Bees for Agriculture

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Abstract

Pollination services are an intermediate input in agricultural production. These services are threatened by external reasons such as pollution and diseases leading to a decline of colonies resulting in a shortage of pollination services all around the globe. As a result, it is critical to understand the influence of pollination on agricultural productivity. The elasticity of substitution between man-made inputs and pollination services is an essential measure to determining the long-run recognition of pollination services for agricultural operations in the context of neoclassical growth models.

I exploit the USDA database, which provides data on every input used in agricultural production at state level. The dataset for the analysis covers the years from 2000 until 2021 and most of the US states. In three out of four specifications, the elasticity of substitution estimates has a value smaller than one.

These estimated values are significant and have an adjusted R-squared value between 0.944 and 0.944 that supports the fit of the data to the model. These estimates indicate that the substitution of pollination services is limited. An important limitation of this thesis is the limited data available for pollination services. Multiple insects provide these services but, due to limited data, honey bee colonies in the USA are used as proxy for pollination services.

JEL Codes: Q15, O13, O11, O41, O44, O51, Q57, Y10
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1 Introduction

The world population has more than doubled since 1960, from 2.9 billion to more than 8 billion today (Roser et al., 2013). The growing population leads to increased demand for global agriculture production, which is successfully been met (Wik et al., 2008). This is impressive considering that the cultivated land increased by 30% while the agricultural output tripled during this period (Wik et al., 2008). However, high environmental costs had to be paid for several reasons (Tilman et al., 2001). The increase in agricultural land resulted in a loss of natural habitats (Hoekstra et al., 2005) and the degradation of complex natural ecosystems in agricultural landscapes (Tscharntke et al., 2005). Other environmental challenges, such as climate change, biotic invasions, and pollution, have undermined ecosystem services (ES) vital to human well-being to the degree where biodiversity has been severely damaged (Millennium Ecosystem Assessment, 2005; Bommarco et al., 2013; Hooper et al., 2005; Watson et al., 2011).

Environmental-friendly policies are essential to continue sustainable economic growth. Quantitative analysis to serve informed policy-making is essential in order to make rational choices and trade-offs concerning natural capital as choices between competing alternatives which implies that one has more value than the other. Therefore, ES should be included in traditional economics (Dasgupta, 2021; Costanza, 2020). This thesis focuses on integrating pollination services, provided by honey bees, in an agricultural production function. The main objective of using this production function is to estimate the elasticity of substitution between pollination services by honey bees, capital, and labour input. The general research question is therefore: *What is the degree of substitutability between pollination services by honey bees, and capital and labour inputs in the USA?*

This main research question is broken down by the following sub-research questions:

1. Are pollination services declining in the USA?
2. What is the degree of substitutability of pollination services with regard to capital and labour in the USA?
3. What are the implications for sustainable growth?

Biodiversity enables nature to be productive and should therefore be included in the financial system (Dasgupta, 2021). Hence, including ES in the economic models could help to manage and mitigate risks resulting from unsustainable engagement with nature. The importance of these ES, among which pollination services, are not represented by traditional economics and thus to less extent explored in current literature. Therefore, I will attempt in this thesis to estimate the elasticity of substitution of pollination services for man-made inputs labour and capital. This contribution starts by reviewing existing literature to better understand the role of pollination services and the role of substitution in the Constant Elasticity of Substitution (CES) production function that is typical for growth models which will address the first sub-question. Accordingly, a CES production function will be formulated by using USDA data on *capital*, *labour*, and *pollination services*. In total, four specifications will be formulated to check robustness. This analysis will provide an answer to the sub-question 2. Finally, I will take advantage of the existing growth model in the literature that incorporates ES as inputs to answer the third sub-question in light of my empirical results.

The USDA database (USDA, 2023b; USDA, 2023a; USDA and NASS, 2023) provide aggregate data for every input used in our agricultural production function. The data for the analysis concerns the year 2000 to 2021 and includes the larger part of the US states. In three out of four specifications, the elasticity of substitution estimates has a value < 1. These estimated values of the baseline model are significant and have an adjusted R-squared value between 0.944 and 0.944 that supports the fitness of the data inputs in the model. These estimates indicate the substitution of pollination services is limited. An important limitation of this thesis is the limited data available for pollination services. Multiple insects provide these services but, due to limited data, honey bee colonies in the USA are used as a proxy for pollination services.

There are limited studies that estimate the substitutability of pollination services. These existing studies focus on the substitution of other ES by analyzing the elasticity of the substitution of ecosystem services focused on consumption items and use a utility function (Baumgärtner et al., 2015; Drupp, 2018; Zhu et al., 2019). Only a few studies use the elasticity of substitution when analyzing ecosystems as an intermediate input. Several studies estimated the elasticity of substitution between ES and other inputs (Lee et al., 2019). In this paper, an attempt is made to estimate the effect of elasticity of substitution of pollination service for agricultural practices. The estimation of the substitutability of pollination services concerning both agricultural capital and labour is scarce in the literature. This could be used as a launching pad for other studies that are interested in the long-term cost and benefits of pollination services.

The paper is organized as follows. Section 2 provides a literature review to underpin the paper theoretically. Section 3 provides background information on pollination services and explores mechanical pollination possibilities. The fourth section discusses the dataset and the methods used to analyze the data. The results will then be discussed in section 5. Section 6 will contain a robustness analysis of the main model by a Cobb-Douglas-in-CES specification and the Kmenta approach. The discussion will be presented in section 7, presenting the limitations and recommendations. Finally, section 8 concludes.

2 Literature review

This section provides an overview of the literature on the main themes of the thesis. I start by presenting a literature review on the substitutability of pollination services. Next, the CES production function is introduced. Finally, discounting with scarce ecosystem services is discussed to create a better understanding of the long-term implications of declining pollination services.

