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The Economic Value of Pollination Services for Seed Production: A Blind Spot Deserving Attention

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Abstract

Animal-mediated pollination is important for agricultural seed and crop production, and critical to overall ecosystem health. However, the scientific literature focused on the economic valuation of pollination services has thus far neglected the role of pollination services in seed production. The marketed food output of many crops is not dependent on pollination services, but these crops indirectly depend on pollination services with respect to their seed production. This study proposes a partial equilibrium framework for identifying the value of pollination services. Using Germany as a case study, we find the value of pollination services is about 33% higher when seed production is considered. This increased valuation is driven by two effects: higher seed costs due to high dependence on pollination services, and a higher demand for seeds due to the land expansion needed to mitigate a potential pollinator collapse. This study demonstrates that more sophisticated approaches are needed to estimate the economic value of pollination services more accurately.

Keywords Ecosystem services · Economic valuation · Pollinator declines · Seed production · Partial equilibrium analysis · Biodiversity

1 Introduction

Animal-mediated pollination services[1] are a crucial determinant of the yield of most food crops (Klein et al. 2007). The growing evidence of declining biodiversity, particularly insect populations, is threatening the provision of these ecosystem services (Hallmann et al. 2021: van Klink et al. 2020), which could have adverse effects on crop production and, ultimately, food security and human health (Smith et al. 2015; Murphy et al. 2022). There are technological substitutes for pollination services through manual labor (Wurz

[1] For brevity, henceforth, pollination services always refer to animal-mediated pollination services.

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et al. 2021) or aerial drones (Hiraguri et al. 2023), but their economic feasibility at large scale and across crops still needs to be determined.

The scientific literature covers various studies and approaches estimating the economic value of pollination services. These approaches differ in terms of geographic scope, coverage of crops, and the underlying economic approach (Hanley et al. 2015; Breeze et al. 2016; Baylis et al. 2021; Champetier 2021). Most studies are based on yield dependence ratios[2], which measure the share of total crop yield lost in the absence of pollination services. Southwick and Southwick (1992) were the first reporting a partial equilibrium model to estimate the value of pollination services assuming a long-term adjustment horizon. They used it to value pollination services of honey bees in the United States. This long-term approach became well-known through the economic valuation of global pollination services by Gallai et al. (2009), but has been subject to various criticisms. For instance, Lippert et al. (2021) argued that the long-term valuation approach is based on unrealistic assumptions of how consumers and producers adjust to price changes in the long term. Therefore, they propose a short-term valuation approach. On the other hand, Bauer and Sue Wing (2016) used a global general equilibrium model that allows to depict market adjustments, but with aggregated data and unclear land market formulations. Overall, economic valuations of pollination services are criticized for simplified approaches ("brute force"), their limitation in capturing the "real value" of pollination services (Melathopoulos et al. 2015), or even for their motivation to monetize an ecosystem service (Spangenberg and Settele 2010).

One overlooked issue in the literature on the economic valuation of pollination services is the economic relevance of pollination services in seed production. Klein et al. (2018, p. 82–83) suggested that past economic valuations of pollination services do not "consider the contribution of bees to crop seed production or to the production of major forage crops like alfalfa, clover, and soybean for dairy and meat production, which is an urgent research task of future investigation"[3]. This was also an explicitly acknowledged limitation of Gallai et al. (2009), which still holds for the more recent studies (Bauer and Sue Wing 2016; Lippert et al. 2021; Murphy et al. 2022; Johnson et al. 2023). Pollination services for seed production indirectly impact human food consumption since they do not concern the output consumed, but impact an intermediate input required for food production. For instance, the production of carrots does not require pollination services since humans eat the root of carrots rather than their seeds. However, the cultivation of carrots requires carrot seeds, for which it is known that pollination services are required. This relationship holds for many food crops, especially vegetable crops. In the case of leguminous forage crops, such as alfalfa and clover, the entire stock of the plant is used as animal fodder. However, their seed production is known to be highly dependent on pollination services (Melathopoulos et al. 2015).

In this context, the dependence on pollination services is indirect as it "only" concerns seed production. Agronomically, this dependence is qualitatively known (Southwick and Southwick 1992; Klein et al. 2007) and has recently been quantitatively reviewed across all relevant FAO crops and forage crops (Krumbe et al. 2023). However, from an economic

[2] A similar method is the "yield analysis" method, which uses the observed yield difference between crops with and without access to pollination, see also Breeze et al. (2016).

[3] Past studies (e.g., Gallai et al. (2009) and Lippert et al. (2021)) have covered the role of pollination services for soybean production.

perspective, the economic relevance of pollination dependence in seed production (hereafter: seed pollination dependence) is unknown. There have been speculations of its relevance (see citations above), but to the authors' best knowledge, no study to date has attempted to quantify it. This paper addresses this research gap. The objectives of this study are to i) extend existing valuation approaches to incorporate the seed pollination dependence and ii) apply this approach to empirical data from the German agricultural sector to investigate the economic relevance of pollination for seed production.

The remainder of this paper is structured as follows. Section two presents how existing theoretical frameworks for the valuation of pollination services can be extended to accommodate seed markets. Section three describes the scenarios and case study data. Results addressing the research objectives mentioned above are presented in section four. Section five discusses the relevance and limitations of the results, and section six concludes.

2 Economic Valuation of Pollination Services in Seed Production

The method to value pollination services for seed production is adapted from existing comparative-static partial equilibrium approaches (Southwick and Southwick 1992; Gallai et al. 2009; Lippert et al. 2021). These approaches require relatively few parameters, but are also subject to strong, simplifying assumptions: They do not consider trade adjustments between regions, there are no cross-price effects, and supply is often assumed to be either perfectly elastic in the long-term (Southwick and Southwick 1992; Gallai et al. 2009) or perfectly inelastic in the short-term (Lippert et al. 2021).

The value of pollination services in seed production is estimated through welfare changes, i.e., the changes in the producer and consumer surplus and, if applicable, the changes in government income. Seeds are intermediate inputs demanded by food crop or animal feed production activities. Any price and quantity changes in the seed market impact consumers only indirectly via changes in the food crop or animal product market[4]. Furthermore, the demand for seeds by farmers depends on to what extent consumers react toward changes in food prices, i.e., the own-price elasticity of derived demand.

The first objective of this study is to extend the existing partial equilibrium approaches to incorporate the role of pollination services in seed production. Section 2.1 below explains why the existing short-term approach is unsuitable for assessing how changes in the seed market transmit to the food crop market. In contrast, Sect. 2.2 shows how the existing long-term approach can be extended straightforwardly to incorporate the role of pollination services in seed production.

[4] Animal feed is an intermediate input to produce animal products, and any change in its price only indirectly impacts consumers. Also, food crops are mostly demanded as intermediate-inputs by agro-processing industries before eventually reaching consumers in various processed forms.

2.1 Extending the Short-Term Approach for the Valuation of Pollination Services in Seed Production

In the short-term approach we assume that in the period $t = 1$ both food crop and seed producers face an unexpected pollinator collapse without the possibility of adjustments on the supply side. In both markets, we would observe an immediate decline in production:

$$Q_z^t = Q_z^0\left(1 - D_z\right) \; z \in Z \tag{1}$$

where index t may denote years or seasons, index z denotes crops Z, Q_z is the production quantity, and D_z is the yield dependence rate on pollination services. The superscript 0 denotes the base equilibrium in which there is no reduction in pollination services. The production changes can be calculated for the subset of food crops, $z \subseteq F$, or seeds, $z \subseteq S$.

In the year of the sudden and hypothetical pollinator collapse the food crops have already been cultivated with seeds grown in the previous years. Hence, the decline in seed production in $t = 1$ would only impact food crop markets in subsequent periods via a change in the seed price and supply[5].

