. Consequently, we went further with the Mixed logit model, which relaxes MNL assumptions.
For the interpretation of these results see https://stats.idre.ucla.edu/stata/output/logistic-regression-analysis/

* Heterogeneity of preferences among the attributes
*Model 1: Introduction of socio-economic variables one by one into the mixed logit model to test their significance.
* Some interaction variables between pollspecies attribute and individual characteristics

```
gen profession_pollspecies = pollspecies*profession
gen education_pollspecies = pollspecies*education
gen revenue_pollspecies = pollspecies*revenue
gen MbrAssEnv_pollspecies = pollspecies*MbrAssEnv
gen gender_pollspecies = pollspecies*gender
gen agriculteur_pollspecies = pollspecies*agriculteur
mixlogit choice_n, group(id) id(n_id)rand(time variety quality diversity
pollspecies profession_pollspecies WTP)
estimates store mixlogit
estimates table mixlogit, star(0.05 0.01 0.001)
mixlogit choice_n, group(id) id(n_id) rand( time variety quality diversity
pollspecies education_pollspecies WTP)
estimates store mixlogit
estimates table mixlogit, star(0.05 0.01 0.001)
mixlogit choice_n, group(id) id(n_id) rand( time variety quality diversity
pollspecies revenue_pollspecies WTP)
estimates store mixlogit
estimates table mixlogit, star(0.05 0.01 0.001)
```

* Some interaction variables between attribute WTP and individual characteristics

```
gen profession_WTP = WTP*profession
gen education_WTP = WTP*education
gen revenue_WTP = WTP*revenue
mixlogit choice_n, group(id) id(n_id) rand(time variety quality diversity
pollspecies profession_WTP WTP)
estimates store mixlogit
estimates table mixlogit, star(0.05 0.01 0.001)
mixlogit choice_n, group(id) id(n_id) rand( time variety quality diversity
pollspecies education_WTP store mixlogit
estimates table mixlogit, star(0.05 0.01 0.001)
mixlogit choice_n, group(id) id(n_id) rand( time variety quality diversity
pollspecies revenue_WTP WTP)
estimates store mixlogit
estimates table mixlogit, star(0.05 0.01 0.001)
```

* Etc., generated all interaction variables the same way *
*Model 2: Only the significant variables in MODEL 1 were reinserted by creating another mixed logit model integrating them directly.

Moedel 1 & Model 2: The coefficients of interaction variables between the attributes and the social-economic characteristics

Interaction variables	Variety of local fruit and vegetables	Quality of local fruit and vegetables	Diversity of wild flowers	Endangered insect pollinator species	Monetary contribution	Variety of local fruit and vegetables	Quality of local fruit and vegetables	Diversity of wild flowers	Endangered insect pollinator species	Monetary contribution
	Model 1					Model 2				
Age	-.34	-.00	.06	.28	.00					-.03**
	(.27)	(.21)	(.11)	(.87)	(.00)					(.01)
Gender	-.64	-.67	-.89	-1.22 *	-.01				3.18*	-.02
	(.48)	(.47)	(.50)	(2.56)	(.00)				(17.45)	(-.08)
Education	.32	-.25	-.32	-.98 ***	-.00 *				**-5.17*** **	-.02*
	(.26)	(.20)	(.18)	(.10)	(.00)				(-1.15)	(-.02)
Sector	.06	-.15	-.25	.64*	-.00				**-1.55** **	
	(.20)	(.17)	(.21)	(1.51)	(.00)				(.15)	
Profession	-.06	.15	.03	-.29	-.00					
	(.11)	(.09)	(.09)	(-.12)	(.00)					
Income	.00	.60 *	-.39	-1.0 ***	-.00		1.01*		-.81*	
	(.17)	(.24)	(.23)	(-.84)	(.00)		(3.51)		(-.83)	
Partner's income	10.	.06	-.38	-.22	-.00					
	(.19)	(.15)	(.20)	(.30)	(.00)					
AssoEnv	-.02	-.28	1.27 *	2.61 **	.01 *			-.012	**10.99*** **	.05
	(.47)	(.64)	(.59)	(4.36)	(.00)			(7.10)	(22.19)	(.13)
Type of role player	1.69 **	-.67	.77	1.75 *	.00	**10.2*** **			**4.57** **	
	(.62)	(.55)	(.67)	(3.69)	(.01)	(4.75)			(12.94	
Resident or not	-.10	.08	.03	-.12	-.00					
	(.09)	(.10)	(.08)	(.60)	(.00)					
Place of birth	31.	.43	.00	-.013	.00					.030**
	(.29)	(.31)	(.34)	(.36)	(.00)					(.02)

Appendix 4. 1. Determinants of farm household decisions particular on production, supply, and food consumption

Farm household	In perfect markets situations	In imperfect markets situation
Supply A farm household can supply a share of its farm products and its household members' time to market.	All products and factors can be tradable with no transaction costs as in the standard supply decision in competitive markets. Follow the law of supply stipulating that an increase in market price increases the quantity supplied Decisions can be taken in terms of market prices Production patterns do not affect consumption patterns and thus supply is independent of household preferences. Production and consumption decisions are made sequentially since farm profits is a part of the household income on which consumption depends. Production decision that maximizes farm profit consists in allocating its resource according to its comparative advantage which would lead to more specialization of agricultural production. Decisions can be analyzed within the framework of standard microeconomic theory of producer. Even if all markets work perfectly some of farm household production is kept for home consumption	All products and factors are either non-tradable or are tradable but at non-competitive prices. An increase in market price of staples results, to some extent, in a decrease in the share of their marketed production. "Prices" are determined internally into the household. Production and supply patterns do affect consumption patterns. Supply and consumption transfer from own products to purchased products changes relatively to an increase in market prices (since market prices can have a direct negative impact on its self-supplied commodities relative to a positive effect it may have on their farm income). Production and consumption decisions are interdependent For optimal solution, a farm household can play as in autarky, a net buyer, or a net seller of his products.
Demand	The demand decisions consider the market price of a good, income, preferences, market prices of substitute and complementary goods, etc. - as a standard consumer. Consumption decision that maximizes utility consists of allocating its budget according to its preferences. Decisions can be analyzed within the framework of standard microeconomic theory of the consumer.	In addition to standard consumer considerations, the demand decisions of a farm household may also consider farm characteristics, household socio-economic characteristics, and its price band (Price band refers to price margins between the low price at which a farm household could sell a commodity and the high price at which it could buy that product on the market (Key et al.2000).

Source: Adapted from de Janvry et al. (1991, 2006), Sadoulet and de Janvry (1995 and 2020), Key et al. (2000).

Appendix 4. 2. Mathematical details for welfare calculation in the case of a farm household

If all things remain the same (e.g., time allocation, input costs, off-farm income, and non-food commodities consumption), a comparison between the baseline situation and the future situations where insect pollination changes (Δα), the variation of W can be theoretically approximated as follows:

$$W_{\alpha=0} = P_c{}^a C_{hc}{}^a + P_c{}^d C_{hc}{}^d + \omega C_{hL} + G_h + P_c{}^a Q_{hc} - P_c{}^a C_{hc}{}^a - \omega l_{hc}{}^H - \sum Z_c{}^j x_{hc}{}^j - A_h + \omega(\mathrm{T} - l_{hc}{}^F - C_{hL}) + Y_h$$

$$W_{\alpha=t} = \alpha D_c P_c{}^a C_{hc}{}^a + \alpha D_c P_c{}^d C_{hc}{}^d + \omega C_{hL} + G_h + \alpha D_c P_c{}^a Q_{hc} - \alpha D_c P_c{}^a C_{hc}{}^a - \omega l_{hc}{}^H - \sum Z_c{}^j x_{hc}{}^j - A_h + \omega(\mathrm{T} - l_{hc}{}^F - C_{hL}) + Y_h$$

$$\Delta \mathrm{W} = W_{\alpha=0} - W_{\alpha=\mathrm{i}} = (P_c{}^a Q_{hc} + P_c{}^d C_{hc}{}^d)(1 - \alpha D_c) \quad (5)$$

The ratio of vulnerability of farm household welfare (RVW) is calculated as follows:

$$RVW = \frac{W_{\alpha=0} - W_{\alpha=\mathrm{i}}}{W_{\alpha=0}} \quad (6)$$

If we assume that;

$\mathrm{T} - \mathrm{l_{hc}}^{\mathrm{F}} - \mathrm{l_{hc}}^{\mathrm{H}} = \mathrm{L}$; Time allocation

$\mathrm{G_h} + \mathrm{Y_h} = \mathrm{B}$; Off-farm benefits

$\mathrm{Z_c}^{\mathrm{j}} \mathrm{x_{hc}}^{\mathrm{j}} - \mathrm{A_h} = \mathrm{F}$; Farming input costs

$$RVW = \frac{(P_c{}^a Q_{hc} + P_c{}^d C_{hc}{}^d)(1 - \alpha D_c)}{P_c{}^a Q_{hc} + P_c{}^d C_{hc}{}^d + \omega L + B - F} \quad (7)$$

Thus; RVW is a function of prices of farm household own and purchased goods and services $\mathrm{P} \in (P_c{}^a, P_c{}^d, \omega)$, farm production $Q \in (Q_{ch})$, and food consumption $C \in (C_{ch})$.

Appendix 4. 3. A guidance for interview with local stakeholders in Rwanda

Introduction

Nom et prénoms :
Structure :
Fonction :

Our project

- *Context:* Ecosystem services refer to the direct and indirect contributions of ecosystems to human well-being. This is especially true for agricultural production that mobilizes a large number of ecosystems such as **water**, **soils**, **pollination** or **genetic diversity**.
- However, worldwide, **the supply of these services is deteriorating rapidly**, even as the increase in population and production results in an increasing demand for these services, leading to a real "ecological crisis".
- This project falls within this context and it responds more specifically to the need to analyze the impacts of impoverishment of natural resources on social welfare. Especially, it proposes to assess the contribution of ecosystems to economic activity in the agricultural sector, which is particularly vulnerable. As example we use pollination. In addition, the loss in pollination services has a negative impact on the nutrition quality.

Objectives of the study

1) To quantify the pollinators' contribution to income and diet in farm households in Rwanda; based on types of crops produced and consumed.

2) To estimate the effects of pollination services decline on Rwandan farmers' social welfare;

3) To identify the perception that local stakeholders have about pollinators and pollination services?

To put efficiently in place the research tools that will respond to the above questions, we are meeting differents local stakeholders in order to gain more information at local level.

Questionnaire : *Local stakeholders perception about pollinators and pollination services*

1. What do you think about the agricultural practices that are commonly applied in the country?
2. What are the priorities in supporting farmers to improve their productivity?
3. Do you provide some training or subsidies for improving agricultural practices?
4. What are the main pest control techniques most recommended?
5. What is the degree of adoption of each on the field?
6. a) Do you think that ecosystem services are being considered in these recommendations?
   b) What concern should/could be made about crops pollination activity and insect pollinators from your point of view?
7. What do you think about the sustainability of the Rwandan farming systems?
   (improvement or degradation ?)
8. What are the main concerns issued from your crops productivity analysis? What measures do you propose to overcome them?
9. What do you think are the comparative advantages or disadvantages that Rwandan value chain has?
10. Can you identify the impacts of networks linking farmers and other stakeholders on the field? Do these impacts have something to do with the management of natural ressources?
11. a) When you reach the farmers in your work, do you put any emphasis on natural services?
    b) Do you have ways/ indicators etc. to follow up the implementation of your advices? If yes, what is your impression?

b11. Is there a framework for consultation between the decentralized technical services of the State, NGOs and farmers on issues relating to the management of natural resources as ecosystem services?

12. What is done concretely by the different actors on the ground?

13. Rwanda is among the most malnourished country in Africa with 35% (FAO, 2010) of undernourished population and 23% of malnourished children (RwGov, 2015). We are testing that the households food habits and crops production are one of the reasons. What do you think can be among the causes of such malnutrition?