2.1 Substitution of pollination services

A recurring discussion in sustainability literature is the use of an economic framework where natural capital is included. The work 'Blueprint for a Green Economy' by Pearce et al. (1994) is the first attempt to understand this concept in economic terms. After this work, the importance of substitutability to determine the policy with regard to natural resource conservation is discussed by multiple authors (Markandya and Pedroso-Galinato, 2007). Critics argue that wealth accounting of certain natural capital is only partly complete as it is difficult to grasp the complete value in monetary terms. Also, in various cases, it is impossible to substitute natural capital for manufactured goods (Markandya and Pedroso-Galinato, 2007; World Bank, 2005). Accounting wealth, including natural capital, is conducted with a production function. The base of the production function includes certain assets, such as labour and capital to create the level of output in certain combinations. Production functions are usually mathematical functions explaining the link between the included inputs. The extent to which input is substitutable is referred to as the elasticity of substitution. The elasticity of substitution is the ratio to which extent a decrease in one input is compensated by the increase in the other inputs given that the output of the function is constant. Therefore, the higher the elasticity, the easier to replace a certain input (Markandya and Pedroso-Galinato, 2007).

The degree of substitution of natural services is a reoccurring topic in the literature (Markandya and Pedroso-Galinato, 2007). Various economists argue that manufactured capital could substitute natural capital to a certain extent (Mäler, 1986; Reijnders, 2021; Cohen et al., 2019; Solow, 1986). Others argue that, when one wants to link substitution with nature, the sum of natural capital and manufactured capital should be constant (Solow, 1986; Arrow et al., 2004). Other economists, such as Goodland and Daly (1996), Pearce (1997), and Ayres (2007), argue that a critical level of natural capital should be conserved in order to sustain long-run growth.

Substitution of ES is may not be easy or even possible when it is being used as input. This is shown by a study of Zhu et al. (2019) where the Ramsey-growth model is used to analyse the role of ES in production. The economy will converge towards a steady state where all the inputs grow at an average growth rate $g*$ while the discount factor converges to state steady state following the Ramsey rule $r = \rho + \gamma g^*$. A decrease in these ecological services will result in less economic growth and a lower discount rate. They assume that man-made inputs have more growth capacity than pollination services, $g_P < g_H$, as pollination services are relatively more scarce over time than man-made inputs. The following equation solves the growth rate over time of input X:

$$g_x(t) = g_H - g_P/1 + he^{1-\rho/\rho(g_H - g_P)t} + g_P, h = \beta P_0^{\rho-1/\rho}/(1-\alpha-\beta)H_0^{\rho-1/\rho} \tag{1}$$

This equation shows that the g_X has two convergence options: (1) towards pollination services P if $\rho < 1$, or (2) towards man-made input H if $\rho > 1$. This would suggest that pollination services would decline if H could be substituted easily, converging economic growth towards the limit of H. On the other hand, if the substitution of H for P would not be easy, economic growth is restricted as pollination services are more scarce over time. Moreover, H_0 and P_0 determine the starting condition of g_X. In the long-run scenario of $\rho > 1$, g_X converges to g_P. This is close to the initial state of g_H if h is either close to 0 or $P_0 > H_0$. Being an (inverse) logarithmic growth curve, pollination services are initially substituted and as g_x comes close to g_H, it converges to g_P when pollination services become relatively scarce. In the long-run scenario if $\rho < 1$, pollination services will not become scarce due to substitution as g_X converges to g_H.

2.2 Constant Elasticity of Substitution production function

A relationship between factor inputs and output is described by a production function. It shows the maximum level of output given the input of the production factor.

The general form of a production function is:

$$Y = f(x_i) \tag{2}$$

where Y represents the total output, x represents the inputs i with $i = 1, 2, ..., n$. An important assumption is that the agent maximizes the profit with the highest output possible. Technology, such as knowledge and required skills, is needed to transform input into output (Frankel and Frankel, 1990).

Several variants of production functions are defined, each for different purposes. Technology is however a central factor in every production function (Cobb and Douglas, 1928). The production function can be estimated by minimizing the cost function (Shephard, 1954). A Cobb-Douglas function is often used as a production function (Cobb and Douglas, 1928; Zhu et al., 2019). Here, it is assumed that the substitution elasticity remains constant and is therefore not applicable to this study (Markandya and Pedroso-Galinato, 2007; Zhu et al., 2019). Another widely used production function is the Leontief function. The downside of this function is the assumption that goods are perfect complements.

However, the objective is to estimate the elasticity of the substitution of pollination services and traditional human-made inputs. A function which fits this purpose and allows for different elasticity rates is the CES production function (Markandya and Pedroso-Galinato, 2007). The CES production function is related to the neoclassical theory of economic growth (Klump and Preissler, 2000) and was contributed by Solow (1956). Arrow et al. (1961) built forth on this work which is considered as the standard specification of the model. The general CES production function is as follows:

$$Y = A(aK^{-\rho} + (1-a)L^{-\rho})^{-1/\rho} \tag{3}$$

In this function, Y is the output, a shows the shares of the inputs K and L which are the quantity of the capital and labour inputs respectively. The input share parameter a is restricted, $0 < a < 1$. Moreover, the efficiency parameter A should be larger than 0 (Kemfert, 1998) and is considered neutral with regard to Hicks (Klump and Preissler, 2000). The elasticity of substitution can be determined by $\sigma = \frac{1}{1+\rho}$. Here, ρ is the substitution parameter.

When $\rho \to 1$, indicates that two-factor inputs can be understood as complements. On the other hand, when substitution elasticity is positive, the two inputs can be understood as substituted. Furthermore, the elasticity of substitution allows us to understand the CES production function as a different production function (Markandya and Pedroso-Galinato, 2007; Zhu et al., 2019). When $\rho \to 0$, the CES function can be understood as a Cobb-Douglas function. Furthermore, the CES function will transform into a Leontief or perfect complement production function in case $\rho \to -\infty$ (Arrow et al., 1961). Furthermore, $\sigma > 1$ indicates that the inputs are good substitutes while $\sigma < 1$ indicates that inputs are poor substitutes (Black et al., 2009).