Following Lippert et al. (2021) the short-term changes in welfare, $\Delta Welfare_z$, for a crop market after a collapse in pollination services, can be quantified as:

$$\Delta Welfare_z = -\frac{\varepsilon_z}{1+\varepsilon_z} P_z^0 Q_z^0 \left[\left(1 - D_z\right)^{\frac{1}{\varepsilon_z}+1} - 1\right] \tag{2}$$

where ε_z is the own price elasticity of demand and P_z the producer price. The welfare change consists of consumer and producer surplus changes, which is graphically shown in Fig. 1. As mentioned in Lippert et al. (2021), the short-term approach assumes that production costs already occurred before the pollinator collapse, i.e., they are sunk costs. This assumption is quite strong, as in the real world, certain costs, such as harvest and transportation costs would certainly decline with lower crop yields.

In the short-term approach, the price change resulting from the pollinator loss (from P^0 to P')—in either the seed or food crop market—can be calculated by equating the respective supply and demand functions (Lippert et al. 2021). The price change in the seed market would change the marginal cost of production of food crops in the next period. However, this excludes many relevant factors. Unlike the demand for food crops, which is predominantly determined by consumption decisions made within the same year, seed demand is primarily determined by farmers' cultivation decisions in $t = 2$ and thereafter. If the decline in productivity persists beyond $t = 1$, farmers will change the cultivated area of pollination-dependent food crops. Moreover, the actual seed supply in $t = 2$ is not only determined by the change in seed output in $t = 1$, but also by the seed storage rate, φ. This rate measures how much of annual seed demand is stored by seed companies in addition to their expected annual production of seeds. The exact magnitude of φ is sensitive information, which is difficult to estimate or obtain from seed companies, particularly if inquired about specific crops. Drawing on personal communication with one horticultural seed company, we know that about two to three times the annual seed demand is stored for seeds

[5] Note that because of various seed treatment processes the seeds harvested in one season may not be directly available to the food crop market in the subsequent season.

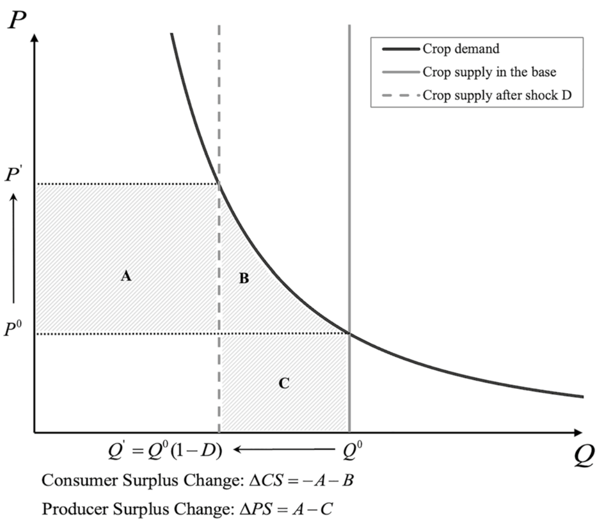

Fig. 1 Graphical representation of a market equilibrium of crop z. Following a sudden pollinator collapse, the inelastic short-term crop supply experiences a left shift determined by the dependence ratio D ("shock D"). The resulting price increase depends on the elasticity of demand. The short-term welfare changes are shown in the shaded areas. Consumer surplus declines by the areas A and B. Due to higher prices, the producer surplus increases by area A, but also declines by area C due to the lower production quantity. The total welfare loss consists of the sum of areas B and C (see also Eq. 2)

with high seed longevity[6] and low cooling requirements. For example, φ is generally higher for tomato seeds, with a high seed longevity, while φ is rather lower for eggplant or pepper, with a low seed longevity.

As Lippert et al. (2021) described, the existing comparative-static short-term approach is limited to a one-period (one-year) time horizon and omits stockholding.[7] The approach can therefore only capture the direct effects on the seed and food crop markets within the same year of the occurrence of the shock. By design, it cannot assess the knock-on effects of a change in seed prices on subsequent periods. To this end, developing a new approach, such as a dynamic partial equilibrium framework is needed, which would require stockholding behavior and knowledge about additional parameters, inter alia φ. This is beyond the study's scope, which focuses on extending existing approaches. Given the limitations of the short-term approach described above –and notwithstanding its advantage of being based on less restrictive assumptions on producers' and consumers' adaptation behavior– we subsequently focus on how the existing long-term valuation approach can be extended to incorporate the role of pollination services.[8]

[6] Seed longevity refers to the duration of time that a seed can remain viable, i.e., its ability to germinate and grow into a healthy plant. It determines the shelf life of seeds for agriculture, horticulture, and conservation purposes.

[7] In contrast to seeds, storage may play a less important role for pollination-dependent food crops such as vegetables and fruits that have relatively high perishability and thus a low degree of storability.

[8] In Appendix D the short-term approach is applied to calculate the welfare effects in both the seed and food crop market separately. The results are contrasted with the long-term approach in the discussion section.

2.2 Extending the Long-Term Approach for the Valuation of Pollination Services in Seed Production

In this section, we demonstrate a parsimonious extension of the long-term approach, resulting in an equation (Eq. 10) for estimating changes in welfare when pollination services decline in both the food crop and seed markets. We extend the theory of the long-term valuation approach in a three-step procedure: Firstly, we describe how the collapse in pollination services and the consequent change in seed yields impact seed market prices. Secondly, we use this information to estimate the resulting changes in the food supply cost. This depends on the seeds' cost share in the total supply of food crops. Thirdly, we show how the change in pollination services will result in a new market equilibrium with quantity and price changes, allowing us to estimate welfare changes that include the role of pollination services in seed production. The subsequent sections detail these three steps.

2.2.1 Changes in Seed Market Prices

In the long-term valuation approach, we assume a perfectly elastic supply curve in both the seed and food crop markets. All farmers produce at the same cost, the marginal production cost remains constant regardless of the area cultivated, and there is no constraint in the availability of arable land. All farm inputs, including land, are available in unlimited quantities at constant cost. In addition, there is perfect competition among farmers. This results in a horizontal seed supply curve. In the base equilibrium, i.e., the situation before the pollinator collapse, the provision of pollination services is intact, and seed producers supply seed at a price P_s^0. The superscript 0 denotes that base. After a pollinator collapse, the new price of seed supply, P_s, is only determined by DS_s, the seed yield dependence rate on pollination services:

$$P_s = \frac{P_s^0}{\left(1 - DS_s\right)} \; s \in S \tag{3}$$

where s is an index for crop seeds S and a subset of inputs I. This equation implies that due to the flat supply curve any change in the crop yield (in this case seed yield) is entirely transmitted to the seed price. This is also graphically depicted in Fig. 2.