Appendix 4. 4. Questionnaire for survey on farming and insect pollination services in Huye District

UBUSHAKASHATSI K'UBUHINZI NO KWIBANGURIRWA KW' IBIHINGWA NI INIGWAHABIRI (Insects) MU KARERER KA HUYE

URUTONDE RW'IBIBAZO

No	0. Amakuru rusange	Igisubizo
0.1	Umurenge :	
0.2	Akagari : Umudugudu :	
0.3	Itariki :	
0.4	Amazina ya Enumerator:	
0.5	Isaha y' igenzura :	
0.6	Numero y' urugo ukoreye uyu munsi:	....
0.7	Usubiza ni nde? 1=Nyir'urugo 2=Uwo bashakanye 3=Undi muntu uba murugo	
0.8	Nyir'urugo ni muntu ki? 1=Umuhinzi usanzwe; 2=Umuyobozi wa koperative/ Itsinda/Company ; 3=Umujyanama w'ubuhinzi	
0.9	Igitsina cya Nyir'urugo : 1= Male (Gabo); 2= Female (Gore)	
0.10	Imyaka ya Nyir'urugo ?	....
0.11	Icyiciro cy'amashuri ya Nyir'urugo: 1=Abanza; 2=Ayisumbuye; 3=Kaminuza; 4=Ntiyize	
0.12	Numero ya telephone y'usubiza niba atari Nyir'urugo ubwe wisubirije	....
0.13	Nomero ya telephone ya Nyir'urugo	
0.14	Umurimo w'ubuhinzi n'ubworozi Nyir'urugo akora : 1=Ubuhinzi bw' ibihingwa bitandukanye, Kawa, n'ubuvumvu; 2=Ubuhinzi bw' ibihingwa bitandukanye, n'ubuvumvu ; 3=Ubuhinzi bwa Kawa gusa n'ubuvumvu; 4=Ubuhinzi bw' ibihingwa bitandukanye na Kawa 5=Ubuhinzi bw'ibihingwa bitandukanye gusa 6=Ubuhinzi bwa kawa gusa 7=Ubuvumvu gusa	

Igika cya I: Uko abahinzi bumva ukubangurirwa kw'ibihingwa

No	Ikibazo	Igisubizo
1.1	Waba uzi ko, mubihingwa, habamo ibyibangurira (twakwita ibinyabibiri) n'ibibangurirwa n'ibindi (ibigore gusa n'ibigabo gusa) ? 1=Yego; 2=Oya	
1.2	Waba uzi icyo kubangurirwa kw'igihingwa (pollinisation) ari cyo ? 1= Yego; 2= Ndumva naba mbizi; 3= Ntacyo mbiziho; 4= Ntagisubizo mfite	
1.3	Niba ari yego, Ko tuziko ibihigwa bitagenda nk' inyamaswa ngo habeho guhererekanya intanga, ni ibiki waba uzi bifasha ibihingwa guhererekanya intanga mugihe cy'ibangurirwa ry'igihingwa rituma haboneka imbuto? (Ibisubizo byinshi biremewe) 1= Umuyaga ; 2= Inyamaswa; 3= Abantu; 4= Birikora byonyine 5= Ibindi. Bivuge: ...	
1.4	Hari inigwahabiri (insects) waba uzi zifasha mw'ibangurirwa ry'ibihingwa? 1=Yego; 2=Oya 1.4.1. Niba ari yego, wampa ingero ?... Niba ari oya Ingero (Share knowledge): inzuki, ibinyugunyugu, amasazi n'izindi	
1.5	Hari ibihingwa waba uzi cg ukeka ko inigwahabiri zibifasha mw'ibangurirwa ryabyo? 1= Yego; 2=Ndumva naba mbizi; 3=Ndumva ntabyo nzi; 4= Oya 1.5.1. Niba ari yego, wampa ingero z'ibyo bihingwa:	
1.6	Waba uzi ahantu inigwahabiri (insects), zifasha mw'ibangurirwa ry'ibihingwa, zikunze kuba (indaro kamere yazo)? 1= Yego; 2= Ndumva naba mbizi; 3= Ntacyo mbiziho; 4= Ntagisubizo mfite 1.6.1. Niba ari yego, tanga ingero nke:	
1.7	Wowe kubwawe, wumva inigwahabiri (insects) zifasha mw' ibangurira ry'igihingwa (ibisubizo byinshi biremewe): 1.7.1. Zifasha mukongera umusaruro w'ibihingwa? 1=Yego 2=Oya 1.7.2. Ziryana, zikaba zanatera uburwayi abahinzi n'abandi? 1=Yego 2=Oya 1.7.3. Zongera ubwiza bw'umusaruro (intungamubiri, ukugaragara neza k'imbuto n'imboga)? 1=Yego 2=Oya 1.7.4. Byongera urusobe rw'ibinyabuzima aho ziherereye? 1=Yego 2=Oya 1.7.5. Zivogera, zikanangiza ibihingwa? 1=Yego 2=Oya 1.7.6. Zihova kubihingwa zigakora ubuki? 1=Yego 2=Oya 1.7.7. Hari ibindi inigwahabiri zikora ku bihingwa waba uzi tutavuze? Ni ibihe: ... 1=Yego 2=Oya	
1.8	Mu myaka mike ishize, haba hari impinduka waba ubonesha amaso mumirima igukikije? 1=Yego 2= Ntayo 3= Simbizi Niba ari yego, Ni izihe mpinduka ubona muri ibi bikurikira (ibisubizo byinshi birashoboka): 1=Amaterasi	

	2=Guhuza ubutaka no guhinga igihingwa kimwe 3=Kugabanuka kugaragara kw'ibiti n'ibihuru mu mirima 4=Ibihingwa gakondo byasimbuwe n'indobanure 5=Ibindi, wasobanura?	
1.9	Urebye muri iyi myaka ishize, waba ubona inigwahabiri zaragabanutse aho wakundaga kuzibona zicaracara mumirima ugereranije na mbere? 1=Yego; 2=Oya	
1.10	Waba uzi ko ubwiganze bw'inigwahabiri zifasha mw'ibangurirwa ry'ibihingwa ahantu runaka rishingiye cyane ku bimera dusanga mubidukikije ni ikirere cyaho? 1= Yego; 2= Ndumva naba mbizi; 3= Ntacyo mbiziho; 4= Hoya	
1.11	Hari uburyo bwifashishwa kuburyo busimbura inigwahabiri mw'ibangurira ry'ibihigwa nko gukoresha amaboko (kujegajeza ibiti) cg izindi tekinoloji. Wumva ubwo buryo bundi mubushobozi bwanyu bwakoreshwa mu mirima yawe? 1= Yego; 2= Oya; 3= Simbizi	

1.12. Wambwira ari kuruhe rugero, hagati ya 1 na 4, waba wemera cg utemera na mba ibyo ngiye kuvuga mu nteruro ikurikira? Mugusubiza urakoresha kuva kuri 1 niba wemera byimazeyo ibyo mba mvuze, 2 wemera biringaniye, 3 utemera cyane, 4 utabyemera nagato.

	Kwimera byimazeyo →			Guhakana byimazeyo
1.12.1. Ni ngombwa gutera cg kugumisha ibiti bimwe na bimwe mu murima.	1	2	3	4
1.12.2. Guhuza ubutaka na gahunda yo guhinga igihingwa kimwe byongereye kuburyo bugaragara amafaranga aturuka mu buhunzi mu ngo	1	2	3	4
1.12.3. Guhuza ubutaka na gahunda yo guhinga igihingwa kimwe byongereye iryo yuzuye(food diversification) mu ngo	1	2	3	4
1.12.4. Ni ngombwa kugira igikorwa mu kurwanya igabanuka rikabije ry'inigwahabiri zifasha mw'ibangurira ry'ibihingwa mu rwego rwokongera umusaruro no kurwanya inzara	1	2	3	4
1.12.5. Ni ibintu bisaba imbaraga nyinhsi umuhinzi kubungabunga inigwahabiri zifasha mw'ibangurirwa ry'ibihingwa, hasigasirwa indiri yazo mu mirima hanaterwa imiti itazibangamira ndetse nibindi.	1	2	3	4

1.13	Wowe ubwawe wumva wakwifatanya nabandi mukubungabunga inigwahabiri zifasha mw'ibangurirwa ry'ibihingwa? 1= Yego 2= Oya 3= Ntacyo mbiziho Niba ari Yego (Ibisubizo byinshi biremewe): 1=Nkoresha neza imiti yica udukoko 2=Ndobanura imiti yatoranijwe idafite cg ifite ingaruka nke cyane kuri zo (pollinators)	

	3=Nubahiriza indaro yazo (pollinators) mu murima 4= Ibindi:	
1.14	Hari ingamba ubushakashatsi buvuga ko ziramutse zikurikijwe ibangurirwa rw'ibihingwa ryarushaho gukorwa neza bityo umusaruro ukiyongera. Ngiye kuzirondora ubwire izo wumva muri zo zashyirwa mu bikorwa kurusha izindi kandi zikanarinda iningwahabiri kurushaho: 1.14.1. Kubungabunga no kongera indaro kamere z'inigwahabiri zifasha mwibangurirwa ry'ibihingwa, ingero z'indaro zazo harimo: urusobe rw'ibimera ku nkengero no kunzitiro z'umurima harimo ibiti, indabo, n'ibiryo by'amatungo. 1= Yego; 2= Oya 1.14.2. Gushyira cg kongera imitiba y'inzuki mu murenge kugirango twongere serivisi z'ibangurirwa ry'ibihingwa. 1= Yego; 2= Oya 1.14.3. Guteza imbere impinduka mu mihingire dushishikariza abahinzi guhinga ibihingwa bitandukanye. 1= Yego; 2= Oya 1.14.4. Guteza imbere uburyo bwo kurinda ibyonnyi mumirima budafite ingaruka ku inigwahabiri zifasha mw'ibangurira ry'ibihingwa. 1= Yego; 2= Oya Uratekereza nk'ubuhe? .... 1.14.5. Indi ngamba waba utekereza: ....1= Yego; 2= Oya	

A. Ibibazo rusange kubinjyanye nibikorwa by'ubuhinzi by'urugo

Igika cya 2. Ibibazo k'umusaruro w' ibikomoka ku buhinzi byose mwabonye mu mwaka ushize.

Igihebwe igihingwa cyasaruwemo 1=Season A 2= Season B 3= Season C	Ikirango	Ibihingwa	2.1. Mwaba mwarahinze iki gihingwa? 1=Yego 0= Oya	2.2. Ubuso igihingwa cyahinzweho	2.3. Inite 1= Ha 2= Intabwe 3= Are	2.4. Aho ubutaka buri 1=Ku butaka buhujwe 2= Ubutaka busazwe	2.5. Muhinga iki gihingwa mwakoresheje abakozi banyakabyizi :		2.6. Muhinga iki gihingwa mwakoresheje abo mumuryango wawe :		2.8 Umukozi yahebwe angahe k'umubyizi ?	2.9. Ingano y'umusaruro wose wabonetse muri 2017 (Kg)	2.10 Umusaruro waguri shijwe	2.10. Umusaruro mwagurishije, mwawugurishije ku mafaranga angahe ku kilo? (Frw/unit)	2.11. Umusaruro mwagurishije, mwawugurishije nabande ? 1=kuri detaye kw'isoko 2=Nagurishirije kumurima 3=Kw'isoko kubarangura 4= N'abaturage mu rugo 5= Na koperative
							2.5.1 bangahe ?	2.5.2 Bahinze imibyizi ingahe ?	2.6.1 bangahe ?	2.6.2 Bahinze imibyizi ingahe ?					
	1. Ibihingwa byerera igihembwe bitamara umwaka mu murima														
	01	Ibigori													
	02	Umuceri													
	03	Amasaka													
	04	Ingano													
	05	Ibindi binyampeke bivuge…………													
	06	Ibishyimbo bigufi													
	07	Ibishyimbo by'imishingiriro													
	08	Amashaza													

	09	Ibindi binyamisogwe bivuge......													
	10	Ibirayi													
	11	Ibijumba													
	12	Inyanya													
	14	Amashu													
	15	Shufureri													
	16	Ibitunguru													
	17	Karoti													
	18	Intoryi													
	19	Soya													
	20	Ubunyobwa													
	21	Ibihwagari													
	22	Ibibiringanya													
	23	Puwavuro (Pepper)													
	24	Dodo,imbwija,inyabutongo													
	25	Sereri													
	26	Epinari & spinaci													
	27	Inkori													
	28	Beterave													
	29	Tungurusumu													
	30	Isogi													
	31	Puwaro													
	32	Imiteja													
	33	Leti													
	34	Brocoli													
	35	Mukuna													
	36	Desimodiyumu													
	37	Uburo													
	101	Ibindi binyabijumba bivuge													
	101														
	38	Kokombre													

	102	Izindi mboga zerera igihembwe zitamara umwaka mu murima Zivuge :													
	102														
	102														
	103	Ibindi bihingwa byerera igihembwe bitamara umwaka mu murima Bivuge :……….													
	103	……………….													
	103	……………….													
	2. Ibihingwa byerera igihembwe bimara umwaka mu murima														
	39	Amateke													
	40	Ibikoro													
	41	Inanasi													
	42	Marakuja													
	43	Ibireti													
	44	Urusenda(pilipili&kamurari)													
	45	Urubingo													
	46	Ubwatsi bw'amatungo													
	201	Ibindi binyabijumba Bivuge : ……….													
	47	Ibihaza/amadegede/imyungu													
	202	Izindi mboga zerera igihembwe zimara umwaka mu murima. Zivuge :………..													
	202														

	203	Ibindi bihingwa byerera igihembwe bimara umwaka mu murima. bivuge :……….													
	203	……………													
	203	…………….													
			3. Ibihingwa bitinda mu murima												
	48	Imyumbati													
	49	Ibitoki bitekwa													
	50	Ibitoki by'imineke													
	51	Ibitoki byo kwengamo inzoga													
	52	Avoka													
	301	Izindi mbuto													
	301														
	301														
	53	Ikawa													
	54	Ibisheke													
	55	Makadamiya													
	56	Imizeti/olivier													
	57	Imyembe													
	58	Pome													
	59	Ipapayi													
	60	Ibinyomoro													
	61	Amacunga													
	62	Indimu													
	63	Amapera													
	64	Ibobere													
	65	Stevia													
	66	Jatrofa													
	302	Ibindi binyabijumba bivuge : …………………													
	67	Imikindo/ingazi /Palmier													

	303	Izindi mboga zitinda mu murima zivuge : …………….													
	304	Ibindi bihingwa bitavuzwe haruguru : bivuge …. ………………….													