In order to include three inputs, this paper uses a nested CES production function which allows the evaluation of the market on a macroeconomic level. The properties of the two-level CES production function used in this paper follow from the general CES function that includes three inputs formed by Zhu et al. (2019):

$$F(P, K, L) = A(\alpha P^{\frac{\sigma-1}{\sigma}} + \beta(K^{\frac{\sigma-1}{\sigma}} + (1-\alpha-\beta)L^{\frac{\sigma-1}{\sigma}})^{\frac{\sigma}{\sigma-1}}) \tag{4}$$

The final agricultural production contains three inputs: *capital* K, *labour* L, and *pollination services* P are proxied by honey bee populations. Capital and labour are nested to test the substitutability of pollination services. Parameter A denotes the total factor productivity which measures the efficiency of the production process. The production shares of respectively capital, labour and pollination services are indicated by parameters α and β.

2.3 Discounting ecosystem services

Ecosystem services could be understood as the benefits obtained from the ecosystem. This comes in different forms, such as structures, functions, and processes contributing to human well-being (Millennium Ecosystem Assessment, 2005). ES could be subdivided into three main services: provisioning services such as food and water, regulating services such as flood and climate control, and cultural services such as enjoyment or spiritual fulfilment (Baumgärtner et al., 2015). According to the Millennium Ecosystem Assessment (2005), 60% of ES worldwide is declining, while the gross domestic product is still growing.

Environmental discounting is used in public cost-benefit analyses to compare ES to other inputs like capital and labour (Baumgärtner et al., 2015; Zhu et al., 2019). The discount rate is central in the debate with regard to the efforts to fight climate change as it is considered crucial to understanding the long-term effects on nature (Gollier, 2010). Discounting is economically justified by a wealth effect (Ramsey, 1928). The main thought behind Ramsey's theory is that future generations obtain more wealth than present generations. This would imply that a unit of consumption now is more valuable than it would be in the future when the marginal utility of consumption is decreasing. The discount rate in literature is often positive due to two main reasons: (1) society is impatient and would prefer a unit of consumption now over a unit of consumption in the future and (2) it is considered fair that consumption is spread over time and generation as these generations are likely to be richer than us (Dasgupta, 2008)

Moreover, opportunity costs increase when production assets are not used immediately (Pearce et al., 2006; Dasgupta, 2008). However, this does not hold when the quality of the environment, or pollination services in this case, is considered. Biodiversity is for example declining which leaves less biodiversity for future generations. This would imply that, when there is evidence that the quality of the environment is declining over time and the assumption is made that the marginal utility of the environment's quality is decreasing, investments in environmental quality are more valuable for future generations than for present generations. Currently, the calculated discount rates without market prices, such as ES, are too high on average (Baumgärtner et al., 2015; Koetse et al., 2008). Therefore, the value of ES should relatively be increased for other factor inputs (Baumgärtner et al., 2015). Another option would be to include time-declining discount rates (Zhu et al., 2019).

3 Background information

This section provides background information on pollination services. Moreover, natural pollination and mechanical pollination are discussed to provide a better understanding of the importance of ecosystem services.

3.1 Pollination services

Pollination service is one of the ES that is critical to human survival (Kremen et al., 2002; Millennium Ecosystem Assessment, 2005). Pollination by wild animals is an essential element of the sexual reproduction of various crops and wild plants (Kremen et al., 2002). Plant species can decline parallel with pollinating species when these decline in population seize (Biesmeijer et al., 2006). One of the most economically valuable pollinators of crops is honey bees (Rucker et al., 2012b). Especially the European honeybee, in specific the Apis mellifera, is worldwide used to pollinate monoculture crops and is responsible for a growing proportion of food production worldwide (McGregor, 1976; Watanabe, 1994; Gallai et al., 2009; Klein et al., 2007). A decrease in the honey bee population could lead to a lower yield of certain seeds, nuts and fruits of almost 90% (Southwick and Southwick Jr, 1992).

An important reason for the declining wild bee population is the fragmentation and deterioration of near- and semi-natural habitats (Kremen et al., 2002; Kremen et al., 2004; Larsen et al., 2005). According to Klein et al. (2007), there are four main reasons why this occurs: pests like parasitic mites such as the Varroa destructor (Downey and Winston, 2001), the small hive beetle (Evans et al., 2003), and microsporidian parasite Nosema ceranae (Higes et al., 2006) (1); the use of both pesticides and herbicides (Ingram et al., 1996) (2); beekeeping is a declining profession in the EU and the USA (3); and finally a decreasing price of supplied goods and services (4) (Klein et al., 2007).

The number of managed colonies is however declining in various parts of the world. Honey bee populations are increasing on a global scale while populations in Europe and North America are declining (vanEngelsdorp and Meixner, 2010). A shortage of wild bees on agricultural sides can be compensated with managed honey bee colonies. Honey bees are not the most effective pollinator for every crop (Klein et al., 2007). On average, 75% of crop species utilized as food rely at least somewhat on insect pollination (Klein et al., 2007). Moreover, 52 of the leading 115 food items in the world depend on honey bee pollination to produce fruit or seeds (Klein et al., 2007). A significant improvement in general knowledge of the advantages of animal pollination to agricultural yields has resulted from more than ten years of pollination research (**e.g**; Klein et al., 2007; Garibaldi et al., 2011; Garibaldi et al., 2013). Increased numbers of pollinator-dependent crops are grown for food, fuel, fiber, and micronutrients which are vital to human health (Rader et al., 2016).

The dependency on insect pollination differs per crop. Important factors are the degree of self-fertility, morphology and the arrangement of plants. The imperfect crops, that separate male and female flowers, are most dependent on insect pollination. Perfect plants, that have both male and female flowers, can optimize efficiency by insect pollination. The most insect pollination depended on crops in the USA are highbush blueberry (Vaccinium corymbosum), apple (Maluspumila), sweet cherry (Prunus avium), tart cherry (Prunus cerasus), almond (Prunus dulcis) (Klein et al., 2007; Reilly et al., 2020). Moreover, Southwick and Southwick Jr (1992) found a high dependency on pollination insects of asparagus seed, sunflower, and cabbage seed too.