The relative change in seed prices, $\Delta P_s / P_s^0$, is derived by dividing by P_s^0 and rearranging:

$$\frac{\Delta P_s}{P_s^0} = \frac{1}{\left(1 - DS_s\right)} - 1 = \frac{DS_s}{\left(1 - DS_s\right)} \tag{4}$$

Figure 2 provides a graphical representation of the changes in the seed market following a pollinator collapse. Note that, due to assuming a perfectly elastic supply, the price changes only depend on the dependence ratio and are independent of both the own price elasticity of demand and any exogenous change in seed demand. The demand for seeds may shift following production decision changes in the food crop market. Figure 2 shows a rightward shift, indicating that the cultivated area needed to produce the food crop supply has increased leading

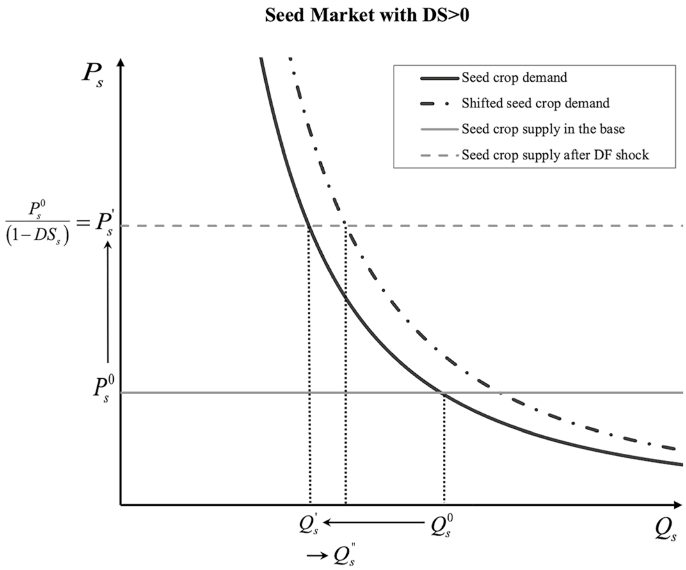

Fig. 2 Graphical representation of the long-term changes in the equilibrium of a seed market with a pollination service dependence ratio in seed production (DS). The collapse of pollinators shifts the seed supply curve upwards, resulting in a price increase and quantity decline. The shift in the seed demand results from a change in seed demand in the corresponding food crop market. A rightward shift is shown; however, depending on the change in the food crop market, it could also be a leftward shift

to higher seed supply. However, this is only shown for illustrative purposes because there also could be a leftward shift indicating a decline in cultivated areas. The change in the seed price is passed on to the consumers on the food crop market via a respective change in the food crop price, as explained in the following.

2.2.2 Changes in the Food Crop Market

Like in the seed market, we assume a perfectly elastic supply for food crops, Q_f, at price P_f^0, where f is an index for food crops F. Following microeconomic theory, the market price per unit sold in a competitive market equals the marginal cost per unit produced (Robinson 1934). The absolute level of marginal costs of a food crop, MC_f, is determined by the input unit costs, C_i, where index i comprises inputs I (which includes production factors such as labor, capital, and land, and intermediate inputs such as seeds, fertilizers, and pesticides). For simplicity, we assume a Leontief production technology, i.e., farmers cannot substitute seeds with other inputs and all inputs have a fixed quantity input share in the output.

Moreover, we consider relative changes in the productivity of food crops, α_f, and relative changes in the input cost prices, β_i.

$$P_f = MC_f = \frac{\sum_i^I C_i^0 (1 + \beta_i)}{(1 + \alpha_f)} \quad f \in F, i \in I, s \subseteq I \tag{5}$$

In the event of all (wild and managed) pollinators collapsing, the food crops' dependence on pollination, DF_f, equals a negative productivity shock of the same absolute magnitude. Assuming that both the food crop and seed production depend on pollination, i.e., $DF_f > 0$ and $DS_s > 0$, then the new equilibrium food price P_f, is affected by direct yield changes $\left(\alpha_f = -DF_f\right)$ and higher prices for seeds, $\beta_s > 0$.

The cost of other inputs ($\beta_{i \notin S} = 0$) remains constant since we are only interested in the seed cost changes. We can thus simplify Eq. 5. Following Eq. 4, we substitute the percentage change in seed cost with $\beta_s = DS_s / \left(1 - DS_s\right)$ and express the seed input cost as a share of the output price, $\gamma_s = C_s^0 \Big/ \sum_i C_i^0$.

$$P_f = \frac{\sum_i C_i^0 + C_s^0 \frac{DS_s}{(1-DS_s)}}{\left(1 - DF_f\right)} = \frac{P_f^0}{\left(1 - DF_f\right)} + \frac{\gamma_s P_f^0 \frac{DS_s}{(1-DS_s)}}{\left(1 - DF_f\right)} \text{ with } P_f^0 = \sum_i C_i \text{ and } Z : S \rightarrow F \tag{6}$$

where among all crops Z for every seed s from S there is a food crop f from F.

The first term, $P_f^0 \Big/ \left(1 - DF_f\right)$, describes how prices for the final food crop output are impacted by the food crop dependence ratio, as already described in Southwick and Southwick (1992). The second term, $\gamma_s P_f^0 \frac{DS_s}{(1-DS_s)} \Big/ \left(1 - DF_f\right)$, describes the cost change due to dependence on pollination services in seed production.

This second term has been ignored in pollination value assessments so far. Note that the numerator describes only the change in seed costs. In contrast, the denominator describes the increase in inputs due to the lower food crop productivity, which triggers an increase in cultivated area and, thus, a higher seed demand.

2.2.3 Estimating Welfare Effects from a Pollinator Collapse Affecting Food Crop and Seed Production

This section estimates the welfare effects of a pollinator collapse affecting food crop and seed production. We assume an isoelastic demand function for food crops f.

$$P_f\left(Q_f\right) = P_f^0 \left(\frac{Q_f}{Q_f^0}\right)^{\frac{1}{\varepsilon_f}} \quad f \in F \tag{7}$$

where Q_f is the food crop quantity and ε the own price elasticity of demand. Isoelastic demand functions are assumed in both the short and long-term approaches because they substantially ease the analysis and allow for a parsimonious valuation framework.

We substitute the left side with Eq. (6) and solve for the new equilibrium quantity Q_f.

$$Q_f = Q_f^0 \left(\frac{1 + \gamma_s \frac{DS_s}{(1-DS_s)}}{\left(1 - DF_f\right)} \right)^{\varepsilon_f} \tag{8}$$

In the long-term equilibrium within a perfectly competitive market, firms freely enter or exit the market driving their average total cost to equal their price, which in turn equals their marginal cost. This results in zero economic profits, as firms cover all their costs, including opportunity costs. Assuming all firms employ the same production technology and face the same change in productivity, any change in marginal costs caused by this uniform change in productivity is equal across all firms. Consequently, all firms continue to earn zero profits, and there is no change in the producer surplus in the long term.

Conversely, however, any change in the cost of supply, and thus prices, will cause a change in consumer surplus, $\triangle CS_f$, which constitutes the change in total welfare:

$$\triangle CS_f = -P_f Q_f - \int_{Q_f}^{Q_f^0} P_f^0 \left(\frac{Q_f}{Q_f^0} \right)^{\frac{1}{\varepsilon_f}} dQ_f + P_f^0 Q_f^0 \tag{9}$$

Equation (9) can be reduced to Eq. (10), which is the final formula used to estimate the welfare effects of pollination services collapse affecting both food crop and seed yields (see Appendix A for more details). This equation extends the calculation of long-term welfare changes reported by Gallai et al. (2009) via seed pollination dependence.

$$\Delta CS_f = -\frac{P_f^0 Q_f^0}{\varepsilon_f + 1} \left[\left(\frac{\left(1 + \gamma_s \frac{DS_s}{(1-DS_s)}\right)}{\left(1 - DF_f\right)} \right)^{1+\varepsilon_f} - 1 \right] \tag{10}$$

Following Eq. 10, we can generally differentiate between four cases of how a crop type is affected by a collapse in pollination services. *Case one* involves crops that only depend on pollination for their food crop yield (i.e., $DF_f > 0$ and $\mathrm{DS}_s = 0$). This group includes many permanent fruit crops, such as apples or pears, where seedlings are primarily produced using vegetative propagation. *Case two* comprises crops dependent on pollination for both food crop and seed yields (i.e., $DF_f > 0$ and $\mathrm{DS}_s > 0$). This group includes oilseeds like rapeseed and sunflowers, as well as many vegetables. *Case three* includes crops for which pollination services only impact their seed yield (i.e., $DF_f = 0$ and $\mathrm{DS}_s > 0$). This group applies to most forage crops like alfalfa and clover, and many vegetables like onions and carrots. *Case four* describes crops without pollination dependence for either food crop or seed yield, e.g., cereals or roots and tubers (i.e., $DF_f = 0$ and $\mathrm{DS}_s = 0$).