Igika cya 3. Ibibazo kw’ikoreshwa ry’umusaruro mwabonye mu mwaka ushize

Igihebwe igihingwa cyasaruwemo 1=Season A 2= Season B 3= Season C	Ikirango	Ibihingwa	3.1 Umusaruro wose wagurishijwe n’ uzagurishwa ungana iki?	3.2 Ku musaruro wose uwakoreshejwe/uzakoreshwa mu rugo ungana iki?	3.3 Ku musaruro wose, uwakoreshejwe /uzakoreshwa nk’uburyo bwo guhemba abakozi ungana iki?	3.4 Ku musaruro wose, uwakoreshejwe/ uzakoreshwa nk’uburyo bwo kwishyura ubukode bw’umurima ungana iki?	3.5 Ku musaruro wose, uwatanzwe/ uzatangwa nk’impano ungana iki?	3.6 Ku musaruro wose w’iki gihingwa, uwaguranywe /uzaguranwa ibindi bintu ungana iki?	3.7 Ku musaruro wose w’iki gihingwa uwakoreshejwe/uzakoreshwa nk’imbuto yo gutera ungana iki?	3.8 Ku musaruro wose w’iki gihingwa, uwakoreshejwe/uzakoreshwa mu kugaburira amatungo ungana iki?	3.9 Ku musaruro wose w’iki gihingwa, uwangiritse ungana iki?	3.10 Ku musaruro wose w’iki gihingwa, uwakoreshejwe/ uzakoreshwa mu bundi buryo butavuzwe ungana iki?
			%	%	%	%	%	%	%	%	%	%
	01	Ibigori										
	02	Umuceri										
	03	Amasaka										
	04	Ingano										
	05	Ibindi binyampeke bivuge…………										
	06	Ibishyimbo bigufi										
	07	Ibishyimbo by’imishingiriro										

	08	Amashaza										
	09	Ibindi binyamisogwe bivuge…………………										
	10	Ibirayi										
	11	Ibijumba										
	12	Inyanya										
	14	Amashu										
	15	Shufureri										
	16	Ibitunguru										
	17	Karoti										
	18	Intoryi										
	19	Soya										
	20	Ubunyobwa										
	21	Ibihwagari										
	22	Ibibiringanya										
	23	Puwavuro										
	24	Dodo,imbwija,inyab utongo										
	25	Sereri										
	26	Epinari & spinaci										
	27	Inkori										
	28	Beterave										
	29	Tungurusumu										
	30	Isogi										
	31	Puwaro										
	32	Imiteja										
	33	Leti										
	34	Brocoli										
	35	Mukuna										
	36	Desimodiyumu										
	37	Uburo										
	101	Ibindi binyabijumba bivuge …………….. ………										
	101											
	38	Kokombre (Cucumber)										
	102	Izindi mboga zerera igihembwe										

		zitamara umwaka mu murima Zivuge :										
	102											
	102											
	103	Ibindi bihingwa byerera igihembwe bitamara umwaka mu murima Bivuge :										
	103											
	103											
	39	Amateke										
	40	Ibikoro										
	41	Inanasi										
	42	Marakuja										
	43	Ibireti										
	44	Urusenda(pilipili&kamurari)										
	45	Urubingo										
	46	Ubwatsi bw'amatungo										
	201	Ibindi binyabijumba Bivuge :										
	47	Ibihaza/amadegede /imyungu										
	202	Izindi mboga zerera igihembwe zimara umwaka mu murima. Zivuge/										
	202											
	203	Ibindi bihingwa byerera igihembwe bimara umwaka mu murima. bivuge :										
	203											
	203											
	48	Imyumbati										
	49	Ibitoki bitekwa										
	50	Ibitoki by'imineke										

	51	Ibitoki byo kwengamo inzoga											
	52	Avoka											
	301	Izindi mbuto											
	301	Izindi mbuto nyamavuta. Zivuge :											
	301												
	53	Ikawa											
	54	Ibisheke											
	55	Makadamiya											
	56	Imizeti/olivier											
	57	Imyembe											
	58	Pome											
	59	Ipapayi											
	60	Ibinyomoro											
	61	Amacunga											
	62	Indimu											
	63	Amapera											
	64	Ibobere											
	65	Stevia											
	66	Jatrofa											
	302	Ibindi binyabijumba bivuge :											
	67	Imikindo/ingazi/Palmier											
	303	Izindi mboga zitinda mu murima zivuge :											
	68	Ibindi bihingwa bitinda mu murima. bivuge :................											

Igika cya 4: Ibyakoreshejwe kugira ngo haboneke umusaruro

Igihebwe igihingwa cyasaruwemo 1=Season A 2= Season B 3= Season C	Ikirango	Ibihingwa	4.1. Ikiguzi cy'imbuto yatewe yose mu mwaka ushize (RWF)	4.2. Mwaba mwarakoresheje ifumbire y'imborera mu mwaka ushize ? 1= Yego 2 = Oya Niba igisubizo ari 2 → r4.4	4.3. Mwatanze amafaranga angahe kugira ngo haboneke ifumbire y'imborera mu mwaka ushize? Ikiguzi (RWF)	4.4. Mwaba mwarakoresheje ifumbire mvaruganda kuri iki gihingwa mu mwaka ushize ? 1= Yego 2= Oya	4.5. Niba ari yego ikiguzi (RWF)	4.6. imiti yica udukoko yakoreshejwe mu mwaka ushize: Uzuza ukoresheje ibirango bikwiye mu birango byatanzwe ku kibazo 4.6.1: Ibirango by'imiti yica udukoko: 6= DITHANE 7= RIDOMIL 8= DIMETHOATE 9= CYPERMETHRINE 10= DURSIBAN 11= TILT 12= PILKARE 13= UNDI MUTI Niba igisubizo ari 2, jya ku kibazo 4.7						4.7. Amafaranga yagiye ku bakozi mw' ihinga mu mwaka ushize ni angahe ?	4.8 Amafaranga a yose hamwe yagiye mw' isarura ni angahe ?
								4.6.1 Mwaba mwarakoresheje imiti yica udukoko kuri iki gihingwa? 1=Yego 2= Oya	4.6.2 Ubwoko bw'umuti wica udukoko wakoreshejwe (reba ibirango hasi)	4.6.3 Ingero: 1=Kg 2= g 3= l 4=CC	4.6.4 Ingano	4.11.5 Ikiguzi (RWF)	4.6.6 Ahantu h'ingenzi umuti wakoreshejwe waturutse 1=Imfashanyo ya Leta 2= inguzanyo ya cooperative 3=Kw'isoko 4= Abacuruza babugenewe		
1. Ibihingwa byerera igihembwe bitamara umwaka mu murima															
	01	Ibigori													
	02	Umuceri													
	03	Amasaka													
	04	Ingano													
	05	Ibindi binyampeke bivuge...........													
	06	Ibishyimbo bigufi													
	07	Ibishyimbo by'imishingiriro													
	08	Amashaza													
	09	Ibindi binyamisogwe bivuge..............													
	10	Ibirayi													
	11	Ibijumba													
	12	Inyanya													
	14	Amashu													

	15	Shufureri													
	16	Ibitunguru													
	17	Karoti													
	18	Intoryi													
	19	Soya													
	20	Ubunyobwa													
	21	Ibihwagari													
	22	Ibibiringanya													
	23	Puwavuro													
	24	Dodo,imbwija,in yabutongo													
	25	Sereri													
	26	Epinari & spinaci													
	27	Inkori													
	28	Beterave													
	29	Tungurusumu													
	30	Isogi													
	31	Puwaro													
	32	Imiteja													
	33	Leti													
	34	Brocoli													
	35	Mukuna													
	36	Desimodiyumu													
	37	Uburo													
	101	Ibindi binyabijumba bivuge …………… …………													
	101														
	38	Kokombre (Cucumber)													
	102	Izindi mboga zerera igihembwe zitamara umwaka mu murima Zivuge :													
	102														
	102														
	103	Ibindi bihingwa byerera													

		igihembwe bitamara umwaka mu murima Bivuge :													
2. Ibihingwa byerera igihembwe bimara umwaka mu murima															
	39	Amateke													
	40	Ibikoro													
	41	Inanasi													
	42	Marakuja													
	43	Ibireti													
	44	Urusenda(pilipili &kamurari)													
	45	Urubingo													
	46	Ubwatsi bw'amatungo													
	201	Ibindi binyabijumba Bivuge : ……….													
	47	Ibihaza/amadegede/imyungu													
	202	Izindi mboga zerera igihembwe zimara umwaka mu murima. Zivuge/													
	202														
	203	Ibindi bihingwa byerera igihembwe bimara umwaka mu murima. bivuge :													
	203														
	203														
3. Ibihingwa bitinda mu murima															
	48	Imyumbati													
	49	Ibitoki bitekwa													
	50	Ibitoki by'imineke													
	51	Ibitoki byo kwengamo inzoga													

	52	Avoka													
	301	Izindi mbuto													
	301	Izindi mbuto nyamavuta. Zivuge :													
	301														
	53	Ikawa													
	54	Ibisheke													
	55	Makadamiya													
	56	Imizeti/olivier													
	57	Imyembe													
	58	Pome													
	59	Ipapayi													
	60	Ibinyomoro													
	61	Amacunga													
	62	Indimu													
	63	Amapera													
	64	Ibobere													
	65	Stevia													
	66	Jatrofa													
	302	Ibindi binyabijumba bivuge :													
	67	Imikindo/ingazi/ Palmier													
	303	Izindi mboga zitinda mu murima zivuge :													

Igika cya 5: Ibikoresho byifashishwa mu mirimo y'ubuhinzi

A. Amazina y'Ibikoresho biciriritse by'ubuhinzi

Ibikoresho	5.1 Mwaguze iki gikoresho Mu mwaka ushize? 1=Yego; 2=Oya Niba igisubizo ari 2 → 5.5	5.2 Muri 2017 mwaguze ibi bikoresho bingahe?	5.3 Ikiguzi cy'igikoresho kimwe ni amafaranga angahe? (Unit Price)	5.4 Agaciro kose k'ibyo bikoresho byaguzwe ni amafaranga angahe? (Total Cost)	5.5 Umubare n'agacirok'ibikoresho mwahawe ku buntu mu mwaka ushize	
					Umubare	Agaciro (RWF)
1. Isuka						
2. Inkonzo/Rasoro						
3. Majagu/Nyamenyo						
4. Rato						
5. Ipiki						
6. Ingorofani						
7. Igitiyo						
8. Imipira y'amazi						
9. Ipombo yo gutera imiti imyaka						
10. Arozwari						
11. Urukero						
12. Inajoro/Akayuya						
13. Sekateri						
14. Uruhabuzo/Igishanguruzo						
15. Umuhoro/Umupanga						
16. Umuhoro w'urunana						
17. Igitebo						
18. Umufuka						
19. Umutiba wo guhunikamo						
20. Intara/Urutaro						
21. Ikibo						
22. Inkangara						
23. Umunzani						
24. Ijerekani						
25. Ingunguru						
26. Igare						
27. Igitogotogo						
28. Ingemeri/Mironko						
29. Shitingi						
30. Umuhini w'isuka						
31. Icyuma kivungura						
32. Ibindi(bivuge) :						

B. Ibikoresho biramba bitunzwe n'umuhinzi n'agaciro kabyo

Ibikoresho	5.6 Mwaba mutunze iki gikoresho? 1=Yego; 2=Oya Niba igisubizo ari **1**, vuga umubare w'ibikoresho atunze Niba igisubizo ari **2**, jya ku gikoresho gikurikiraho		5.7 Niba ibikoresho byaraguzwe andika agaciro kakimwe (RWF)	5.8 Mwaguze iki gikoresho mumwaka ushize? 1=Yego; 2=Oya Niba igisubizo ari 1, vuga umubare w'ibyaguzwe. Mwishyuye amafaranga angahe ku gikoresho kimwe mu byaguzwe mu mwaka ushize? (unit price) Niba igisubizo ari 2→5.10				5.9 Garagaza umubare n'agaciro k'ibikoresho biramba mwabonye ku buntu mu mwaka ushize		5.10 Mwatiye iki gikoresho mumwaka ushize? 1=Yego; 2=Oya		
	5.6.1 Ikirango	5.6.2 Umubare		5.8.1 Ikirango	5.8.2 Umubare	Price(RWF) 5.8.3 Agaciro ka kimwe	5.8.4 Agaciro kose(RWF)	5.9.1 Umubare	5.9.2 Agaciro (RWF)	5.10.1 Ikirango	5.10.2 Umubare	5.10.3 Agaciro (RWF)
1. Ubwanikiro												
2. Ubuhunikiro/Ikigega												
3. Ipikipiki/Moto												
4. Ikindi kinyamitende												
5. Imodoka zifashishwa mu buhinzi												
6. Imashini ihinga												
7. Imashini itera												
8. Imashini itonora/Imashini ishishura												
9. Imashini ivomerera/yuhira												
10. Imashini itera imiti mu myaka												
11. Imashini ifumbira												
12. Imashini isarura (Harvesting machine)												
13. Ibindi. Bivuge :............												
14. Mumiyoboro y'amazi												

15. Amafaranga mbumbe yagiye ku bindi bintu muri rusange muri uru rugo umwaka ushize (nk'amafaranga y'ishuri, imyenda, n'ibindi) ? ....