The economic advantage of this benefit is estimated to be €153 billion yearly, or 9.5% of the value of agricultural products worldwide (Gallai et al., 2009), demonstrating the significance of the ecosystem services that pollinators provide (Dasgupta, 2021). When the aggregate values of nature's values are considered, the critics could ask whether it is worth restoring populations. An example is given by Dasgupta (2021) regards agricultural production. Pollination contributes £510-690 million to agricultural production yearly, which seems like a significant value. On a national level, this is around 5% of the total agricultural output and 0.03% of the GDP. However, because proportionate figures do not indicate value, we should not devalue pollinators as pollinator projects are only included with their accounting prices in national assessments (Dasgupta, 2021). Moreover, besides the provision of ecosystem service by crop pollination, bees pollinate more than 16% of the flowering plants worldwide (Buchmann and Nabhan, 1996). Natural ecosystems profit from bees as plants grow that reduce erosion risks, create an environment that can be enjoyed by humans, and increase property value. Moreover, the pollinated plants provide food for other animals in the food chain (Delaplane and Mayer, 2022).

3.2 Mechanical vs natural pollination

3.2.1 Natural pollination

Pollination is an essential part of plant procreation. The flower is designed for sexual reproduction which exists in various inflorescences types (Wardhaugh, 2015). Within these flowers, the main stem is called peduce and while the other stems are pedicles. The corolla protects the sexual interior as being the outer petals of the flower. The stamens are male flower elements made consisting of a short filament bearing an anther at the tip. When the anther matures, it opens and releases pollen grains. The female components of a flower are termed the pistil, and each one consists of an ovary with ovules and a stalk-like style with a sticky stigma on top. Some of the released pollen land on a receptive female stigma. Then, a pollen tube is grown towards the ovary allowing the pollen to fertilize and ovule. These ovules develop into seeds and the surrounding develops into fruit also known as fruit-set. Fruit-set is not guaranteed after a pollination round as there are various bottlenecks along the way. A shortage of pollinator populations or bad weather could prevent pollination. The pollination method differs per flowering trend and is as follows: cross-pollination, self-fertile, self-sterile, monoecious, and parthenocarpic

(Delaplane and Mayer, 2022).

Insects collect pollen as food by visiting flowers. The majority of pollination insects are flies, beetles, and bees. Beetles and flies are expected to be the largest group with regard to species richness (Wardhaugh, 2015; Grimaldi and Engel, 2005). Bee-pollinated flowers and bees are however depending on each other (Delaplane and Mayer, 2022). They own characteristics such as plumose hairs that pick up pollen, feeding pollen to their larvae, and a broader first foot segment that functions as a pollen basket (Delaplane and Mayer, 2022; Michener, 2000). Both act however selfishly as the benefits must be higher than the costs of the cooperation. Nectar is offered by flowers to attract pollination insects. The production of nectar costs the plants however a lot of energy. Therefore, this production should be a balanced return with regard to successful reproduction. From a bee's perspective, travelling and working are energy extensive and must be beneficial with regard to nectar yield (Delaplane and Mayer, 2022; Southwick et al., 1981). Pyke et al. (1977) found that bees tend to travel less and spend more time when flower patches contain a rich amount of pollen and nectar. The bees move rapidly between the flowers with a higher rate of pollination as a result. Moreover, bees tend to visit these food sites more often (Southwick et al., 1981) and fly shorter distances (Pyke, 1978).

3.2.2 Mechanical pollination

The agricultural industry in certain regions cannot rely on natural pollinators to pollinate the crops. Therefore, production prices are increasing as honeybee colonies must be rented to meet the demand for the pollination of monoculture crops (Watson et al., 2018) which is also the case for the USA (Reilly et al., 2020). According to Broussard et al. (2023), the supply of hives during the pollination window is limited due to the following reasons: (1) the increase in the extreme weather events resulting in the destruction of hives and resources (Chaffer, 2020); (2) transportation of the beehives is limited (Bixby et al., 2020; Attia et al., 2022); (3) loss of colonies due to pesticides (Tosi et al., 2022); and (4) competing producers for the available hives (Rucker et al., 2012a). Due to the declining pollinating insects, among which the honey bees, scientific interest with regard to artificial plant pollination is upcoming (Nimmo, 2022; Broussard et al., 2023; Mashilingi et al., 2022).

Two main challenges arise with regard to artificial pollination as a result of the different quantities of pollen required differ per species and pollination method: the collection of inexpensive but high-quality, and prevent the waste of as much pollen as possible (Nimmo, 2022). Some trees, such as wind-pollinated trees, produce large amounts of pollen which are relatively easy to collect while other crop species produce less pollen and are therefore more difficult to collect (Broussard et al., 2023; Vaknin et al., 1999). The best moment to collect pollen is prior to the anthesis window to prevent the loss of pollen (Pinillos and Cuevas, 2007). According to Broussard et al. (2023), there are three main approaches to collecting pollen: (1) the collection of pollen by hand-picking or mechanically, (2) extracting pollen directly from flowers, and (3) pollen traps attached to bee hive entrance to collect pollen from bees. The collection of pollen by hand can be easily done when the crop either produces copious quantities of pollen (Salomón-Torres et al., 2021) or is wind-pollinated (Zeraatkar et al., 2013; Ascari et al., 2017; Ahı Koşar et al., 2023). Plants pollinated by insects produce usually less pollen. These entomophilous plants make the collection of pollen harder. Pollination of these plants could be done manually by excising the anthers from each individual flower. This is however a very labour-intensive production method making it only economically relevant for small-scale production. Production on a larger scale is possible too by separating the pollen from whole flowers mechanically. This is possible for multiple crops such as Almond (Pinillos and Cuevas, 2007; Gianni and Vania, 2018; Salomón-Torres et al., 2021). Before separating the pollen by vacuum, flowers are dried and milled to separate the anthers where both anthers and pollen are dried again (Broussard et al., 2023). Rising labour costs drive the development of mechanical harvesting techniques. However, these techniques are relatively expensive for certain crops (Broussard et al., 2023; Salomón-Torres et al., 2021). To reduce costs, interest arose in pollen collected by honey bees. This pollen includes some impurities due to pollen being mixed with nectar nut trials on several crops such as almond (Cunningham et al., 2020) and fruits like kiwi, apples and pears (Pyke and Alspach, 1991; Parker et al., 2015; Okada et al., 1983; Johansen, 1956). It was found that fruit drop was higher while the fruit weight was lower when plants were pollinated with bee-collected pollen instead of pure pollen. Moreover, this method currently is not being used on a larger scale (Broussard et al., 2023). Another method to collect pollen is vacuuming the crop directly obtaining a higher yield than other methods in general (Pinillos and Cuevas, 2007). This can either be by hand-held as mechanised devices (Baldet, Philippe, et al., 1993). Harvested and processed pollen could be stored in cold circumstances (Dinato et al., 2020; Salomón-Torres et al., 2021).