Figure 3 graphically derives the long-term welfare changes following a collapse of pollination services for cases *one, two,* and *three*. In cases *two* and *three*, the change in the seed price (see Fig. 3) (co-)determines the welfare change.

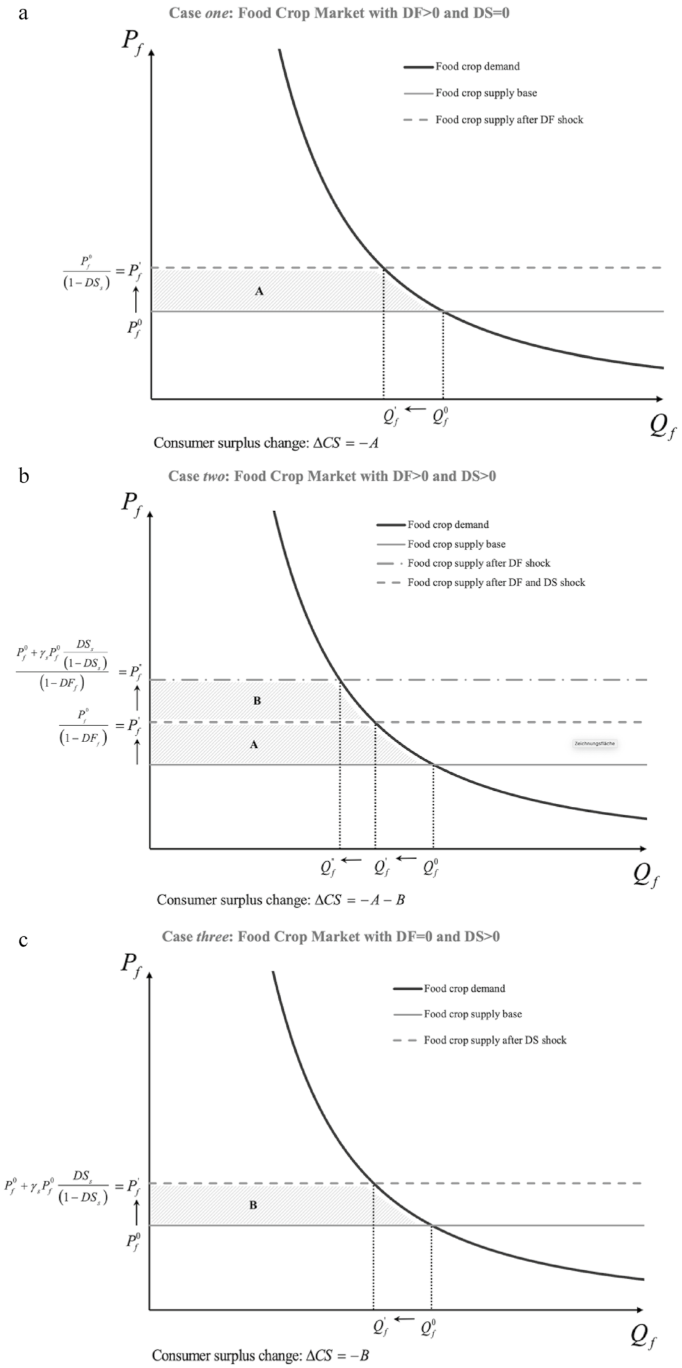

Fig. 3 Graphical derivation of the welfare changes for the three cases of dependence on animal-mediated pollination services. Case one (a) involves crops that only depend on pollination for their food crop yield ("shock DF"), case two (b) comprises crops dependent on pollination for both food crop and seed yields ("shock DF and DS"), and finally case three (c) includes crops for which pollination services only impact their seed yield ("shock DS")

3 Scenarios and Case-Study Data

3.1 Scenarios

Two scenarios are used to assess the value of pollination services in seed production. The first scenario assumes that pollination services collapse only for food production, while crop yields for seed production are unaffected. This has been the implicit assumption in pollination service valuation studies so far. The second scenario assumes that pollination services collapse for both seed and food production. In both scenarios, the collapses affect all regions of the world equally, while we only focus on the impacts on Germany. A complete collapse of pollination services is a hypothetical scenario that is highly unlikely. Still, it is commonly used to evaluate pollination services as it avoids speculating about the relationships between partial declines in pollination services and changes in crop yields (e.g., Gallai et al. 2009; Lippert et al. 2021; Murphy et al. 2022).

3.2 Case Study Data

Data on the crops' demand for seed inputs (the seed cost share) and the seed pollination dependence are required to investigate the economic relevance of pollination services in seed production. This data is not readily available on a global or local scale. Therefore, we use Germany as an illustrative case study to test whether the value of pollination services in seed production substantially impacts the total value of pollination services. To this end, the necessary data for all relevant crops cultivated in Germany were compiled (Table 1). The estimation of crop-specific production value and seed cost shares is documented in Appendix B. The data on food crop yield dependence ratios are based on Klein et al. (2007). The data on seed dependence ratios are taken from Krumbe et al. (2023), who, in addition to reporting the raw mean dependence ratios, also categorized the dependence ratios on seed dependence in similar stylized intervals as Klein et al. (2007). Appendix C documents the sources used to determine the crop-specific own price elasticity.

The dependence ratio mainly drives the long-term welfare changes of a hypothetical global pollinator collapse. The true dependence ratios of crops are unknown and in addition to the mean values, Table 1 reports a minimum and maximum estimate. To account for this space of parameter values, we conduct a stochastic Latin Hypercube Sampling (LHS) experiment that assumes a triangular distribution. LHS is a stratified sampling method that reduces the number of draws needed to represent a distribution of parameter values. Applying Eq. (10), the welfare effects are computed with 1,000 draws of the food crop and seed yield dependence ratios.[9] For this, the package *lhs* of the statistical software R (v4.2.0) is used (Carnell 2020). The dependence ratios are assumed to be statistically independent across crops. However, for the same crop, a perfect correlation is assumed for the dependence ratios for food crops and seed yield. The data and underlying code are available in the supplementary electronic materials.

[9] Convergence tests for an increasing sequence of iterations (500 – 10,000) were conducted with the threshold that the mean and median results stabilize within a 1% corridor. Convergence was achieved with 1,000 iterations.

Table 1 Production value, seed cost share and dependence ratios for food crop and seed yield for cultivated crops in Germany