No	Ikibazo	Igisubizo
6.1	Imirima yawe iri kubuso bungana bute? 1=<0.5 ha; 2=0 .5 to 1 ha; 3=1 to 5 ha; 4= 5 to 10 ha; 5=> 10 ha	
6.2	Uru rugo rwaba rworoye amatungo? 1=Yego 2= Oya Niba ari yego, Ni yahe? Ni angahe? 6.2.1 .... 6.2.2 .... 6.2.3	
6.3	Uru rugo rwaba rworoye inzuki? 1=yego 2= Oya (Niba ari oya njya kubibazo 6.5) 6.3.1 Niba ari yego, rufite imitiba ingahe? .... 6.3.2 Ni iyihe mpamvu mworoye inzuki?	
6.4	Ni ibihe biryo byi ibanze by'inzuki zanyu?	
6.5	Waba utekereza ko inzuki zifasha mw'ibangurira ry'ibihingwa, bigatuma umusaruro w'ibihingwa wiyongera? 1=Yego 2=Oya	
6.6	Ese utekereza ko abaturanyi bawe baba bazi akamaro k'inzuki k'umusaruro uturuka mu buhinzi? 1=Yego 2= Oya	
6.7	Waba ufite igitekerezo ku binjyanye ni ihuriro ryaba riri hagati y'inzuki n'uburyohe bwa kawa? 1=Yego 2= Oya	
6.8	Wabwira ugereranije amafaranga yose waba ukura mubuhinzi mu mwaka? (andika umubare wayo, RWF)	....
6.9	Wabwira ugereranije amafaranga yose agenda kubikorwa by'ubuhinzi mu mwaka ? (andika umubare wayo, RWF)	....
6.10	Wabwira ugereranije amafaranga yose ubona nk'inyungu akomotse mu buhinzi ku mwaka? (andika umubare wayo, RWF)	
6.11	Haba hari amafaranga wakoresheje mubijyanye nubuhinzi mu mwaka ushize wagujije ? 1=yego 2=Oya (Niba ari 2→ 6.15)	
6.12	Niba ari yego, wayagujije he muri aha hakurikira? 1= Bank 2= Cooperative 3= Inshuti cg Umuturanyi	
6.13	Niba ari yego, Angahe?	....
6.13	Waba warishyuye angahe? (Niba bikubangamiye gusubiza iki kibazo , ntakibazo wakireka)	....
6.15	Hari imfashanyo cg inyunganizi yo mubuhinzi uru rugo rwaba rwarabonye mu mwaka ushize ? 1=yego 2=Oya (If 2→6.17)	
6.16	Ni izihe mfashanyo cg inyunganizi zo mubuhinzi mwabonye (ibisubizo byinshi biremewe) : Zari izihe ? Ingano Zaturutse he ? 1=Imbuto yo gutera ... ... 2=Imiti yica udukoko ... ... 3=Ifumbire mvaruganda ... ... 4=Ibindi, Bivuge	
6.17	Umubare w'ibihingwa uru rugo rwahinganga kera, ku mirima y'ingenzi, waba waragabanutse? 1=yego 2=Oya (If 2→6.19) 6.17.1 Niba ari yego, Wabwira ibihingwa utagihinga kera wahingaga ?	
6.18	Impinduka mumihingire y'ibyo bihingwa yaba yaratewe: 1=Gahunda ya Leta 2=Kugabanuka k'umusaruro w'ibyo bihongwa bitagihingwa	

	3=Ku kugabanuka, by'umwihariko, kw'inigwahabiri zifasha mw'ibangurire ry'ibihingwa aho byahingwaga 4=Izindi mpamvu, zivuge: ...	
6.19	Imirima yawe imwe nimwe yaba iri mu butaka buhujwe ? 1=yego 2=Oya (If 2→6.21)	
6.20	Niba ari yego, Yaba kimwe cya kabiri cy'imirima uru rugo rutunze iri ku butaka buhujwe? 1=yego 2=Oya Ni ku kihe kigereranyo (%).............................	
6.21	Utekereza ko impinduka mu mihingire no mu bwoko bw'ibihingwa ku mirima yanyu bwaba bwaragize ingaruka ku mirire y'indyo yuzuye muri uru rugo ? 1=Yego 2= Oya (If 2→6.23)	
6.22	Niba ari yego, gute ? (Sobanura)	
6.23	Umwe mubatuye muri uru rugo yaba ari umunyamuryango wa Koperative ? 1=yego 2=Oya (If 2→6.25)	
6.24	Niba ari yego, koperative ikora iki (niba ari nyinshi ni izihe)?	....
6.25	Niba ari ntawe, kubera iki ?	....
6.26	Haba hasabwa iki ngo umuntu abe umunyamuryango wa koperative ?	
6.27	Ni izihe nyungu ku m'imirima yawe kuba umwe muri uru rugo yaba umunyamuryango wa koperative ?	
6.28	Hari bimwe mubihingwa byanyu byaba bifite certificat? 1=yego 2=Oya (If 2→6.30)	
6.29	6.29.1. Niba ri yego, Ni ibihe bihingwa ? .... 6.29.2. Ku kigereranyo kingana iki ?(%)	
6.30	Waba uzi ibisabwa ngo bimwe mu bihingwa bwanyu bibe byagira certificat ? 1=Yego, 2=Oya Niba ari yego, ni ibiki ?.....................	
6.31	Hari inyungu ubona mukuba umusaruro wawe waba ufite certificat ?	
6.32	Abakangura mbaga batandukanye mu byubuhinzi cg ba koperative baba barabahuguye kubinjyanye n'imihingire na pratike zinoze ? 1=yego 2=Oya (If 2→7.1))	
6.33	Utekerezako se ubumenyi mubinjyanye na pratike nziza z'ubuhinzi bwiyongereye ugereranije na mbere ? 1=yego 2=Oya	
6.34	Niba ari yego ni izihe pratike nshya wungutse ?	....
6.35	Hari pratike nshya watangiye gushyira mubikorwa ugambiriye kongera umusaruro mu mirima yawe ndetse na akarima k'igikono niba ugafite ? 1=yego 2=Oya	
6.36	Hari inyungu se umaze kubona nyuma yo gushyira mubikorwa izo pratike nshya ? 1=yego 2=Oya Niba yego, Izo nyungu ni nk' izihe ?	
6.37	Hari ingaruka mbi se umaze kubona nyuma yo gushyira mubikorwa izo pratike nshya ? 1=yego 2=Oya Niba yego, Izo ngaruka ni nk' izihe ?..	

No	***7. Muri pratike ziri mu mbonerahamwe ikurikira wabwira izo twasanga mu mirima yanyu ?***	**Igisubizo (code)**
7.1	Waba uvanga ibihingwa ku murima umwe, mu mihingire yanyu, mu: (intercropping)	7.7.1 ....

	7.1.1 Ibihingwa byerera igihembwe bitamara umwaka mu murima. 1=Yego 2=Oya 7.1.2 Ibihingwa byerera igihembwe bimara umwaka mu murima. 1=Yego 2=Oya 7.1.3 Ibihingwa bitinda mu murima. 1=Yego 2=Oya	7.7.2 ...... 7.7.3 ....
7.2	Mwaba muhinduranya ibihingwa k'umurima umwe? (rotation) 1=Yego 2=Oya Niba ari yego ; (Mu bikora:1=Buri season; 2=Buri mwaka; 3=Mu kindi gihe: ... 7.2.1 Ibihingwa byerera igihembwe bitamara umwaka mu murima 1=Yego 2=Oya 7.2.2 Ibihingwa byerera igihembwe bimara umwaka mu murima. 1=Yego 2=Oya 7.2.3 Ibihingwa bitinda mu murima. 1=Yego 2=Oya	7.2.1 ..... 7.2.2 .... 7.2.3 ...
7.3	Mwaba mukoresha umuti wica udukoko mumirima yanyu kenshi? 1=yego 2=Oya	
7.4	Waba utekereza ko imikoreshereze mibi yi imiti yica udukoko yagira ingaruka mbi: (ibisubizo byinshi biremewe) 1=K' ubwiza bw' amazi 2=Kubuzima bwawe n'ubwabandi 3=Ku kurabya kw'ibihingwa 4=Ku kubangurirwa kw'ibihingwa 5=K' umusaruro w'ibihingwa 6=Nta nimwe	
7.5	Haba hari urusobe rw'ibimera ku nkengero, mu mirima, cg se no kunzitiro z'imirima yanyu harimo nk' ibiti byi imbuto, ibindi biti , indabo, n'ibiryo by'amatungo, nibindi ntavuze. 1=yego 2=Oya	
7.6	Niba ari yego, Ni izihe mpamvu ugumisha cg ushyira ibyo bintu ku mirima yawe? 1= Kugira ngo bihe igicucu imyaka 2= Kugirango bigabanye ubushyuhe 3= Kugirango bihe indaro inigwahabiri zifasha mw'ibangurirwa ry'ibihingwa 4= Mu kurwanya isuri 5= Nuko bihenze kubivana mu mirima 6= Sinzi impamvu mbikora, namye mbibona uko 7= Ibiryo by' amatungo 8=Izindi mpamvu, zivuge:	

7.7	Ni ibihe bihingwa 3 by'ingenzi muhinga, urebeye hamwe imirima yanyu yose? 1. ……………………… 2. ……………………….. 3. ………………………..	
7.8	Umusaruro wa kimwe cg bibiri muri ibyo bihingwa uramutse ugabanutsemo nk'icyakabiri cyawo cyose, Wakomeze kugihinga? 1=yego 2=Oya Niba utakomeza kugihinga wagisimbuza ikihe gihingwa ? ……………………………………………………………………………………………………..	