The application of pollen to pollinate the crop is the next phase. There are two main approaches. The first approach is to apply the pollen dry. An advantage of this method is that dry pollen remains viable for a longer period of time than wet pollen and can be redistributed by bees (Broussard et al., 2023; Thomson and Eisenhart, 2003). Secondly, pollen can be applied wet. Here, the pollen is mixed with aqueous liquid and ensured isotonic balances. The advantage of this approach is the increased target delivery when pollinator insects are limited (Gianni and Vania, 2018). Moreover, the wind is not able to disperish the pollen due to the liquid mass. Within these approaches, several methods to pollinate crops could be used: (1) hand-pollination (2) hand-held devices, (3) Vehicle-mounted devices, (4) unmanned aerial vehicles (UAVs), and (5) robotics and autonomous pollination (Broussard et al., 2023). There is an increasing focus on both drones and robotics. Several challenges have to be tackled before these solutions make them attractive for wide commercial use with an exception for some crops such as walnut, tomato and hybrid maize seeds (Broussard et al., 2023). It has been argued that mechanical pollination could replace living pollinators by reducing pollination ecology into an economic function. Moreover, they expected to achieve higher pollination efficiency than living pollinators. However, these machines still have to overcome key challenges to replace living pollinators. According to Nimmo (2022), this confidence comes forward from confident expectations of progress. These methods can not compete with actual pollinator insects as these work non-stop and with large amounts. With the decline of pollinator insects, they are used as supplementary devices to bees when conditions are not optimal. Mechanical pollination should replace human labour when living pollinators are lacking given that the price of mechanical pollination is lower than labour.

4 Data and Methods

4.1 Data

Data sets from the USDA are used to estimate the elasticity of the pollination services in the US. Aggregated time panel data for capital and labour is drawn from the USDA (2023a) concerning the period 2000 to 2021. Nominal aggregated agricultural labour expenses per state represent labour input. The choice to use labour expenses as a proxy for labour inputs was made because it creates a good understanding of the magnitude of the labour expenses per state in the agricultural sector. Both cash and non-cash labour expenses are included in total labour expenses. Herein, cash labour expenses are the sum of contract and hired labour. Non-cash labour exists out of cash values of commodities and other payments for farm work which is provided for hired labour, including among others: feed, fuel, housing, etc (McGath et al., 2009).

Aggregated agricultural capital consumption per state represents the capital input and is retrieved from the USDA (2023b). Capital consumption per state is the estimated cost of capital within its useful service time that is used in agricultural production. The estimation of these costs is done for each year's production and could be understood as compensation for the maintenance of the capital stock. Capital consumption is estimated for multiple capital items such as trucks, tractors, farm machinery and operator dwellings. The capital stock, which is the undepreciated aggregate of capital expenditure, is maintained for each type of asset. The final calculation for the estimate is done by multiplying the capital stock with a certain percentage matching the asset's average service life (USDA, 1988; McGath et al., 2009).

As discussed in section 3, the honey bee provides considerable value to agriculture since they are dedicated to flower feeding. Therefore, honeybees are used as a proxy for pollination services. Aggregated time series data of honey-producing colonies, retrieved from the USDA, from 2000 to 2022 is used (USDA and NASS, 2023). To be specific, this is the maximum number of colonies that produced honey which was harvested. Honey can be harvested from colonies that did not survive the whole year. The choice for this physical input was made because it is, in this USDA data, the only variable that directly explains the magnitude of the honey bee population. Table 1 summarizes the variables. The data set exhibits 900 observations from 44 states. Capital and labour values are both nominal and corrected for inflation by the US Bureau of Economic Analysis. Price Index for Gross Domestic Product (USDA, 2023b; USDA, 2023a).

Table 1: Variables Description and Unit of Measurement

Variable	Description	Unit of Measurement
Labour	Total labour expenses, including operator dwellings	In \$1000 (Nominal)
Capital	Capital consumption, including operator dwellings	In \$1000 (Nominal)
Pollination services	Honey producing colonies	×1000

4.2 Methodology

The empirical specification of the CES function used to estimate the elasticity of substitution builds forth on functions (3). The baseline specification, similar to the method of Papageorgiou et al. (2017), is selected to identify the substitution parameter ρ between the capital-labour nest and pollination services. Then, the elasticity of substitution σ can be calculated. Moreover, neutral technical change and production shares are assumed. In the ideal scenario, all the relevant inputs would be included. To cover this, the data input is from a national database collecting data by census and covers important aspects of both production and labour costs. Specified to calculate for gross output of the agricultural sector in the USA, the CES specification with equal production shares and neutral technical change is:

$$Y_{it} = A + a_i + a_t + \frac{1}{\rho_{(KL)P}} * ln(\delta((\beta K_{it}^{\rho_{KL}} + (1+\beta) * L_{it}^{\rho_{KL}})^{\frac{\rho_{(KL)P}}{\rho_{KL}}} + ((1-\delta) * P_{it}^{\rho_{(KL)P}})) + \epsilon_{it}. \quad (5)$$

Here, Y_{it} represents the agricultural output in state i in year t, A represents the factor-augmenting technology parameter, L_{it} is the labour input, K_{it} is the capital input and P_{it}. The production shares are the weights within the capital-labour nest β, and between the capital-labour nest and pollination δ. The initial values in the model of the production values are kept at 0.5 respectively. The choice for neutral production shares is for simplicity reasons as more research is needed to decide what the exact production shares within and between the inputs are.