Group	Crop	Production value	Own price elasticity	Seed cost share	Food crop yield dependence ratio			Seed yield dependence ratio			
					Mean	Min.	Max.	Mean	Min.	Max.	Raw
		in million EUR	–	in %	in %	in %	in %	in %	in %	in %	in %
Fruiting vegetables	Cucumber†	25.49	−0.51	3.93	65.0	40.0	90.0	95.0	90.0	99.0	99.0
	Cucumber gherkins†	127.30	−0.51	2.77	65.0	40.0	90.0	95.0	90.0	99.0	99.0
	Pepper†	13.47	−0.25	7.14	5.0	0.0	10.0	65.0	40.0	90.0	47.5
	Squash†	71.36	−1.20	3.94	95.0	90.0	100.0	95.0	90.0	99.0	99.0
	Tomato†	46.90	−0.45	1.10	5.0	0.0	10.0	65.0	40.0	90.0	54.7
	Zucchini†	38.06	−1.20	2.47	95.0	90.0	100.0	95.0	90.0	99.0	99.0
Cruciferous vegetables	Broccoli	37.76	−1.05	3.47	0.0	0.0	0.0	65.0	40.0	90.0	81.7
	Brussels sprouts	4.79	−1.50	5.42	0.0	0.0	0.0	65.0	40.0	90.0	81.7
	Cauliflower	33.87	−1.05	4.55	0.0	0.0	0.0	95.0	90.0	99.0	96.4
	Chinese cabbage	16.73	−1.05	3.07	0.0	0.0	0.0	65.0	40.0	90.0	87.9
	Kale	20.53	−1.50	3.11	0.0	0.0	0.0	65.0	40.0	90.0	81.7
	Kohlrabi	22.97	−1.05	9.10	0.0	0.0	0.0	65.0	40.0	90.0	81.7
	Red cabbage	15.53	−1.05	3.11	0.0	0.0	0.0	65.0	40.0	90.0	87.9
	Savoy cabbage	12.61	−1.05	1.73	0.0	0.0	0.0	65.0	40.0	90.0	87.9
	White cabbage	69.85	−1.05	4.66	0.0	0.0	0.0	65.0	40.0	90.0	87.9
Leafy or stem vegetables	Asparagus	709.49	−0.58	0.72	0.0	0.0	0.0	95.0	90.0	99.0	99.2
	Chicory	16.07	−1.05	2.13	0.0	0.0	0.0	25.0	10.0	40.0	10.0
	Leek	69.42	−1.05	4.17	0.0	0.0	0.0	65.0	40.0	90.0	86.5
	Rocket	49.17	−1.50	4.07	0.0	0.0	0.0	65.0	40.0	90.0	89.7
	Stalk celery	7.29	−0.15	3.30	0.0	0.0	0.0	25.0	10.0	40.0	10.0

Table 1 (continued)

Group	Crop	Production value	Own price elasticity	Seed cost share	Food crop yield dependence ratio			Seed yield dependence ratio			
					Mean	Min.	Max.	Mean	Min.	Max.	Raw
Root and tuber vegetables	Carrots	223.29	−0.90	5.82	0.0	0.0	0.0	65.0	40.0	90.0	82.1
	Knob celery	25.87	−0.15	19.21	0.0	0.0	0.0	25.0	10.0	40.0	10.0
	Onion	123.47	−0.20	9.87	0.0	0.0	0.0	65.0	40.0	90.0	89.3
	Radish radies	56.06	−1.05	16.81	0.0	0.0	0.0	95.0	90.0	99.0	97.3
	Radish rettich	3.71	−1.05	20.97	0.0	0.0	0.0	95.0	90.0	99.0	97.3
	Spring onions	70.22	−0.20	8.62	0.0	0.0	0.0	65.0	40.0	90.0	89.3
Pulses	Broad beans‡	13.10	−0.59	10.12	25.0	10.0	40.0	25.0	10.0	40.0	25.0
	Bush bean‡	113.02	−0.59	1.28	25.0	10.0	40.0	25.0	10.0	40.0	25.0
	Runner beans‡	2.39	−0.59	5.21	25.0	10.0	40.0	25.0	10.0	40.0	25.0
Oil crops and fodder pulses	Horse beans‡	37.38	−0.59	15.86	25.0	10.0	40.0	25.0	10.0	40.0	25.0
	Linseed‡	10.56	−1.50	3.54	5.0	0.0	10.0	5.0	0.0	10.0	5.0
	Lupin	8.80	−1.50	22.43	0.0	0.0	0.0	25.0	10.0	40.0	12.1
	Soybean‡	25.68	−0.37	35.48	25.0	10.0	40.0	25.0	10.0	40.0	25.0
	Spring rapeseed‡	3.56	−0.81	7.46	25.0	10.0	40.0	25.0	10.0	40.0	25.0
	Sunflower‡	14.74	−0.76	17.77	25.0	10.0	40.0	25.0	10.0	40.0	25.0
	Winter rapeseed‡	1,200.13	−0.81	7.03	25.0	10.0	40.0	25.0	10.0	40.0	25.0
Forage crops	Alfalfa	71.55	−0.67	7.29	0.0	0.0	0.0	95.0	90.0	99.0	96.2
	Other clovers	131.61	−0.67	4.44	0.0	0.0	0.0	65.0	40.0	90.0	70.3
	Red clover	177.73	−0.67	5.82	0.0	0.0	0.0	95.0	90.0	99.0	96.9

Table 1 (continued)

Group	Crop	Production value	Own price elasticity	Seed cost share	Food crop yield dependence ratio			Seed yield dependence ratio			
					Mean	Min.	Max.	Mean	Min.	Max.	Raw
Fruits	Apple†	623.70	−0.57	0.00	65.0	40.0	90.0	0.0	0.0	0.0	0.0
	Blueberry†	78.33	−1.49	0.00	65.0	40.0	90.0	0.0	0.0	0.0	0.0
	Currant†	33.47	−1.50	0.00	25.0	10.0	40.0	0.0	0.0	0.0	0.0
	Gooseberry†	5.31	−1.50	0.00	25.0	10.0	40.0	0.0	0.0	0.0	0.0
	Pear†	28.08	−1.16	0.00	65.0	40.0	90.0	0.0	0.0	0.0	0.0
	Plums†	46.27	−0.92	0.00	65.0	40.0	90.0	0.0	0.0	0.0	0.0
	Raspberry†	19.82	−1.66	0.00	65.0	40.0	90.0	0.0	0.0	0.0	0.0
	Sour cherry†	28.29	−0.41	0.00	65.0	40.0	90.0	0.0	0.0	0.0	0.0
	Strawberry†	308.11	−0.60	0.00	25.0	10.0	40.0	0.0	0.0	0.0	0.0
	Sweet cherry†	128.58	−0.41	0.00	65.0	40.0	90.0	0.0	0.0	0.0	0.0

The dependence ratios are based on Klein et al. (2007) (denoted by † if only the food crop yield is based on Klein et al., and by ‡ if both dependence ratios are based on Klein et al.) and Krumbe et al. 2023. In cases denoted by ‡, the raw seed yield dependence ratio is identical with the mean ratio reported by Klein et al. The estimation of the production value and the seed cost share is documented in Appendix B in the supplementary materials. The sources for the own price elasticities are provided in Appendix C

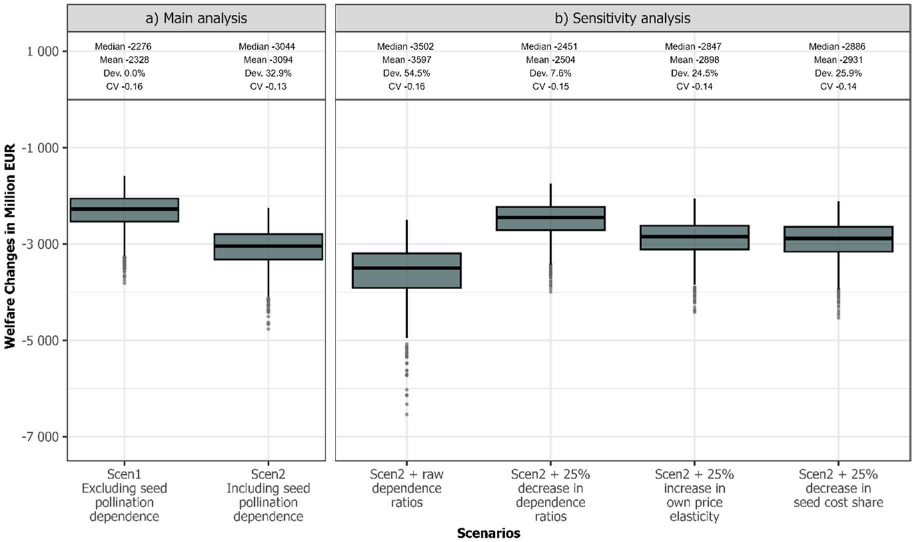

Fig. 4 **a** The main analysis presents the long-term welfare effects of a pollinator collapse using the economic valuation approach presented without and with seed dependence. Food crop and seed dependence are varied in a Latin Hypercube Sampling (LHS) experiment with 1,000 iterations. The box shows the interquartile range (IQR) of the simulated results (between the 25% and 75% quantile). The whisker length represents 1.5 times the IQR and outliers are plotted beyond this range. "Dev." reports how much the mean deviates (percentage-wise) from the mean result in Scen1. "CV" is the coefficient of variation, i.e. the standard deviation divided by the mean. **b** The sensitivity analysis shows variants of the welfare changes when the seed pollination dependence is included. The "raw" dependence ratios refer to the uncategorized seed pollination dependence ratios, as reported in Table 1

4 Results

4.1 Value of Pollination Services in Germany with and without Seed Production

Figure 4a presents the main analysis, calculating the total long-term welfare effects of a pollinator collapse in the German agricultural sector, excluding or including seed pollination dependence. In the long term, the valuation approach assumes a perfectly elastic supply behavior, which is why the welfare changes represent only changes in consumer surplus. The changes are calculated by applying Eq. (10) as presented in Sect. 2.2.3.