Igika cya 8 : Imirire y'urugo

Ikirango	Ibihingwa	8.3.1 Ugereranije ingano yose igurwa y' iki gihingwa ingana iki ? (in Kgs)			8.3.2 Ingano yose yakiriwe y'iki gihingwa nk'uburyo bw'igihembo ungana iki?(Kgs)	8.3.3 Ingano yose yakiriwe y'iki gihingwa nk'uburyo bwo kwishyurwa ubukode bw'umurima ungana iki?(Kgs)	8.3.4 Ingano yose yakiriwe y'iki gihingwa nk'impano ungana iki?(Kgs)	8.3.5 Ingano yose yakiriwe y'iki gihingwa nki ingurane y'ibindi bintu ungana iki? (Kgs)	8.3.6 Ingano yose yakiriwe y'iki gihingwa, mu bundi buryo butavuzwe ungana iki? (Kgs)
		8.3.1.1 Mu cyumweru	8.3.1.2 Mu mwaka	8.3.1.3 Igiciro/Kg					
1. Ibihingwa byerera igihembwe bitamara umwaka mu murima									
01	Ibigori								
02	Umuceri								
03	Amasaka								
04	Ingano								
05	Ibindi binyampeke bivuge...........								
06	Ibishyimbo bigufi								
07	Ibishyimbo by'imishingiriro								
08	Amashaza								
09	Ibindi binyamisogwe bivuge....................								
10	Ibirayi								
11	Ibijumba								
12	Inyanya								
14	Amashu								
15	Shufureri								
16	Ibitunguru								
17	Karoti								
18	Intoryi								
19	Soya								
20	Ubunyobwa								
21	Ibihwagari								
22	Ibibiringanya								
23	Puwavuro								
24	Dodo,imbwija,inyabutongo								
25	Sereri								
26	Epinari & spinaci								
27	Inkori								
28	Beterave								
29	Tungurusumu								
30	Isogi								
31	Puwaro								
32	Imiteja								
33	Leti								

34	Brocoli								
35	Mukuna								
36	Desimodiyumu								
37	Uburo								
101	Ibindi binyabijumba bivuge ………………………								
	Kokombre (Cucumber)								
101 38 102	Izindi mboga zerera igihembwe zitamara umwaka mu murima Zivuge :								
102									
102 103	Ibindi bihingwa byerera igihembwe bitamara umwaka mu murima Bivuge :								
103									
103									
2. Ibihingwa byerera igihembwe bimara umwaka mu murima									
39	Amateke								
40	Ibikoro								
41	Inanasi								
42	Marakuja								
43	Ibireti								
44	Urusenda (pilipili&kamurari)								
45	Urubingo								
46	Ubwatsi bw'amatungo								
201	Ibindi binyabijumba Bivuge : ……….								
47	Ibihaza/amadegede/imyungu								
202	Izindi mboga zerera igihembwe zimara umwaka mu murima. Zivuge/								
202									
203	Ibindi bihingwa byerera igihembwe bimara umwaka mu murima. bivuge :								
203									
203									
3. Ibihingwa bitinda mu murima									
48	Imyumbati								
49	Ibitoki bitekwa								
50	Ibitoki by'imineke								
51	Ibitoki byo kwengamo inzoga								
52	Avoka								
301	Izindi mbuto								

301	Izindi mbuto nyamavuta. Zivuge :								
301									
53	Ikawa								
54	Ibisheke								
55	Makadamiya								
56	Imizeti/olivier								
57	Imyembe								
58	Pome								
59	Ipapayi								
60	Ibinyomoro								
61	Amacunga								
62	Indimu								
63	Amapera								
64	Ibobere								
65	Stevia								
66	Jatrofa								
302	Ibindi binyabijumba bivuge :								
67	Imikindo/ingazi/Palmier								
303	Izindi mboga zitinda mu murima zivuge :								
	Ibihingwa								
4. None crop consumption food commodities									
401	Inyama z'inka								
402	Ifi /Fish								
403	Amagi/ Eggs								
404	Inkoko/ Chicken meet								
405	Amata/ Milk								
406	Ibindi biribwa tutavuze haruguru :								

8.1. Muri uru rugo, ni inshuro zingahe mugura ibiribwa ?
1=Buri munsi ; 2=Rimwe mu cyumweru ; 3=Rimwe mu kwezi ; 4= Ikindi gihe, kivuge : ………..

8.2. Mu rugo rwanyu, ibiribwa bibatwara amafaranga angahe, mu gereranije, mu cyumweru ?
……………….

8.3. Ni ibihe biribwa n'ibinyobwa bikunzwe kuboneka cyane muri uru rugo n'ibiciro byabyo iyo biguzwe ? Uzuza imbonerahamwe ikurikira :

8.4. Igiciro cy'ibiribwa by'ingenzi mukunze kugura cyikubye kabiri, mwakomeza kubigura cyangwa mwabisumbuza ibindi biribwa ? 1= Yego 2= Oya

8.4.1. Niba mwabisimbuza, Ni ibihe biribwa mwasimbuza buri kimwe mu bisazwe bigurwa cyane ?

……
…………………………………………………………………………….

Igika cya 9 : Amakuru bwite (Income and Social economic data)

No	Niba usubiza ari Nyir'urugo njya kukibazo → 9.3	Igisubizo
9.1	Respondant's years old Imyaka y'uwasubije niba atari Ny'irurugo :	
9.2	Respondant education level Icyiciro cy'amashuri cy'uwasubije: 1=Abanza (Primary); 2=Ayisumbuye (High school); 3=Kaminuza (University); 4=Ntiyize (None)	
9.3	Hari association cg itsinda rizwi cg ritazwi ubarizwamo rifite rifite aho rihurira ni ibikorwa ibyo aribyo byose bigamije kubungabunga ibidukikije? 1= Yego; 2= Oya	
9.4	Nyir'urugo ni : 1=Ingaragu 2= Arubatse 3=Umupfakazi 4=Yatandukanye nuwo bashakanye 5=Ikindi, kivuge: ...	
9.5	Ni abantu bangahe batuye muri uru rugo ?	
9.6	Ni abantu bangahe hano batuzwe na Nyir'urugo ?	
9.7	Guhinga niwe murimo wibanze utunze uru rugo ? 1=Yego 2= Oya	
9.8	Ni amasaha angahe mumara mumirimo y'ubuhinzi ku munsi ?	....
9.9	Hari indi mirimo cg ibikorwa bibinjiriza amafaranga mukora ? 1=Yego 2= Oya (If 2→ 9.11)	
9.10	Niba hari indi mirimo mukora, ni amasaha angahe ku munsi mumara muri iyo mirimo y' indi ?	....
9.11	Ni amasaha angahe Nyir'urugo afatamo ikiruhuko ku munsi ? (ayo amara ntacy akora, aruhuka)	

9.12. Amafaranga yinjira murugo ku mwaka ; Uzuza imbonerahamwe ikurikira :

No	Izina ry' umuntu utuye muri uru rugo ufite umushahara abona uvuye mutundi tuzi	9.12.1. Isano afitanye na Nyir'urugo 1=Uwo bashakanye; 2=Umwana we; 3=Umuvandimwe we; 4=Umubyeyi we; 5=Irindi sano	9.12.2. Amafaranga yinjiza ku mwaka

9.13. Turangije uru rutonde rw'ibibazo. Nkaba mbashimira cyane kuba mwitabiriye. Mwaba mwifuza kumenya ibizaba muri ubu bushakashatsi ? 1=Yego 2=Oya

Niba ari yego, Email yanyu cg aho twabikoherereza :..................................

9.14. Mwaba mufite igitekerezo cg amakuru mwifuzaga kudusangira ?

....

Appendix 4. 5. The econometric model of production function

Household production	Coef.	Std. Err.	t	P>|t|	[95% Conf. Interval]	
Seeds	.0041	.0027971	1.47	0.143	-.001	.0095
Organic fertilizer	-.0023	.0024868	-0.93	0.355	-.007	.0025
Chemical fertilizer	.0189	.002596	7.31	**0.000**	.0138	.0240
Pesticides	-1,165	1.758754	-0.66	0.508	-4.61	2,285
Total wages	.0017	.0001558	11.03	**0.000**	.0014	.00202
_cons	110,483	9.959157	11.09	0.000	90.94	130.02

Number of obs = 1063 R-squared = 0.4563

F(5, 1057) = 177.45 Adj R-squared = 0.4538

Prob> F = 0.0000 Root MSE = 273.43

Appendix 4. 6. Share of inputs expenditure costs

Crop category	Hired Labor costs	Seed costs	Organic fertilizer costs	Chemical fertilizer costs	Pesticide cost
Cereals	18%	17%	20%	37%	23%
Fruits	1%	2%	5%	2%	3%
Oil crops	2%	4%	5%	1%	0%
Pulse	18%	37%	22%	11%	3%
Roots and Tubers	19%	20%	21%	4%	8%
Spices	0%	0%	0%	1%	1%
Stimulant crops	32%	1%	7%	18%	6%
Sugar crops	0%	0%	0%	0%	0%
Vegetables	11%	18%	20%	27%	**56%**
	67%	**10%**	**11%**	**10%**	**2%**

Résumé de la thèse

Depuis la déclaration de São Paulo sur les pollinisateurs (1999), une des résultats de la troisième conférence des parties (COP3) de la Convention sur la Diversité Biologique (CDB), les pollinisateurs ont fait l'objet d'une attention croissante en tant que composants clés de la biodiversité dans les arènes scientifiques et politiques mondiales (Dias et al., 1999 ; IPBES, 2016). Les pollinisateurs sont des animaux qui contribuent à la pollinisation des plantes : ils comprennent principalement des espèces d'abeilles - tant les abeilles sauvages que les abeilles domestiques gérées (Klein et al., 2007) - et d'autres insectes (par exemple, les mouches, les papillons et les coléoptères ; Garibaldi et al., 2013). En se nourrissant de nectar, les pollinisateurs transportent le pollen des parties mâles vers les parties femelles des fleurs de la même espèce, ce que l'on appelle la pollinisation. La pollinisation permet la fécondation et la reproduction des cultures à fleurs et d'autres espèces végétales. Les pollinisateurs jouent donc un rôle crucial pour la nature et l'humanité. Les pollinisateurs bénéficient au bien-être des humains en améliorant la quantité (Williams, 1994 ; Klein et al., 2007) et la qualité (Klatt et al., 2014) des produits alimentaires - notamment la qualité nutritionnelle (Chaplin-Kramer et al., 2014 ; Sluijs et al., 2016) - la qualité des paysages par le maintien de la flore sauvage (Ashman et al., 2004 ; Ollerton et al., 2011), etc.

En particulier, il est important de prêter attention aux pollinisateurs et à leurs avantages dans la production alimentaire, car près de 690 millions de personnes dans le monde souffrent encore aujourd'hui de la faim en raison du manque d'aliments suffisants et nutritifs (FAO, FIDA, UNICEF, PAM et OMS, 2020). De même, l'Organisation mondiale de la santé prévient que la malnutrition mondiale est en augmentation avec des niveaux croissants de sous-alimentation et d'obésité (OMS, 2018). Bien que la malnutrition soit un problème multifactoriel, de nombreuses cultures qui fournissent des nutriments essentiels (par exemple, des vitamines, des antioxydants et des fibres) sont pollinisées par des insectes (par exemple, les fruits et légumes ; Eilers et al., 2011). Plusieurs études scientifiques en sciences naturelles (par exemple, l'écologie, la biologie et l'agronomie) ont signalé des chevauchements entre la nutrition et la production de micronutriments dépendant des pollinisateurs (par exemple, Eilers et al., 2011 ; Chaplin-Kramer et al., 2014 ; Sluijs et al., 2016). Cependant, ces chevauchements restent peu étudiés et mal compris en économie.

D'où notre intérêt à étudier à la fois les aspects économiques et nutritionnels des bénéfices des pollinisateurs. Ce résumé donne un aperçu de ce travail de thèse en soulignant son contexte et l'énoncé du problème, les objectifs, les hypothèses, la portée de la méthodologie, les principaux résultats et sa structure.

Menacées par divers facteurs, dont les activités économiques humaines, notamment l'utilisation intensive de pesticides (Pfiffner et Muller, 2014), l'intensification de l'agriculture et la conversion des habitats (Aizen et Feinsinger, 2003), les espèces envahissantes (Schweiger et al., 2010), les agents pathogènes introduits (Cameron et al., 2011) et le changement climatique (Hegland et al., 2009), l'abondance et la diversité des insectes pollinisateurs sont en déclin (Potts et al., 2010). Ce déclin conduit à une " crise de la pollinisation " dans les systèmes de production agricole dans de nombreuses régions du monde (voir, par exemple, Holden, 2006 ; Goulson et al., 2015). Une crise de pollinisation renvoie à l'idée qu'un déclin des pollinisateurs peut menacer l'alimentation humaine (Cell Press, 2009), tant en termes de quantité que de qualité nutritionnelle, alors que le coût de ce déclin pour la société humaine reste mal connu.

Ainsi, les politiques publiques sont souvent sollicitées pour atténuer le déclin des pollinisateurs. A cette fin, les décideurs politiques ont montré leur intérêt et ont exprimé le besoin de comprendre les coûts et les bénéfices que les pollinisateurs génèrent pour les populations afin de prendre des décisions efficaces. Cette nécessité d'évaluer les avantages de la nature a déjà été soulevée à plusieurs reprises par des auteurs tels que Daily et al. (1997, 2000) et Costanza et al. (1997), soulignant le rôle des évaluations économiques pour un tel processus décisionnel. Ces auteurs soutiennent que la comparaison des coûts et des bénéfices apportés par la Nature à l'aide d'une métrique compréhensible peut être utile aux décideurs politiques et, plus largement, à toutes les parties prenantes.

Cette thèse s'inscrit donc dans l'effort continu d'ajustement des outils d'évaluation économique afin de rendre compte des bénéfices des pollinisateurs et des coûts de leur déclin pour la société.