Moreover, the initial value of the technology parameter A is kept neutral at 1 assuming endogenous growth. Furthermore, the initial value of $\rho_{(KL)P}$ is kept at 0.5. This suggests that pollination is a poor substitute for man-made inputs which is in line with the necessity of pollination described by the background literature. Finally, the initial value of ρ_{KL} is set at 1 meaning that capital and labour have an elasticity which is indifferent.

The estimation of the elasticity of substitution between pollination services and traditional man-made inputs is represented by $\sigma_{(KL)P}$. Here, $\sigma_{(KL)}$ is the elasticity of substitution between the capital-labour aggregate. The production function is nonlinear in ρ and the elasticity within the capital-labour aggregate is σ_{KL} is nonlinear too. Because the man-made inputs are aggregated, the main focus of this study is on $\sigma_{(KL)P}$ instead of the elasticity of substitution of man-made inputs $\sigma_{(KL)}$. The substitution elasticities can be estimated by:

$$\sigma_{(KL)P}=\frac{1}{1+\rho_{(KL)P}} \tag{6}$$

or

$$\sigma_{KL}=\frac{1}{1+\rho_{KL}} \tag{7}$$

Furthermore, the model includes two fixed inputs d_i which represents the dummy variable for *state* fixed inputs and d_j represents the dummy variable for *state* fixed inputs. The baseline specification includes both *year* and *state*. In order to check the robustness of the model, three other specifications are tested: neither *year* nor *state* is included, only the *year*, and finally only *state*. Modifying the model by adding or removing regressors creates the opportunity to examine how the core estimates behave as an indication of the structural validity of the model (Lu and White, 2014). According to growth theory, the main aim is not to analyse the influence of input on price increases. The aim is to determine if pollination is a critical input for agricultural objectives.

5 Main Results

The CES function in equation (5) is estimated for the agricultural sector in the USA. The output is measured as the total production of the agricultural sector. A nonlinear least squares estimation is applied, which uses nonlinear optimisation techniques to determine values for the parameters that minimise the residual sum of squares and estimate confidence intervals for these estimations.

Equation (5) is run for four different specifications. Table 2 shows the estimated results for the substitution parameter and substitution elasticity for the different specifications. In the first specification, neither *year* nor *state* fixed effects are included. The substitution parameter between pollination and man-made materials is around -0.153. This implies that the elasticity of substitution between pollination and man-made materials is 0.868. Both estimation values are significant as a p-value of 0.000 indicates that these are precise estimates. And it is statistically smaller than one. From the growth theory perspective, this would suggest that pollination is a poor substitute for man-made materials. The second specification includes only *year* fixed effects. The substitution parameter is 0.021 leading to a substitution parameter between pollination and man-made materials of 1.022. This implies that pollination could be substituted for man-made materials as $\sigma_{(KL)P} > 1$. However, the standard error for the substitution parameter is relatively large while the z-value is relatively small resulting in an insignificant estimate. Furthermore, it is not statistically different from 1. The estimate of the elasticity is on the other hand significant and includes a relatively small standard error. Specification three includes only the *state* fixed effects. This results in a $\sigma_{(KL)P}$ of 0.837 and $\rho_{(KL)P}$ of 0.021 and both of these estimates are significant. In the fourth specification, which is the main specification, both *year* and *state* fixed effects are included. The elasticity of substitution is around 0.806 and a substitution parameter of -0.240 with a small p-value. Moreover, the adjusted R-squared values in all specifications are between 0.944 and 0.984 implying therefore a good fit of the inputs in the model. Also, the model seems to behave somewhat similarly to each specification indicating a certain level of robustness.

Three out of four specifications show pollination and man-made inputs are poor substitutes. In the context of growth theory, considering the four specifications, this would indicate that both inputs are complementary and thus both necessary in the agricultural production processes.

Table 2: Estimation results (NLS)

	(1)	(2)	(3)	(4)
$\sigma_{(KL)P}$	0.868	1.022	0.837	0.806
s.e.	(0.003)	(0.209)	(4.68e-11)	(0.0002)
z	265.68	4.88	1.8e+10	344.00
$P > \|z\|$	0.000	0.000	0.000	0.000
$\rho_{(KL)P}$	-0.153	0.021	-0.194	-0.240
s.e.	(0.004)	(0.201)	(6.67e-11)	(0.004)
z	-35.17	0.11	-2.9e+09	-66.60
$P > \|z\|$	0.000	0.916	0.000	0.000
Year ID	No	Yes	No	Yes
State ID	No	No	Yes	Yes
N	900	900	900	900
Adj R^2	0.944	0.955	0.978	0.984

6 Robustness Analysis

Although the CES production function can estimate the elasticity of substitution and robustness is checked by constructing the model in four varieties, robustness is checked by two other methods. First, a production function for the agricultural sector is formulated. Assuming neutral technical change, the following regression is obtained:

$$lnY_{it} = a_i + d_{it} + \frac{1}{\rho}ln(\delta P_{it}^{\rho} + (1-\delta)X_{it}^{\rho} + \epsilon_{it} \quad (8)$$

Here, Y_{it} represents the agricultural output in state i in year t, and X_{it} is the aggregate of labour and capital. The production shares are represented by δ and a_i is the technical change controlled via state-fixed effects. Finally, d_t presents the dummies for each year. Again, the elasticity of substitution is obtained by $\sigma = \frac{1}{1-\rho}$ where ρ is the substitution parameter.