The conventional approach of calculating the welfare changes excludes the seed pollination dependence (i.e., $DS_s = 0$). In this case, the welfare effects amount to a mean value of 2.3 billion EUR. When including the seed pollination dependence based on the data presented in Table 1, the total mean welfare changes equal 3.1 billion EUR. Hence, accounting for the dependence on pollination services in seed production results in a 33% higher estimate for the value of pollination services. In relation to the absolute mean, the variation in welfare outcomes within the interquartile range is comparable for both cases. The interquartile range for possible welfare outcomes is 0.48 and 0.53 billion EUR for the case without and with considering the seed pollination dependence, respectively.

Figure 4b presents a sensitivity analysis of the main parameters determining the welfare changes from seed pollination dependence. A major determinant is the magnitude of dependence ratios. We classified the dependence ratios according to the categorial system suggested by Klein et al. (2007). However, using the raw (i.e., original) seed dependence ratios reported in (Krumbe et al. 2023) (see also Table 1), we would obtain an even higher total welfare estimate when including seed pollination dependence. The raw dependence ratios for seed dependence in many cases are equal to 0.99 (see Table 1). This produces outlier results as reflected in the boxplot (Fig. 4b) and in the higher coefficient of variation (CV). The remaining three sensitivity scenarios either comprise a 25% reduction of all seed dependence ratios, a 25% increase in the absolute own price elasticity of crops with a seed pollination dependence (i.e., all crops with seed pollination dependence are assumed to be 25% more elastic), or a 25% reduction in seed cost shares. The welfare results when including seed pollination dependence (Scen2) are most sensitive to a 25% reduction in dependence ratios resulting in a 21% decrease in welfare changes. In contrast, equal relative changes in the seed cost share or the own price elasticity reduce the welfare changes by only about 6% in both cases. Overall, the sensitivity analysis suggests that even a significant change in valuation parameters does not affect the main result of this study: there is a considerable difference in the calculation of welfare results when the dependence on pollination services in seed production is neglected.

4.2 Welfare Changes by Crop Type

Welfare changes and pollination services' economic relevance in seed production vary markedly across crop types and specific crops. Table 2 shows that specific crop types only contribute to the total change in welfare when the seed pollination dependence is considered. This holds for cruciferous vegetables, forage crops, leafy or stem vegetables, and root and tuber vegetables. These crop types comprise 545 million EUR in welfare losses, representing about 18% of total welfare changes (when calculated with seed pollination dependence). Consequently, these crop types explain 71% of the difference in welfare estimates calculated without or with seed pollination dependence. Welfare changes in forage crops make up 244 million EUR and they, therefore, almost explain a third of the total difference between when pollination services in seed production are excluded (Scen1) or included (Scen2).

In terms of area, crops with only seed pollination dependence comprise merely 18% of the total area of pollination-dependent crop production in Germany (Table 3). However, most of these crops are high-value crops, as reflected by their combined share in total production value of about 39%. Moreover, seed dependence ratios are generally higher than food crop dependencies, which especially holds for crops with only seed pollination dependence. Fruiting vegetables, pulses, and oil crops (including fodder pulses) are crop types with both food crop and seed pollination dependence. They make up 82% of the cultivated area of pollination-dependent crops and 61% of production value (Table 3). Yet, oil crops and fodder pulses are mainly characterized by relatively low seed dependence ratios. As a result, the welfare loss for these crop types increases only moderately once pollination dependence in seed production is considered. Fruits comprise only 4.5% of the cultivated area but 26% of the production value. Since fruit tree seedlings are propagated vegetatively, seed production does not depend on pollination services[10]. Their contribution to total welfare changes drops from 61 to 46% once the dependence on pollination services in seed production is considered (Table 2).

[10] This also holds for some field crops. For example, strawberries' food crop and seed yield depend on pollination services. But strawberries are, in practice, predominantly propagated vegetatively, which is why we neglect their seed pollination dependence.

Table 2 Welfare changes at the crop type level excluding or including the dependence on pollination services in seed production

Crop type	Scen1—Excluding seed dependence			Scen2—Including seed dependence			Abs. difference in welfare between Scen1 and Scen2
	Welfare changes	Share in welfare changes	Welfare changes per hectare	Welfare changes	Share in welfare changes	Welfare changes per hectare	
	in million EUR	in %	in EUR per hectare	in million EUR	in %	in EUR per hectare	in million EUR
Cruciferous vegetables	0	0.0	0	39	1.3	2069	39.2
Forage crops	0	0.0	0	244	7.9	1329	244.0
Fruiting vegetables	484	20.8	60,207	665	21.5	82,796	181.5
Fruits	1418	60.9	21,232	1418	45.8	21,232	0.0
Leafy or stem vegetables	0	0.0	0	111	3.6	3498	111.1
Oil crops and fodder pulses	386	16.6	337	424	13.7	370	38.1
Pulses	40	1.7	8,471	41	1.3	8709	1.1
Root and tuber vegetables	0	0.0	0	151	4.9	4506	151.0
Total	2,328	100.0	1559	3094	100.0	2,072	765.9

Source Authors' own analysis

Table 3 Main descriptors for crop types (aggregated based on Table 1)

Crop type	Cultivated area	Share in cultivated area	Production value (avg. 2017–2019)	Production value per area	Share in total prod. value	Seed cost share†	Dep. ratio in food production†	Dep. ratio in seed production†
	in hectares	in %	in million EUR	in EUR per hectare	in %	in %	in %	in %
Cruciferous vegetables	18,934	1.3	235	12,392	4.7	4.4	0.0	69.3
Forage crops	183,599	12.3	381	2,075	7.6	5.6	0.0	84.6
Fruiting vegetables	8,033	0.5	323	40,155	6.4	3.0	63.9	89.4
Fruits	66,800	4.5	1,300	19,460	25.9	0.0	54.3	0.0
Leafy or stem vegetables	31,744	2.1	851	26,822	17.0	1.2	0.0	88.9
Oil crops and fodder pulses	1,146,067	76.7	1,301	1,135	25.9	8.0	24.7	24.8
Pulses	4,710	0.3	129	27,284	2.6	2.3	25.0	25.0
Root and tuber vegetables	33,499	2.2	503	15,004	10.0	9.2	0.0	66.5
Total	1,493,386	100.0	5,021	3,362	100.0	4.1	25.2	44.2

†Aggregated using production-values as weights. Source: Aggregated from Table 1

4.3 Crop-Specific Welfare Changes

The welfare changes per crop, as shown in Fig. 5, are either calculated with only food crop pollination dependence or also including seed pollination dependence. The crops are moreover grouped by their type of dependence. The top side facet shows only crops with food crop pollination dependence, the middle side facet shows only crops with food crop and seed pollination dependence, and the bottom side facet shows only crops with seed