L'évaluation économique des bénéfices des pollinisateurs a pris de l'ampleur dans la littérature économique mondiale depuis que certaines études alertent sur l'impact de la rareté de la pollinisation par les insectes aux Etats-Unis d'Amérique (USA) au début des années 2000 (Porto et al., 2020 ; vanEngelsdorp et al., 2009). En effet, en améliorant la pollinisation, les pollinisateurs diminuent les coûts marginaux de production, ce qui permet d'augmenter les rendements agricoles à moindre prix (Winfree et al., 2011). La plupart des études économiques évaluent l'impact du déclin des pollinisateurs dans les pays en mettant l'accent sur la diminution de la quantité de production végétale (Southwick et Southwick, 1992 ; Morse et Calderone, 2000 ; Leonhardt et al., 2013 ; Tibesigwa et al., 2019). En bref, le déclin des pollinisateurs menace la production agricole. Par exemple, Morse et Calderone (2000) ont estimé la valeur de la pollinisation des cultures par les seules abeilles domestiques aux États-Unis à 14,6 milliards de dollars par an. La contribution des pollinisateurs à la valeur du secteur agricole mondial a été estimée entre 153 et 260 milliards d'euros (voir Gallai et al., 2009 ; Lautenbach et al., 2012), ce qui représente environ 8 à 10% de la valeur de la production mondiale de cultures comestibles (IPBES, 2016). Les études économiques actuelles commencent à étendre cette évaluation aux bénéfices des pollinisateurs que l'on trouve dans les éléments du paysage tels que les paysages floristiques (par exemple, Breeze et al., 2015 ; pour le Royaume-Uni).

La littérature non économique (par exemple, la biologie, l'écologie), cependant, dépeint plus de rôles des insectes pollinisateurs pour l'humanité, y compris leur contribution à la formation de nutriments dans les cultures. Par exemple, Ellis et al. (2015) ont constaté que les cultures dépendant des pollinisateurs contribuent jusqu'à 40 % de l'approvisionnement mondial en nutriments, tandis que Eilers et al. (2011) ont constaté qu'environ 90 % de la vitamine C dans les cultures est produite grâce à la pollinisation par les insectes.

À ce jour, la littérature sur l'évaluation économique des pollinisateurs n'est pas allée assez loin pour comprendre les conséquences du lien entre le déclin des pollinisateurs et la malnutrition pour la société humaine. Ainsi, les avantages globaux des pollinisateurs, y compris la qualité nutritionnelle des cultures, sont encore peu étudiés. Par conséquent, les différentes valeurs des bénéfices des pollinisateurs restent encore sous-estimées par les politiques publiques. Par exemple, si la qualité nutritionnelle des cultures est bien identifiée par le prix du marché des cultures, la contribution de la pollinisation par les insectes à cette qualité ne l'est pas. Pourtant, la contribution nutritionnelle que les bénéfices des pollinisateurs offrent aux humains, qui a un impact sur la santé, serait précieuse pour les décideurs publics et le grand public. Il est essentiel d'identifier ces avantages des pollinisateurs, de les mesurer et donc de les évaluer selon des paramètres facilement compréhensibles par tous, afin de sensibiliser le grand public aux pollinisateurs menacés et aux conséquences de leur déclin, ce qui peut motiver des actions étendues.

L'évaluation économique permet d'agréger des mesures compréhensibles et utilisables de différents types de valeur en une seule mesure de la valeur économique, simplifiant ainsi l'analyse à des fins d'évaluation et de prise de décision. La valeur économique est particulièrement utile car elle permet de couvrir toutes les expressions des valeurs, y compris les coûts de la dégradation ou les avantages du maintien des pollinisateurs. Cependant, cette valeur agrégée ne prend en compte que les avantages connus des pollinisateurs pour l'homme à l'heure actuelle - alors que les connaissances sur tous les aspects des pollinisateurs sont encore limitées - et entraîne donc une sous-estimation de la valeur des avantages globaux que les pollinisateurs peuvent générer.

En effet, plusieurs études ont contribué à faire comprendre qu'un déclin des pollinisateurs augmentera le coût de la production agricole, ou réduira la productivité, et par conséquent augmentera les prix du marché (voir par exemple Gallai et al., 2009 ; Garibaldi et al., 2011a). C'est notamment le cas des cultures dépendant des pollinisateurs, qui comprennent de nombreux fruits et légumes (Chaplin-Kramer et al., 2014 ; Sluijs et al., 2016). Par conséquent, la demande et l'offre de cultures dépendant des pollinisateurs se modifieront à mesure que les gens s'adapteront et réagiront au déclin des pollinisateurs. Les gens peuvent remplacer les cultures dépendantes des insectes pollinisateurs par des cultures non dépendantes des insectes pollinisateurs moins nutritives pour la consommation. En retour, la production et l'offre s'adapteront organiquement à la demande.

En ce qui concerne l'ajustement et l'atténuation du déclin des pollinisateurs, Bauer et Wing (2016) soulignent que la spécialisation peut avoir lieu entre les pays et les régions. En d'autres termes, les pays relativement dotés en pollinisateurs peuvent s'adapter aux technologies de production en se concentrant sur l'offre de cultures dépendantes des pollinisateurs, tandis que d'autres pays peuvent s'adapter aux technologies de production en se concentrant sur la production d'autres cultures. Ainsi, à travers la demande et l'offre, les processus d'ajustement des mécanismes économiques au déclin des pollinisateurs peuvent être considérés comme des "processus de substitution" (c'est-à-dire comme dans Fisher et Pry, 1971 ; Maguire, 2004).

Cependant, les phénomènes résultant de ces processus de substitution peuvent se produire à l'intérieur d'un pays, dans les champs, et donc dans les systèmes de production ainsi que dans la consommation des ménages. Bien sûr, ces changements et ajustements peuvent prendre des formes différentes selon les pays, les régions et les villages où les acteurs opèrent selon des normes, des connaissances, des habitudesdifférentes, etc.

Néanmoins, à l'ère où le commerce international intervient de plus en plus dans la vie économique des pays et des communautés locales, il semble nécessaire de prendre en compte ces processus de substitution et leurs impacts. Ainsi, comment être sûr que les pays poussés par les mécanismes du commerce international à produire des biens dépendant des pollinisateurs protégeront ces derniers pour maintenir l'équilibre alimentaire mondial ? Comment pouvons-nous être sûrs que ces biens seront accessibles à tous par le biais du commerce ? Et comment pouvons-nous être sûrs que ces pays protégeront les pollinisateurs pour maintenir la biodiversité mondiale ou d'autres avantages locaux des pollinisateurs qui ne sont pas valorisés par le marché ?

Il est également crucial de ne pas sous-estimer les processus de substitution similaires qui peuvent avoir lieu à d'autres échelles plus petites que l'échelle internationale, comme l'échelle nationale ou plus locale. À cet égard, il est nécessaire de s'assurer que les pays protègent leurs pollinisateurs par des solutions stratégiques impliquant une pluralité d'acteurs utilisant la pollinisation par les insectes dans des contextes différents, avec des pratiques sociales diverses et des intérêts parfois contradictoires.

D'un point de vue économique, il est aisé d'imaginer les interdépendances et les complémentarités des différentes réponses aux enjeux du déclin de la pollinisation. En conséquence, il semble nécessaire d'avoir des approches internationales et nationales ainsi que locales pour sauvegarder durablement les pollinisateurs. L'évaluation économique devrait tenter d'englober davantage et mieux cette multiplicité d'échelles et, idéalement, les phénomènes dus à leur fonctionnement simultané.

En effet, d'une part, l'évaluation économique des bénéfices des pollinisateurs est concentrée à l'échelle nationale et uniquement sur leurs dimensions quantitatives ; alors que leurs dimensions qualitatives (ex. qualité nutritionnelle), notamment dans la consommation des ménages, et le rôle des pollinisateurs dans la régulation de la biodiversité sont peu étudiés en économie. D'autre part, cette valorisation se concentre dans les pays développés (Porto et al., 2020), alors qu'elle reste rare dans le contexte des pays en développement où l'agriculture de subsistance est encore plus courante, tout comme l'auto-approvisionnement et la consommation alimentaire des ménages. En effet, le contexte des pays en développement doit être considéré à part entière car les types de coordination et d'arbitrage peuvent être différents de ceux des pays développés. Par exemple, des ménages agricoles des pays en développement ont été considérées comme particulières du fait qu'ils sont consommateurs des cultures qu'ils produisent et que, par conséquent, leurs décisions de production et de consommation sont souvent interdépendantes (Barnum et Squire, 1979 ; Sadoulet et de Janvry, 1995). Ainsi, tout choc affectant la production agricole a un impact direct sur le revenu et la consommation alimentaire de ces ménages agricoles, en termes de quantité et de qualité.

Porter une plus grande attention aux bénéfices économiques et sanitaires des pollinisateurs et, par conséquent, au coût du déclin des pollinisateurs à différentes échelles avec une méthodologie bien adaptée, est donc un défi important que cette thèse contribuera à relever. Plus précisément, cette thèse vise à aider à comprendre les aspects économiques et nutritionnels qui peuvent être associés au déclin des pollinisateurs afin d'inspirer les politiques publiques et de sensibiliser le grand public. Ce faisant, elle cherche à mettre en lumière les conséquences que les ajustements des mécanismes économiques au déclin des pollinisateurs peuvent avoir sur la quantité et la qualité nutritionnelle de la production et de la consommation alimentaire.

Pour atteindre ce but, les objectifs de cette thèse sont de soulever de nouvelles questions, de suggérer des analyses supplémentaires et d'étendre les approches analytiques existantes concernant l'évaluation économique des bénéfices des pollinisateurs en se concentrant sur différentes échelles spatiales afin de mieux dépeindre les réponses complémentaires qui peuvent atténuer le déclin des pollinisateurs.

Plus précisément, nous suggérons d'aborder les questions suivantes :

1) Quelles seraient les conséquences de ce déclin des pollinisateurs non seulement sur la quantité mais aussi sur la qualité nutritionnelle de l'offre et de la demande mondiales de cultures comestibles compte tenu des mécanismes du commerce international ?
2) Quelle pourrait être la volonté du grand public de protéger les pollinisateurs ?
3) Quels pourraient être les impacts du déclin des pollinisateurs sur la production alimentaire des ménages agricoles et donc sur la consommation de nutriments de ces ménages ?

Nous distinguons deux contextes, l'un dans une région d'un pays développé (France) et l'autre dans une région d'un pays en développement (Rwanda).

Suite à ces questions, trois hypothèses peuvent émerger. Étant donné que le déclin des pollinisateurs aura un impact sur la productivité des cultures, la première hypothèse est que les processus de substitution, compris comme des ajustements des mécanismes économiques au déclin des pollinisateurs, auront lieu à différentes échelles. Ces processus de substitution pourraient réduire la diversité de la production et de la consommation alimentaires. Par conséquent, le déclin des pollinisateurs entraînerait des carences tant au niveau de l'offre que de la consommation de nutriments essentiels. Il convient donc d'aborder conjointement les aspects économiques et nutritionnels susceptibles d'être affectés par ce déclin.

La deuxième hypothèse est qu'il est nécessaire de considérer différentes échelles spatiales pour aborder le déclin des pollinisateurs. Cette nécessité est due au fait que la perception de l'importance des pollinisateurs peut dépendre de l'échelle de l'analyse, des caractéristiques des zones étudiées et de la définition de l'"agent économique" comme unité d'analyse, mais les réponses au déclin des pollinisateurs à chaque échelle ainsi que les différentes échelles sont complémentaires. D'une part, à mesure que la pollinisation gratuite que les pollinisateurs peuvent offrir diminue dans les exploitations agricoles, d'autres moyens de pollinisation peuvent augmenter les coûts de production, exigeant ainsi des ressources supplémentaires de la part des producteurs opérant sous différents systèmes agricoles. Une telle augmentation des coûts de production entraînera une hausse des prix du marché qui, à son tour, nuira au surplus du consommateur. Dans certains pays, cette augmentation des coûts de production est due à l'introduction de méthodes de pollinisation alternatives coûteuses, comme la location de ruches ou des moyens mécaniques. Cet impact correspond à la réduction des avantages commercialisés des pollinisateurs (naturels), car leur nombre diminue. Cependant, un mécanisme insidieux de processus de substitution peut avoir lieu au niveau des consommateurs, qui peuvent remplacer dans leur régime alimentaire les cultures pollinisées par des cultures ne nécessitant pas de pollinisation mais contenant moins d'apports nutritifs (par exemple en remplaçant certains fruits et légumes par des céréales dans leur régime alimentaire). Ce remplacement peut avoir des effets négatifs sur le bien-être humain. Cela est particulièrement probable pour les sociétés moins fortunées qui peuvent ne pas être en mesure d'investir dans le substitut coûteux des moyens de pollinisation pour soutenir leur production ou pour faire face à l'augmentation des prix du marché, d'où un potentiel d'accroissement des inégalités dans la société. Cet impact négatif doit être ajouté à celui sur la biodiversité et les paysages (offerts par les fleurs sauvages, par exemple) qui ne sont pas actuellement pris en compte ou échangeables par le marché. On les appelle les "bénéfices non marchands". En tant que tels, ils peuvent être négligés si les processus de substitution conduisant à la spécialisation dans certaines cultures sont soutenus ou prévalent.