The first check for robustness is conducted by assuming unitary elasticity of substitution between pollination service P and man-made inputs X. The Cobb-Douglas-in-CES specification features aspects of the Cobb-Douglas and CES production functions which allow the elasticities and shares parameters to be combined. This allows for more flexibility in modelling production relationships by capturing different degrees of substitutability between different inputs. This results in the following Cobb-Douglas-in-CES specification:

$$lnY_{it} = a_i + d_t + \frac{1}{\rho} ln(\delta P_{it}^{\rho} + (1-\delta)(K^{\beta}L^{1-\beta})_{it}^{\rho}) + \epsilon_{it} \quad (9)$$

β represents the distribution within the man-made inputs aggregate. The results of the Cobb-Douglas-in-CES specification are presented in table 3. Except for scenario 1, the elasticity estimates are significant with relatively small standard errors. The elasticities are smaller than 1 indicating that pollinating services are poor substitutes for man-made materials. The estimation of the substitution parameters seems however more challenging as standard errors are relatively high with large p-values indicating that the estimates are insignificant. Moreover, the adjusted R^2 are located in an acceptable range indicating a sufficient goodness of fit.

Table 3: Cobb-Douglas-in-CES specification

	(1)	(2)	(3)	(4)
$\sigma_{(KL)P}$	-0.138	0.881	0.962	0.968
$s.e.$	(-)	(0.251)	(0.061)	(0.242)
z	-	3.50	15.83	4.00
$P > \|z\|$	-	0.000	0.000	0.000
$\rho_{(KL)P}$	8.254	-0.135	-0.039	-0.033
$s.e.$	(-)	(0.324)	(0.066)	(0.258)
t	-	-0.42	-0.59	-0.13
$P > \|t\|$	-	0.679	0.556	0.898
Year ID	No	Yes	No	Yes
State ID	No	No	Yes	Yes
N	900	900	900	900
$Adj R^2$	0.944	0.956	0.981	0.984

The second robustness method to the nonlinear regression is the Kmenta approximation (Kmenta, 1967). The non-linear Kmenta model is used for estimating the parameters of the relationship between one or more independent variables and a dependent variable.

Compared to linear models, this form of model allows for more flexible and complicated connections between variables. This is a translog function variation that represents the first-order condition of equation (8) with the substitution parameter $\rho = 0$. This formula is as follows:

$$lnY_{it} = a_i + d_t + \delta lnP_{it} + (1-\delta)lnX + (1-\delta)\frac{\rho}{2}(lnP - lnX)^2 \tag{10}$$

δ represents the distribution between pollination services and man-made inputs. The results are presented in table 4 and show small elasticities of substitution when $\rho = 0$. All four specifications show elasticity of substitution smaller than 1. Stata did not calculate the standard errors and the p-values and are therefore not provided. The Adjusted R^2 values are again close to 1 indicating a sufficient goodness of fit.

Table 4: Kmenta approach with $\rho = 0$

	(1)	(2)	(3)	(4)
$\sigma_{(KL)P}$	0.628	0.715	0.477	0.541
ρ	-0.592	-0.0399	-1.098	-0.847
Year ID	No	Yes	No	Yes
State ID	No	No	Yes	Yes
N	900	900	900	900
Adj R^2	0.947	0.952	0.979	0.984

Expression (9) can be rewritten per capital units indicated by lowercase variables normalized by dividing Y_{it} and P_{it} by X in the following equation:

$$lny_{it} = a_i + d_t + \beta_1 lnp_{it} - \beta_2 lnp_{it} + \epsilon_{it} \tag{11}$$

Parameter $y_{it} = \frac{Y_{it}}{X_{it}}$ expresses the per capital units. Here, y_{it} represents the agricultural output for each state i and year t per man-made input. Furthermore, p_{it} can be calculated by $\frac{P_{it}}{X_{it}}$ and represents per capital unit of pollination. The CES parameters can be calculated by:

$$\sigma = \beta_1(1-\beta_1)/(\beta_1(1-\beta_1) - 2 * \beta_2) \tag{12}$$

where $\beta_1 = \delta$ is the distribution parameter between pollination services and man-made inputs and β_2 can be calculated by $y = \frac{2}{\beta_2}$.

The results are presented in table 5. The translog function has the disadvantage that the two-input elasticities converge to one for large input ratios. Moreover, the conditions for a neoclassical production function are only locally satisfied. The elasticity of substitution tends to bias elasticity parameters of CES towards 1 when ρ is around zero (Papageorgiou et al., 2017), which is in line with the results. The estimations of β_1 are significant but the estimations of β_2 are, excluding specification 3, insignificant indicating that.

Table 5: Kmenta in per capital units

	(1)	(2)	(3)	(4)
$\sigma_{(KL)P}$	1	1.001	1.046	1
$s.e.$	(-)	(0.020)	(0.025)	(-)
z	-	49.87	41.35	-
$P > \|z\|$	-	0.000	0.000	-
β_1	15.659	16.68868	15.033	12.721
$s.e.$	(0.453)	(3.380)	(2.365)	(0.638)
t	34.55	4.94	6.36	19.95
$P > \|z\|$	0.000	0.000	0.000	0.000
β_2	-9.59e-10	-0.168	-4.678	-2.51e-11
$s.e.$	(14.069)	(2.689)	(0.925)	(5.823)
t	-0.00	-0.06	-5.06	-0.00
$P > \|z\|$	1.000	0.950	0.000	1.000
Year ID	No	Yes	No	Yes
State ID	No	No	Yes	Yes
N	900	900	900	900
Adj R^2	0.932	0.935	0.970	0.983

7 Discussion

The elasticity of substitution between pollination and man-made materials is of great concern for the agricultural sector due to the decrease in bee populations, especially in the EU and the USA. Therefore, this thesis undertakes an attempt to estimate the elasticity of substitution between man-made inputs and pollination services. The elasticity of substitution below 1 suggests that pollination is a necessary input to create long-run growth for the agricultural sector. Even if a neutral or endogenous directed technical change is assumed, the substitution parameter has a fundamental impact on long-term growth. The empirical results support that the elasticity between pollination and man-made inputs recede 1 significantly. Therefore, the first piece of econometric evidence is presented that provides an indication of the importance of pollination services.