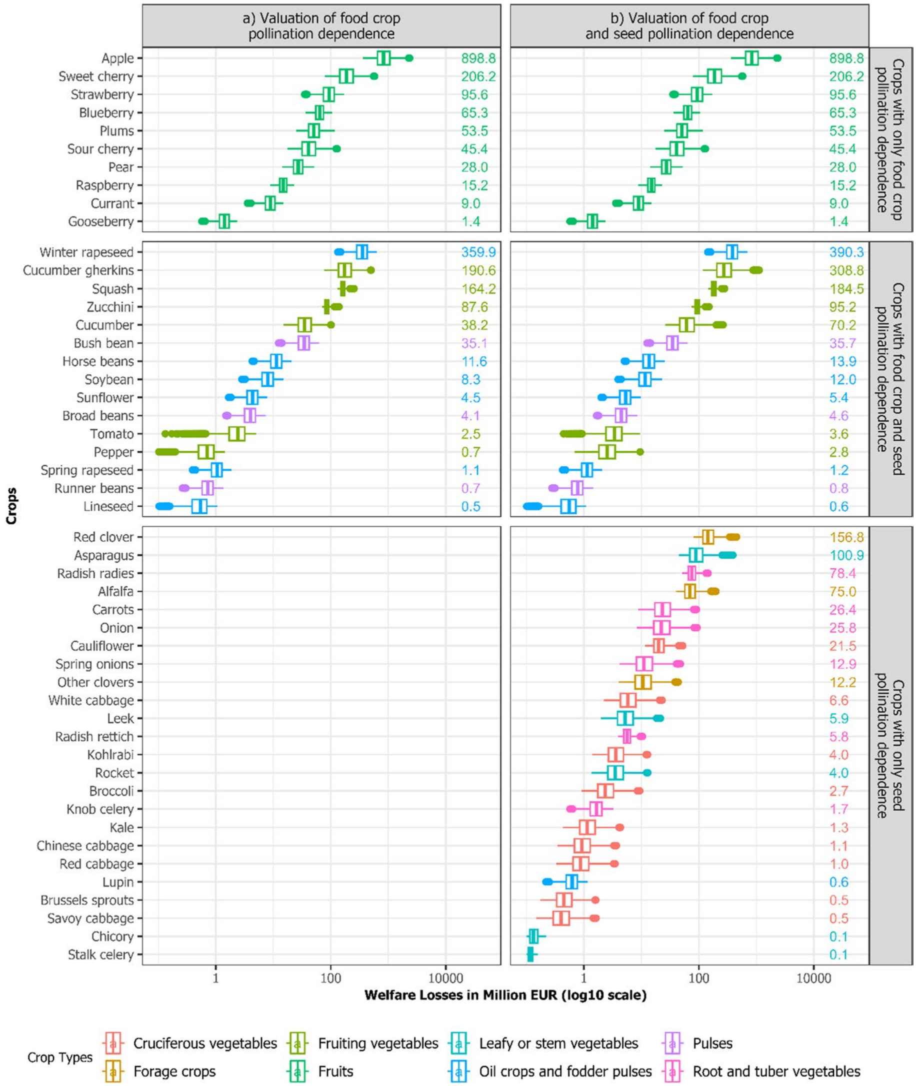

Fig. 5 Crop specific welfare losses when assessing the value of pollination services when **a** only the pollination dependence in food crop production or **b** both the pollination dependence in food crop and seed production are considered. The crops are grouped by their dependence profiles. The mean welfare loss for each crop is reported at the far right of each facet

pollination dependence. For red clover, welfare changes are highest on average among all crops that only have a seed pollination dependence. This is particularly of interest, as red clover belongs to the group of forage crops for which the literature has often highlighted the economic relevance of pollination services (Southwick and Southwick 1992; Melathopoulos et al. 2015), however without being able to underpin this with actual data.

5 Discussion

This study extends the theory of the long-term valuation approach of pollination services by incorporating the role of pollination services in seed production. Applying the extended long-term approach to data from Germany shows that the dependence on pollination services in seed production comprises a non-trivial share of the total value of pollination services. The value of pollination services in Germany is estimated to be 3.1 billion EUR, which is about one third (32.9%) higher compared to the value estimated excluding the value of pollination. This difference is primarily explained by crop-type welfare changes that depend only on pollination services in seed production. Such a relative difference demonstrates the economic relevance of pollination services in seed production.

The main findings also hold when applying the short-term valuation approach (see Appendix D for more details). Following the short-term approach, the mean welfare changes in the food crop market amount to 2.9 billion EUR. Including the seed market, the mean total welfare changes increased to 4.6 billion EUR, representing a surge of 56% compared to 33% in the long-term approach. Nonetheless, it is essential to note that the short-term approach may be susceptible to artifacts, especially in the seed market. This susceptibility is evident in the wide range of estimated welfare changes and the considerably higher coefficients of variation. Lippert et al. (2021, see their footnote 9) previously noted the risk of artifacts. Crops with high dependence ratios would experience a substantial leftward shift of the supply curve, as illustrated in Fig. 1. This reduction in supply can result in large welfare losses, especially when demand for these crops is inelastic resulting in significant price increases. This is due to the asymptotic nature of isoelastic demand curves, where consumers' willingness to pay escalates infinitely as the quantity approaches the y-axis.

In contrast, the long-term approach assumes an upward shift of the elastic supply curve (as illustrated in Fig. 3), resulting in more modest welfare changes and substantially lower coefficients of variation across all scenarios and variants. Both approaches affirm the economic relevance of pollination services in seed production, an aspect that has previously been overlooked and under-researched. Nevertheless, it is worth noting that the long-term approach tends to produce more conservative results due to its lower susceptibility to yielding artifact-induced outcomes and its implicitly assumed adaptation of supply.

The magnitude of the additional welfare effects, once seed pollination dependence is considered, stems from generally high seed pollination dependence ratios, most exceeding 65% (Table 1). Using dependence ratios is associated with limitations of its own and affects food crop and seed pollination dependence ratios alike. They are prone to bias since they are derived from studies that use different methods and references of "optimal" open pollination to measure a crop's dependence on pollination (Hanley et al. 2015). They do not provide information on marginal changes in pollinator populations (Lippert et al. 2021), and they neglect differences in output quality and varieties (Garratt et al. 2014; Hanley et al. 2015). The limited knowledge of how exactly crop yields depend on different degrees of pollination services is a caveat that could be rectified by better knowledge of the functional agro-ecological relationship. Such data is only available for selective crops or pollinators (Groeneveld et al. 2010; Reilly et al. 2020). Given the absence of this information, the valuation of pollination services across the full spectrum of crops still relies on the hypothetical scenario of a total collapse of all pollinators (whether globally or in a selected region). Future research is needed to address the respective data gaps allowing for the assessment of empirically realistic scenarios.

The uncertainty inherent in dependence ratios is addressed in this study through stochastic uncertainty analysis and additional sensitivity analysis. They show a moderate uncertainty in the magnitude of welfare effects when dependence ratios are varied between their minimum and maximum values. The sensitivity analysis specifically shows that the finding on the economic relevance of seed dependence is most sensitive towards changes in the dependence ratio and least sensitive to changes in the seed cost share. Moreover, it is shown that using the original literature-based seed dependence ratios would have resulted in an even higher difference compared to the conventional way of estimating pollination services.