Ces considérations nous amènent à notre troisième hypothèse, à savoir que la volonté du grand public de protéger les pollinisateurs dépendra de la sensibilisation du public à la contribution des pollinisateurs au bien-être humain. En effet, les bénéfices des pollinisateurs peuvent être principalement menacés dans leur voisinage, les sociétés ayant une biodiversité plus riche et des paysages multifonctionnels (par exemple, la production agricole, le tourisme touristique, la recherche et les activités culturelles, etc.) peuvent être exposées et sensibles aux conséquences directes du déclin des pollinisateurs, et donc leur volonté de protéger les pollinisateurs peut être plus importante que pour les autres sociétés.

La partie suivante expose la portée de la méthodologie qui sera utilisée pour répondre aux questions de recherche susmentionnées et tester ces hypothèses.

Plusieurs auteurs ont souligné qu'il est crucial de prendre en compte la question des échelles dans l'analyse économique des avantages que les écosystèmes procurent aux humains (MAE, 2003, 2005; TEEB, 2010; UNEP, 2016), y compris la pollinisation (Hein et al., 2009; IPBES, 2016, Ch. 4) pour informer efficacement les décideurs. Il pourrait donc être nécessaire de comprendre les impacts du déclin des pollinisateurs sur le bien-être des acteurs opérant dans différents contextes à différentes échelles pour informer efficacement les décideurs sur les tendances des coûts sociaux en cas de déclin des pollinisateurs. Mais, pour l'instant, il n'existe pas suffisamment de statistiques à différentes échelles et provenant de différents contextes (par exemple, économique, social, écologique, etc.) (par exemple, Porto et al., 2020), ni de théorie économique appropriée (par exemple, Gómez-Baggethun et al., 2010) pour permettre une analyse théorique de la complexité de ce sujet de thèse. Cependant, à travers l'observation des acteurs qui sont liés d'une manière ou d'une autre aux bénéfices des pollinisateurs en se concentrant sur des indicateurs spécifiques, il est possible d'identifier les coûts que le déclin des pollinisateurs peut générer pour eux. Pour ce faire, nous proposons d'utiliser une variété d'études de cas.

Comme mentionné précédemment, de nombreuses études axées sur l'évaluation économique des pollinisateurs ont concentré leurs estimations sur la contribution des pollinisateurs au secteur des cultures en utilisant les prix du marché à l'échelle nationale (par exemple, Southwick et Southwick, 1992) et internationale (par exemple, Kevan et Phillips, 2001 ; Bauer et Wing, 2016). D'autres études économiques ont abordé la question du déclin des pollinisateurs en se concentrant sur les fluctuations des rendements des cultures à l'échelle de l'exploitation (par exemple, Nderitu et al., 2008). De même, quelques études économiques se sont concentrées sur les bénéfices que les pollinisateurs génèrent pour le bien-être humain à l'échelle locale et territoriale mobilisant l'approche des préférences déclarées, particulièrement connue pour évaluer la valeur des caractéristiques des biens autres que leur quantité de production (e.g. Breeze et al., 2015 ; Mwebaze et al., 2018). Cependant, si les agriculteurs peuvent être directement témoins des impacts du déclin des pollinisateurs sur leurs moyens de subsistance, aucune des études précédentes n'a abordé les impacts de ce déclin sur le bien-être de leur ménage.

Grâce aux différentes opportunités que nous avons eues tout au long de ce travail de recherche de thèse, nous étudions les bénéfices des pollinisateurs à travers trois études de cas se déroulant dans des contextes différents, en nous concentrant sur différentes échelles, notamment l'échelle globale, l'échelle du territoire et l'échelle des ménages. Afin d'estimer les impacts du déclin des pollinisateurs sur le bien-être humain, nous nous concentrons sur les indicateurs économiques standards, notamment les caractéristiques de prix, de quantité et de qualité. Nous présentons ci-dessous i) les études de cas, ii) les échelles et iii) les indicateurs.

i. Les études de cas

Du point de vue de la collecte des données, nous avons mené une enquête à partir de la base de données FAOSTAT, une enquête par questionnaire dans le territoire du Comminges, dans le Sud-Ouest de la France, un pays développé, et une enquête par questionnaire dans le district de Huye, dans le Sud du Rwanda, un pays en développement.

La raison pour laquelle nous nous sommes concentrés sur la base de données FAOSTAT était double. D'une part, l'engagement dans cette recherche doctorale a été initié par une collaboration plus étroite que nous avons eue avec l'équipe de coordination de l'Initiative internationale pour les pollinisateurs de l'Organisation des Nations unies pour l'alimentation et l'agriculture (FAO) à Rome dans le cadre d'un stage de maîtrise. Cela nous a permis d'acquérir une expérience pratique sur ce sujet et dans la base de données FAOSTAT. D'autre part, FAOSTAT est la principale base de données qui fournit les données les plus complètes sur l'agriculture.

Pour l'étude de cas du Comminges, les observations ont été réalisées dans le cadre du projet SEBIOREF, qui vise à promouvoir les Services Ecosystémiques rendus par la BIOdiversité à l'agriculture : de la production de REFerences, aux conseils et propositions d'outils incitatifs, en lien avec la transition agro-écologique en France. Le projet a été financé par la Région Occitanie (France) et l'Institut national de la recherche agronomique (INRA) dans le cadre du programme PSDR4 " Pour et Sur le Développement Régional ", 2016-2020 . Plus précisément, nous avons contribué au chapitre sur l'évaluation économique de SEBIOREF, où nous avons évalué la volonté des acteurs locaux de payer pour les bénéfices qu'ils tirent des pollinisateurs.

Quant au cas rwandais, nous avons été motivés non seulement par les expériences vécues mais aussi par le fait que, sous le partenariat de la FAO, ce pays cherche des moyens efficaces d'adopter des pratiques d'intensification des cultures tout en tenant compte des modèles environnementaux. L'agriculture intensive désigne un système dominé par l'introduction de systèmes de monoculture, d'engrais inorganiques et d'une forte utilisation de pesticides (Perfecto et al., 2019), alors que l'activité agricole dans ce pays reste généralement dominée par des pratiques traditionnelles visant une production de subsistance (NISR, 2019b). Le Rwanda fait en effet partie des quelques partenaires de projet de la FAO qui collaborent activement pour une manière plus intégrée de soutenir le développement agricole en liant l'utilisation efficace d'intrants à forte valeur ajoutée à l'utilisation des ressources naturelles pour une production intensive durable (FAO, 2017, 2017b). Cependant, pour l'instant, ce pays connaît une perte de biodiversité dans ses agroécosystèmes sur l'ensemble du territoire, notamment là où l'intensification agricole a lieu (Wong et al., 2005).

Ces études de cas permettent d'analyser les impacts du déclin des pollinisateurs dans des contextes économiques, sociaux et écologiques strictement différents. Par contextes économiques, nous entendons le contraste entre les pays développés et les pays en développement, et plus précisément la différence entre leurs niveaux de revenus (pays à faible revenu et pays à revenu élevé) tels que définis par la Banque mondiale. Pour les contextes sociaux, nous faisons référence aux différentes normes, connaissances, habitudes, cultures, traditions, histoire, etc. qui caractérisent les populations et les relations de ces populations entre elles et avec leur écosystème naturel. Quant aux contextes écologiques, nous nous référons aux différents climats, sols et génétiques des plantes qui participent au fonctionnement d'un écosystème.

Afin d'informer efficacement les décideurs politiques, comme mentionné précédemment, il est essentiel de considérer non seulement différents contextes mais aussi différentes échelles afin d'aborder les différents angles du bien-être social que le déclin des pollinisateurs peut impacter et, ainsi, transmettre une multitude de réponses possibles impliquant divers acteurs opérant à différents niveaux. Par conséquent, notre analyse dans ce travail de thèse prend également en compte différentes échelles.

ii. Échelles

D'un point de vue analytique, nous suggérons de se concentrer sur les échelles : mondiale, territoriale et des ménages. A travers les mécanismes du commerce international, l'analyse à l'échelle globale se concentre sur les incidences du déclin des pollinisateurs sur la quantité et la qualité nutritionnelle de l'offre et de la demande alimentaire. Une telle analyse implique de prendre en compte les effets du processus de substitution et les changements dans l'apport en nutriments des produits alimentaires. Cependant, ce niveau d'analyse ne nous permet pas de prendre en compte les avantages non marchands liés au contexte local et ne peut fournir des solutions adaptées aux divers contextes sociaux, écologiques et économiques. Nous étendons ensuite notre analyse à l'échelle des territoires et des ménages afin de dépasser ces limites macroéconomiques et de prendre en compte les avantages non marchands liés au contexte local, tels que la biodiversité de la flore et de la faune, les paysages et les aliments non échangeables produits par les ménages agricoles.

L'analyse à l'échelle territoriale se concentre donc sur les avantages commercialisés et non commercialisés des pollinisateurs. Cette analyse permet non seulement d'évaluer les incidences du déclin des pollinisateurs qui sont spécifiques à un contexte territorial, mais aussi de comprendre la sensibilisation et les préoccupations du grand public concernant le déclin des pollinisateurs et la rareté de la pollinisation par les insectes. En particulier, une échelle territoriale chevauche une échelle écologique où les acteurs peuvent travailler ensemble pour gérer et protéger les pollinisateurs (voir TEEB, 2010). C'est pourquoi il est important de prendre en compte la sensibilisation des personnes à cette échelle.

L'analyse à l'échelle des ménages agricoles se concentre sur les mécanismes des incidences du déclin des pollinisateurs sur la quantité et la qualité nutritionnelle des aliments disponibles ou accessibles pour la subsistance des ménages agricoles. En particulier, les incidences de ce déclin sur les ménages agricoles dans un contexte de pays en développement où ces ménages sont à la fois producteurs et consommateurs des cultures qu'ils produisent.

iii. Indicateurs

Les indicateurs font référence aux éléments de données qui peuvent être utilisés pour représenter des caractéristiques spécifiques, observables et mesurables d'un sujet étudié (UNECE, 2000). Comme indiqué précédemment, cette thèse combine les aspects économiques et nutritionnels dans l'évaluation des impacts du déclin des pollinisateurs sur le bien-être humain. En tant que tel, en nous concentrant sur les indicateurs économiques standard (par exemple, les prix, les caractéristiques de quantité et de qualité), nous nous sommes appuyés sur des éléments de données que l'on peut trouver sur les marchés, les paysages et ceux spécifiques aux ménages agricoles.

Pour les aspects économiques, nous nous concentrons sur les bénéfices commercialisés et non commercialisés des pollinisateurs. Dans le cas où les bénéfices des pollinisateurs sont échangés sur le marché (par exemple, les cultures dépendant des pollinisateurs), des courbes d'offre et de demande standard peuvent être construites sur la base des prix (voir Hein, 2009). Dans le cas contraire, si certaines de ces cultures ne sont pas commercialisées sur le marché, comme c'est le cas pour certains ménages agricoles ruraux dans les pays en développement (voir Sadoulet et de Janvry, 1995), il était utile de considérer également les caractéristiques de l'autoconsommation des ménages agricoles.

En outre, l'état de la flore et de la faune dans un paysage, qui offrent des avantages qui ne sont pas échangés sur un marché, est un autre indicateur que nous proposons d'examiner. Plus précisément, cela permet d'évaluer les avantages non commercialisés des pollinisateurs. Dans ce cas, une série d'approches d'évaluation a été développée dans la littérature économique, y compris des méthodes de préférences révélées et déclarées (voir, par exemple, Pearce et Moran, 1994 ; Hanley, 2001).

Pour les aspects nutritionnels, nous considérons à la fois les dimensions quantitatives et qualitatives des apports en nutriments. Les nutriments représentent les caractéristiques mesurables des cultures, notamment les fibres, les vitamines, les minéraux, etc. (OMS, 2021).

Nos résultats peuvent être résumés comme suit.