The estimations are interesting but should be handled with care as the empirical estimation is not without limitations. To estimate the pollination services, the number of production colonies is used. As discussed in the background information, various species contribute to the pollination of crops (Klein et al., 2007). Although the sample contains 900 observations, honey bees do not represent pollination services by themselves and are therefore a limited proxy for pollination services. This would suggest that the total production values of pollination services are underestimated. However, it is also confirmed by literature that honey bees are the most valuable pollinator because they are widely used for agricultural pollination. Therefore, honey bees are considered a valid proxy.

Furthermore, man-made inputs labour and capital are partly represented by the data. In an ideal scenario, every aspect of labour and capital input would be included. These two inputs are covered by 'total labour expenses' and 'capital consumption'. Especially capital might be underestimated compared to labour as the total expenditures on labour are used as a proxy while total capital expenses are only partly included. However, the choice for these proxies is made because both contain some of the key elements which provide an understanding of the magnitude of both inputs.

Some critical notes could be placed on the model used to estimate the parameters. Neutral technical change has been assumed. But, according to the literature, there is a lot of interest to develop new technical pollination methods that could be of increasing significance in future crop pollination. This could indicate a larger growth potential for the agricultural sector. Although technical change can be expected, it is held neutral to imply endogenous growth leading to an underestimation of growth of the agricultural sector. However, it has been established that technology is complementary to natural pollination. Finally, the R^2 values are within the acceptable goodness of fit band which suggests that the data fits the model well. However, it could also indicate multicollinearity. This might occur due to the combination of aggregated data including time series and growth per state (Papageorgiou et al., 2017). The consequence would be that the explanatory variables might not be precisely estimated. In addition, dummy variables tend to be correlated with one another, particularly with multiple categories. This can lead to multicollinearity, which makes interpreting the individual effects of the multiple categories on the dependent variable challenging due to overestimated standard errors and unstable coefficients (Frost, 2023).

This thesis presents an analysis of a first attempt and a point of reference for the elasticity of pollination services. Future research may use this as inspiration. The elasticity of substitution is an important parameter to get a better understanding of discounting rates which explains the growth rate over time. Interesting follow-up research might be to test the results of this thesis with other estimation approaches. In the background information, it has been discussed that crops have co-evolved with different pollinator species. The effectiveness of honey bee pollination differs therefore per crop. Generalization of the results to all the crops should be carefully handled because crops are not independently examined. Moreover, including data which includes the added value of other pollinators, such as wild bees, might be interesting to create a more in-depth and comprehensive understanding of the elasticity of substitution. Furthermore, this thesis could serve as a launching pad for researchers interested in the growth rate of the agricultural sector or who want to identify the long-term costs and benefits of honey bee colonies to estimate their corresponding values. Also, using the constructed data source, the elasticity of substitution of pollination per state can be evaluated to get a better understanding of the state's dependency on pollination services.

8 Conclusion

Pollination services are an intermediate input in agricultural production. These services are threatened by external reasons such as pollution and diseases leading to a decline of colonies resulting in a shortage of pollination services in certain places. Therefore it is crucial to understand the importance of pollination for agricultural production. The elasticity of substitution between man-made inputs and pollination services represents an important parameter, within the context of growth models with neoclassical production functions, in assessing the conditions necessary to long-run recognition of pollination services for agricultural practices. In this thesis, I present the econometric evidence of elasticity on a macroeconomic level.

This contribution started by reviewing existing literature to create a better understanding of the role of pollination services and the role of substitution in CES functions that are typical for growth models. Equation (3) leads to the production function shown in equation (5) that can be used in econometric analysis to estimate the elasticity of substitution. Moreover, using the USDA data, a data set is constructed by combining the USDA data including capital, labour, and pollination input. These inputs are combined for 45 different states from 2000 to 2021. Finally, evidence is presented that man-made materials in the form of a capital-labour nest are a poor substitute for pollination services.

The elasticity of substitution estimates has a value < 1 in three out of four specifications. These estimates are significant and have an adjusted R-squared value between

0.944 and 0.944 that supports the fitness of the data inputs in the model. In the context of growth economy, this indicates that both inputs are necessary for agricultural production in the USA. As $\rho < 1$ in every specification, it is suggested that pollination would not become scarce in the long run.

Thus, pollination services seem a necessity for agricultural practices and should be used complementary to man-made inputs. If pollination would have been an ordinary economic input, it would not become scarce over time. However, due to all sorts of external threats, it might not be within the power of the market to decide the fate of pollination services.

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Table 6: Estimation results

	(1)	(2)	(3)	(4)
$\sigma_{(KL)P}$	0.868	1.022	0.837	0.806
s.e.	(0.003)	(0.209)	(4.68e-11)	(0.0002)
z	265.68	4.88	1.8e+10	344.00
$P > \|z\|$	0.000	0.000	0.000	0.000
$\rho_{(KL)P}$	-0.153	0.021	-0.194	-0.240
s.e.	(0.004)	(0.201)	(6.67e-11)	(0.004)
z	-35.17	0.11	-2.9e+09	-66.60
$P > \|z\|$	0.000	0.916	0.000	0.000
Year ID	No	Yes	No	Yes
State ID	No	No	Yes	Yes
N	900	900	900	900
Adj R^2	0.944	0.955	0.978	0.984