The decomposition of the total value of pollination services reveals that many crops contribute to the estimated value of pollination services which only have a seed pollination dependence. These include particularly forage crops (e.g., alfalfa and clover) and different types of vegetables, which were excluded in previous economic valuations of pollination services. Hence, the implications for a nutritious and healthy diet of a pollinator decline would be more severe as the seed pollination dependence would lead to even higher price increases covering a large range of vegetables, as previously known (Smith et al. 2015; Garibaldi et al. 2022). The study focused on Germany, a large net fruit and vegetable importer. Applying the short- and long-term approach to a single country assumes that changes in the consumer surplus are only based on the domestic production value, as they only consider the domestic production value and assume no changes in trade volumes. This implies that a net-importer's consumer surplus estimate is likely underestimated because the actual consumption volume is higher than the domestic production value. Likewise, estimates for consumer surplus changes would likely be overstated in net exporter countries.

Forage crops have received particular attention from some scholars (Melathopoulos et al. 2015) since they contribute to livestock production as animal fodder. Earlier studies (Martin 1973; Levin 1984; Winston, M.L, Scott-Dupree, C., 1984) reported that livestock production represents the largest share of estimated values of pollination services (Melathopoulos et al. 2015). This is not confirmed by this study, which finds that forage crops contribute less than 8% of total welfare losses. Humans do not directly consume forage crops; they are used as animal fodder in livestock production. This study, however, treats forage crops as any other crop directly consumed by households using demand elasticities for livestock products (see Appendix C). Even though forage crops are primarily used as on-farm inputs, there is nevertheless data available to estimate the market production value of these crops or their transformation, e.g., silage (KTBL 2020). In contrast, the earlier studies cited above used very rough assumptions. Levin (1984) for instance assumed that 10% of livestock output value is accredited to pollination services.

5.1 Limitations of the Existing Long- and Short-Term Valuation Methods

The existing short- and long-term comparative-static partial equilibrium approaches are straightforward methods based on rather restrictive assumptions (Kevan and Phillips 2001;

Lippert et al. 2021). They do not capture cross-price effects on both the supply and demand side. Yet, producers may substitute pollination-dependent crops with other crops that do not suffer from a decline in productivity. Similarly, consumers would be incentivized to turn to food that is not pollination dependent. Both approaches neglect trade between regions by implicitly assuming constant trade flows and prices. In a global pollinator decline scenario, assuming that agricultural import prices increase and that trade flows adjust would be reasonable. Assuming no trade adjustments implies that changes in consumer quantity and prices affecting welfare calculations are only determined by shifts in domestic production, which is unrealistic. Moreover, as stated before, it means that welfare changes are generally underestimated (overstated) for net importing (exporting) countries.

Moreover, they do not account for technological change that could allow to mitigate pollination services such as manual pollination. Finally, which only concerns the long-term approach, the perfectly elastic supply curve assumes unlimited availability of production inputs (land, labor, capital, water, etc.) at constant cost. This assumption may be adequate for crops with rather small acreages, particularly for vegetables and areas dedicated to seed production. However, the assumption is unrealistic for crops with very specific agroclimatic requirements (Lippert et al. 2021) or large absolute land expansion (e.g., for pollination dependent oilseed crops).

These limitations are particularly relevant for the long-term approach in which agents have sufficient time to adjust their behavior. In contrast, the short-term approach, assuming a time horizon of one year or less, deals with immediate responses to shocks, such as a pollinator collapse. In this period, the scope of adjusting production decisions and substituting seeds or pollination services with other inputs or technologies is either very limited or even non-existent. For these reasons, inter alia, Lippert et al. (2021) argued in favor of the short-term approach when valuing pollination services. However, as described in Sect. 2.1, the existing short-time approach does not allow to assess how changes in the seed market affect the food crop market in subsequent periods. In contrast, this study shows that the existing long-term valuation approach allows for a straightforward incorporation of pollination services in seed production. The extended valuation method is parsimonious regarding the parameters it is based on. However, for now, this comes with the disadvantage of accepting the previously mentioned limitations. Extending the approach to also include mechanisms for substitution and mitigation options would dampen the increase in producer prices and, therefore, reduce the welfare effect estimations. This would imply that the values presented above are more likely upper bounds. Conversely, replacing the assumption of unlimited resources would, in turn, result in increased producer prices, indicating that the estimates could also be lower bounds.

The methodological shortcomings of the valuation approaches presented have been discussed extensively in the literature (Melathopoulos et al. 2015; Lippert et al. 2021). Addressing them was not the goal of this study. Instead the aim was to extend existing methods to investigate the economic relevance of pollination services in seed production. While we focus on the long-term approach, using the short-term approach (see Appendix D) also confirms our main result that the value of pollination services in seed production makes up a considerable share of total pollination services.[11] As presented next, the avenues for future research could reveal how sensitive our results are once the limitations mentioned above are adequately addressed in more sophisticated extensions of the valuation frameworks.

[11] The short-term approach only allows to assess the isolated welfare effects of a pollinator collapse in the seed and food crop markets.

5.2 Avenues for Future Research

The above-mentioned limitations present many avenues for future research to extend the valuation approaches used for pollination services. Future extensions could particularly focus on the role of mitigation options allowing for the technological substitution of pollination services. Pollination services are a production input and not a good of its own (Mace et al. 2012; Bateman et al. 2014). A collapse of pollination services from both wild and managed pollinators can (partially) be mitigated by manual pollination (Fitter 2013) or mechanized pollination for instance by drones (Hiraguri et al. 2023). However, knowledge about the technical effectiveness and economic viability of such mitigation technologies is still in its early stages (Popak and Markwith 2019; Wurz et al. 2021). Future research in this direction may test the hypothesis that manual pollination yields a higher economic return in seed production, because of the higher dependence ratio and higher value per unit of output.

This study assumes the Leontief technology for input substitution on the supply side of the food crop market, i.e., seeds cannot be substituted by other inputs. This assumption ignores that seeds can be substituted to a limited extent, for instance, by reducing seed rates and enhancing the use of other inputs (fertilizer, water, etc.). Future research could consider using production functions such as constant elasticity of substitution functions, that explicitly depict production inputs and allow for input substitution. Similarly, substitution effects can be modeled on the demand side, which includes animal fodder. Forage crops like alfalfa could be replaced with other animal fodder not dependent on pollination. This would require a production function approach (Barbier et al. 2021) and knowledge about substitution elasticities, mostly available only at aggregated levels (e.g., crop types) and rarely for individual crops. Future extensions should also address the role of trade, as welfare changes are among others affected by changes in trade flows and prices. Studies that used partial or general equilibrium simulation models address some previously mentioned limitations (e.g., Bauer and Sue Wing 2016; Smith et al. 2022). However, they, unfortunately, operate at a much more aggregated level, masking the individual crops. Moreover, these models do not depict an explicit seed production sector.

The study further emphasizes the necessity of evolving the current short-term approach into a dynamic multi-period model that incorporates stockholding. This requires additional data and insight into parameters, such as the seed storage rate. Stockholding may be considered less critical in long-term approaches, where technological advances and market adjustments help alleviate shocks. This enhancement might preclude a straightforward approach consisting solely of a single formula to calculate welfare changes, unlike the extension of the long-term approach in this study.

6 Conclusion

This study makes two significant contributions to the literature. First, an established comparative-static partial equilibrium framework is extended to capture the role of pollination services in seed production. This allows for straightforward incorporation of the seed pollination dependence. Second, using data on seed cost shares and pollination dependence ratios in seed production, the economic relevance of pollination services in seed production is assessed for the case of Germany. We find that pollination services in seed production increase the estimated value of pollination services by about one third. Hence, ignoring the role of pollination services in seed production results in substantially downward-biased estimates of the value of pollination services. Such insights have important implications for policymakers, agricultural practices, and conservation efforts. We highlight shortcomings in the choice of the theoretical framework and use of dependence ratios and present future avenues of research.

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Declarations

Conflict of interest The authors have no conflict of interest.

Human or animal rights This research did not involve human participants nor animals.

Informed consent Therefore, no informed consent was necessary.

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