La question des échelles étant importante, nous proposons dans chaque chapitre d'évaluer les impacts du déclin des pollinisateurs à l'échelle considérée et de discuter des réponses possibles à ce déclin au niveau des politiques publiques et des initiatives collectives à travers les échelles. De manière générale, cette thèse montre que le déclin des pollinisateurs aura un impact sur l'économie y compris sur la qualité nutritionnelle des aliments de diverses manières aux différentes échelles étudiées. Notre travail montre également que le déclin des pollinisateurs aura un impact sur le bien-être humain à travers les pays grâce aux mécanismes du commerce international. Par conséquent, le rapprochement des préoccupations des parties prenantes et des décideurs influençant la gestion des pollinisateurs à différentes échelles peut illustrer les interdépendances et la complémentarité des diverses réponses aux problèmes liés aux pollinisateurs.

Plus spécifiquement, les résultats de cette thèse sont encadrés par trois idées principales. Premièrement, cette thèse montre qu'avec le déclin des pollinisateurs, les niveaux de production agricole et de consommation de nutriments peuvent diminuer si les cultures dépendantes des pollinisateurs ne sont pas relativement remplacées par d'autres cultures. En conséquence, il y aura une perte globale de bien-être humain à l'échelle mondiale. Malheureusement, certains pays sont déjà sous-alimentés. Ce déclin peut donc aggraver la malnutrition dans les pays déjà touchés, mais pas exclusivement. Nos résultats soulignent le fait que le déclin des pollinisateurs peut avoir un impact sur les pays non seulement à travers leur production de cultures dépendant des pollinisateurs, mais aussi à travers leur demande de produits agricoles. En d'autres termes, le déclin des pollinisateurs est une préoccupation mondiale car il augmentera les coûts marginaux des cultures dépendant des pollinisateurs, ce qui peut créer une incertitude sur le revenu des pays exportateurs, tandis que les pays importateurs consommeront moins de ces produits si les prix augmentent, ce qui peut créer une incertitude sur leur consommation de nutriments. Ces résultats impliquent que les mesures de protection des pollinisateurs doivent être prises à l'échelle spatiale locale, nationale et mondiale.

Deuxièmement, cette thèse montre également que dans le territoire du Comminges, dans le sud-ouest de la France, les personnes interrogées considèrent comme très importants les avantages qu'elles tirent des insectes pollinisateurs et, par conséquent, elles sont fortement disposées à payer pour éviter les scénarios de déclin des pollinisateurs. De manière significative, les préférences et les choix individuels favorisent la sauvegarde des espèces de pollinisateurs en danger, des variétés de fruits et légumes locaux, des fleurs sauvages et de la qualité des fruits et légumes locaux. Dans cette zone rurale, les acteurs s'approvisionnent souvent sur les marchés locaux, notamment en fruits et légumes frais locaux qu'ils consomment chez eux, et visitent assez souvent les paysages floristiques qui les entourent. Ils se disent préoccupés par la question du déclin des pollinisateurs, notamment sur leur territoire. En d'autres termes, ces résultats montrent que, dans cette région, les gens accordent une grande importance à la biodiversité de la flore et de la faune par le biais des pollinisateurs. En effet, ils apprécient les pollinisateurs non seulement parce qu'ils en bénéficient, mais aussi parce qu'ils les considèrent comme des animaux à part entière dans leur monde. Ces résultats soulignent le fait que les préoccupations du public concernant le déclin des pollinisateurs peuvent varier en fonction des contextes économiques, sociaux et écologiques locaux. Par conséquent, une politique économique empirique visant à conserver les espèces d'insectes pollinisateurs en voie de disparition est supposée être spécifique aux caractéristiques de la zone considérée.

Troisièmement, cette thèse montre enfin que dans le district de Huye au sud du Rwanda, la pollinisation par les insectes apporte une contribution non négligeable à la production agricole et aux revenus des ménages agricoles ainsi qu'à leur consommation. La pollinisation par les insectes contribue également à la qualité nutritionnelle des aliments produits par et pour les ménages agricoles, permettant ainsi à ces ménages de s'auto-approvisionner en nutriments essentiels contenus dans les cultures dépendant des pollinisateurs comme les fruits, les légumes et les oléagineux. Elle montre que si les insectes pollinisateurs disparaissent totalement, plus de la moitié des nutriments contenus dans les fruits consommés par ces petits ménages agricoles seront perdus. En résumé, les ménages agricoles des pays en développement peuvent être affectés par la disparition des pollinisateurs, notamment en termes de revenus et de consommation de nutriments, car la consommation alimentaire de ces ménages dépend, dans une certaine mesure, de l'auto-approvisionnement en cultures riches en micronutriments. Par conséquent, ces ménages sont particulièrement exposés et sensibles au déclin des pollinisateurs.

Enfin, dans ce qui suit, nous présentons l'organisation de cette thèse. Cette thèse se compose de quatre chapitres.

Le chapitre 1 présente l'état de l'art de cette thèse. Ce faisant, il donne un aperçu des approches d'évaluation économique des bénéfices des pollinisateurs, des échelles spatiales des causes et des impacts du déclin des pollinisateurs, ainsi que des réponses politiques existantes concernant la dégradation des pollinisateurs. Plus précisément, il fait correspondre les préoccupations des parties prenantes aux décideurs qui influencent la gestion des pollinisateurs à différentes échelles. Ensuite, il décrit les interdépendances des phénomènes écologiques et économiques et la complémentarité des diverses réponses aux problèmes liés aux pollinisateurs.

Ces idées sont mises en pratique dans les trois chapitres indépendants suivants.

Le chapitre 2 évalue les impacts économiques et nutritionnels du déclin des pollinisateurs sur les consommateurs et les producteurs du monde entier, soulève de nouvelles questions sur la pénurie alimentaire mondiale et étend les approches d'analyse existantes. A partir de différentes bases de données mondiales et de revues de littérature (FAOSTAT ; Banque Mondiale ; Eurostat ; Klein et al., 2007, Chaplin-Kramer et al., 2014), nous mobilisons la méthode de simulation d'équilibre partiel de marché (rappelée au chapitre 1). Cette méthode implique de mesurer les variations relatives des prix du marché des cultures, de la demande et des quantités offertes qui peuvent résulter de changements marginaux dans les services de pollinisation par les insectes (e.g., Gallai et al., 2009). Plus précisément, nous utilisons l'approche de la fonction de production, qui intègre le ratio de dépendance de la production végétale aux pollinisateurs (i.e., Bauer et Wing, 2016), et prenons en compte les ratios de nutriments dans les cultures (voir Chaplin-Kramer et al., 2014). Sur cette base, nous estimons ensuite la variation relative de l'apport en nutriments due au nouvel équilibre du marché des cultures pour différents scénarios de déclin des pollinisateurs, ce qui constitue un aspect original de ce travail de recherche. Ce chapitre soutient que la crise de la pollinisation devrait être abordée comme une préoccupation collective entre les pays exportateurs et importateurs de cultures dépendant des pollinisateurs.

Le chapitre 3 examine la volonté du grand public de protéger la pollinisation des insectes et de conserver les espèces d'insectes pollinisateurs menacées à une échelle territoriale dans le territoire du Comminges, dans le sud-ouest de la France. Nous étendons les quelques analyses existantes sur la volonté de payer (Willingness to Pay, WTP) pour protéger les pollinisateurs en incluant plus de bénéfices des pollinisateurs (par exemple, la qualité nutritionnelle, l'existence des insectes pollinisateurs) dans notre évaluation que dans celles considérées dans les travaux précédents, car elles se concentrent uniquement sur les produits agricoles et les fleurs sauvages (par exemple, Breeze et al., 2015). À l'aide d'une enquête par expérience de choix, nous identifions les avantages locaux des pollinisateurs comme des attributs des pollinisateurs : la qualité et les variétés des fruits et légumes locaux, la diversité des fleurs sauvages et la " valeur d'existence " des insectes pollinisateurs. Cette dernière représente la satisfaction que les individus peuvent retirer du simple fait de savoir que les insectes pollinisateurs existent (i.e., Davidson, 2013). Ensuite, différents niveaux de ces attributs sont définis, et des scénarios de marché hypothétiques sont conçus. La volonté de payer a été estimée à l'aide d'un modèle logit mixte basé sur la théorie de l'utilité aléatoire. L'étude discute des implications de ces résultats sur les pratiques agricoles et les politiques publiques liées à la pollinisation et à d'autres services écosystémiques connexes.

Le chapitre 4 soulève de nouvelles questions sur les risques auxquels l'agriculture à petite échelle peut être confrontée en cas de déclin des pollinisateurs et propose une approche d'analyse quantifiant les effets de ce déclin sur la production agricole et la consommation nutritive des ménages agricoles. Plus précisément, nous avons mené une enquête auprès de ménages agricoles dans le district de Huye, dans le sud du Rwanda. Il s'agit d'une perspective de ménage dans un contexte particulier où la production et la consommation sont souvent liées. D'un point de vue analytique et théorique, nous nous sommes inspirés de la théorie des ménages agricoles développée pour la première fois dans des modèles économiques analysant l'interdépendance entre les décisions de maximisation de l'utilité et du profit des ménages agricoles (par exemple, Kuroda et Yotopoulos, 1978 ; Barnum et Squire, 1979 ; Dillon et Barrett, 2017 ; Chenoune et al., 2017). Cette théorie postule que le bien-être des ménages agricoles dans les économies en développement dépend de décisions conjointes de production et de consommation, étant donné que l'utilité de ces ménages est soumise à des contraintes de production agricole et de flux de trésorerie (revenus sur et hors exploitation). En raison de ces décisions conjointes de production et de consommation, le déclin des pollinisateurs aurait un impact simultané sur le revenu et la consommation alimentaire des ménages agricoles. Sur le plan analytique, notre analyse s'appuie sur l'approche de la fonction de production (rappelée au chapitre 1) en se référant au modèle de Gallai et al. (2009) qui mobilise la méthode du ratio de dépendance culture-pollinisateurs (définie au chapitre 1). Pour les aspects nutritionnels, nous basons notre analyse sur les ratios de nutriments développés dans Chaplin-Kramer et al. (2014) (c'est-à-dire comme dans le chapitre 2). Du point de vue de la collecte des données, pour identifier les impacts du déclin des services de pollinisation sur les ménages de petits exploitants agricoles, nous examinons de plus près leur production, leur approvisionnement et leur consommation alimentaires à l'aide d'une enquête par questionnaire. Nous soutenons que, dans les pays en développement, les politiques publiques devraient promouvoir des politiques de transformation de l'agriculture en tenant compte des caractéristiques des petites exploitations, qui pourraient être bénéfiques aux pollinisateurs (voir Garibaldi et al., 2016 ; Smith et al., 2017) et des conditions de vie des ménages agricoles à faible revenu.

Evaluating the Impacts of Pollinators Decline on Social Welfare at Different Spatial Scales

Economic and Nutritional Aspects

The decline of pollinators is of concern in many parts of the world. This thesis values the economic and nutritional impacts of their decline on human well-being in order to support decision-making. For the economic aspects, it focuses on both marketed and non-marketed benefits, and for the nutritional aspects, it integrates both quantitative and qualitative dimensions of nutrient intake. Three scales of analysis involving international trade, territories, and local landscapes in different contexts are examined alternately. In light of welfare economics, our analysis combines analytical approaches, field surveys, and simulations. Results show that the decline of pollinators threatens human well-being at local and global scales, as it jeopardizes worldwide food consumption, smallholder farm household livelihoods, and biodiversity. Thus, local decision-makers, national and international organizations, and the general public should work together to mitigate pollinator decline.

Keywords: Economic valuation, Ecosystem Service, Pollination, Well-being, Nutrition, Spatial Scales

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Évaluation des Impacts du Déclin des Pollinisateurs sur le Bien-être Social à Différentes Échelles Spatiales:

Aspects Économiques et Nutritionnels

Le déclin des pollinisateurs est préoccupant dans de nombreuses régions. Cette thèse évalue les impacts économiques et nutritionnels du déclin des pollinisateurs sur le bien-être humain. L'accent est mis sur les bénéfices marchands et non marchands et sur les dimensions quantitatives et qualitatives de l'apport en nutriments. Trois échelles d'analyse portant sur le commerce international, les territoires et les paysages locaux dans différents contextes sont tour à tour examinées. L'analyse combine des approches analytiques, des enquêtes de terrain et des simulations. Les résultats montrent que le déclin des pollinisateurs menace le bien-être humain à l'échelle locale et mondiale, car il met en péril la consommation alimentaire humaine, les moyens de subsistance des ménages de petites exploitations et la biodiversité. Les décideurs locaux, les organisations nationales et internationales et le grand public doivent donc travailler ensemble pour atténuer le déclin des pollinisateurs.

Mots clefs : Évaluation économique, Service Écosystémique, Pollinisation, Bien-être, Nutrition, Échelles Spatiales