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Analysis

Revisiting the economic valuation of agricultural losses due to large-scale changes in pollinator populations

Christian Lippert[a,*], Arndt Feuerbacher[b], Manuel Narjes[a]

[a] Department of Production Theory and Resource Economics, Institute of Farm Management (410a), Universität Hohenheim, D-70593 Stuttgart, Germany
[b] Department of Agricultural and Food Policy, Institute of Agricultural Policy and Markets (420a), Universität Hohenheim, D-70593 Stuttgart, Germany

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ABSTRACT

We discuss comparative static partial equilibrium approaches for large-scale monetary valuations of animal-mediated crop pollination. These approaches rely upon reported crop production values, own-price elasticities of demand and experimentally found dependence ratios that express crop-specific yield shares due to pollinators. We dismiss the established long-term approach given the difficulty of anticipating the adaptation of the bioeconomic system to changes of pollinator abundance. Instead, we suggest another more parsimonious method, which assesses the short-term welfare effects following a sudden change in pollinator abundance. Using 2016-2018 data on agricultural production, we estimate the worldwide welfare effects due to a pollinator collapse for a range of plausible own-price elasticities, both from short-term and long-term perspectives. For the former we also simulate a global recovery scenario. Depending on the overall price elasticity assumed, the short-term effects of a total pollinator loss lie between 1 and 2 % of global GDP. We also apply the different valuation approaches to more detailed German 2006-2016 crop production data, where we account for crop-specific demand. As the reported dependence ratios vary in wide ranges, we rely upon stochastic simulations to obtain likely distributions of the German welfare effects.

1. Introduction

In light of the growing evidence of a global decline in insect abundance and diversity (Potts et al. 2010; Hallmann et al. 2017; Sánchez-Bayo and Wyckhuys 2019; Seibold et al. 2019; Cardoso et al. 2020), attempts to evaluate the economic losses in agricultural production resulting from a reduction in insect pollination[1] have gained in importance (see the reviews by Bauer and Wing 2010; Hanley et al. 2015; Breeze et al. 2016). Public concerns over declines in crop pollinator populations and their potential impact on food production have increased the need for economic valuations of the corresponding ecosystem services, particularly as policymakers have to justify costly agro-environmental measures to sustain them. In general, sound global-scale valuation methods are important as worldwide biodiversity is under extreme pressure, with one million species threatened with extinction (IPBES 2019).

A widely-used approach to value crop pollination is based on a partial-equilibrium model without cross-price relationships. The approach allows to calculate changes in long-term consumer surplus resulting from pollinator decline induced yield losses and was introduced by Southwick and Southwick (1992). The underlying price effects are obtained from assumed or estimated demand functions, whereas the crop yield effects are based on pollinator dependence ratios that quantify the share of yield that is due to pollinators. Thus, the welfare effects of large-scale changes in pollinator abundance result from both the scarcity induced price reactions of producers and consumers within the economic system and from the impact of pollinators on the different crops within the agroecological system. Therefore, the assumptions made with respect to both systems and the model representation of these systems strongly influence the outcomes of pollinator valuations.

Quantifying the monetary value of a complete worldwide pollinator collapse does not fully account for the overall ecological implications of such a catastrophic event to humans, which would probably consist in negative welfare effects that reach far beyond the mere damages from crop yield reductions. Monetary estimates of the pollinator-related

* Corresponding author.
E-mail addresses: Christian.Lippert@uni-hohenheim.de (C. Lippert), a.feuerbacher@uni-hohenheim.de (A. Feuerbacher), manuel.narjes@uni-hohenheim.de (M. Narjes).

[1] Notice that besides insects, which provide for a huge share of pollination services in many parts of the world and especially in the moderate latitudes, there are also other pollinating animals like birds or bats.

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benefits to worldwide agriculture can raise and maintain awareness of the importance of sound pollinator-sustaining ecosystems. However, besides pollination of commercial crops, there are several other regulating and supporting ecosystem services linked to pollinating insects, such as their contribution to biological control or their share in the preservation of genetic diversity. Also cultural ecosystem services providing spiritual, aesthetic and arts inspiring benefits are likely to depreciate with a decline in pollinator incidence. In this article, however, we exclusively focus upon the market benefits that result from pollinating ecosystem services. The aforementioned correlated value components are not and cannot be captured by the crop production based valuation approaches treated in the following.

With this article, we make three contributions: Firstly, applying common microeconomic theory, we revisit the established partial equilibrium approach and present an alternative partial equilibrium approach, which strongly differs in its basic assumptions. Secondly, as the dependence ratios obtained from the available literature are uncertain and vary in wide ranges, we consider them as stochastic variables and conduct a comprehensive sensitivity analysis of their impact on the value of a country's pollination services. Thirdly, applying and illustrating the previously analyzed approaches we produce own estimations of the value of pollination services for recent global and (in more detail) German crop production data.

In section 2 of this article, we review the recent literature that is relevant for the valuation approaches treated in the following. In Section 3, we present the mentioned partial equilibrium approaches and provide a general analytical framework for evaluating short-term (Section 3.1) and long-term (Section 3.2) welfare effects of pollinator declines. In Section 3.3, we analyze the implications of removing the assumption of full pollinator potential in the ecological reference equilibrium and simulate the welfare effects of an assumed recovery in pollinator services. In the empirical part of our research, to illustrate the differences in the obtained welfare effects, we first apply the different approaches to the global crop production values that were used in Gallai et al. (2009) and then come up with corresponding estimates for more recent global data (Section 4.1). Finally, we demonstrate the ranges of the welfare effects that result from the uncertain dependence ratios by conducting a stochastic Latin Hypercube Sampling (LHS) experiment for recent data on the pollinator-dependent crop production in Germany (Section 4.2). In Section 5, we interpret and discuss the results for the different scenarios presented in the previous sections and make a case for the short-term partial equilibrium approach.

2. Relevant literature

The body of literature on the monetary valuation of pollination services comprises studies that rely on a variety of methods of diverse complexity and applicability. The comprehensive reviews by Hanley et al. (2015) and Breeze et al. (2016) systematically classify these methods into approaches that, to a greater or lesser extent, depend on the representation of the economic and agroecological systems for the measurement of the economic impacts of a change in the provision of pollination services.

With regard to the economic system, the long-term partial equilibrium approach is a (simple) method to estimate large-scale or even global welfare effects. Changes in consumer surplus that would result from a hypothetical complete pollinator disappearance are calculated based on given demand functions, the parameters of which are estimated (as in Southwick and Southwick 1992) or simply assumed and subject to sensitivity analyses (as in Gallai et al. 2009). To our knowledge, this approach was first suggested by Southwick and Southwick (1992) to calculate the value of honeybee induced production gains for an array of pollinator-dependent agricultural crops in the United States. Later, in a much-cited article, Gallai et al. (2009) used it to assess the value of worldwide pollination services. An advantage of this method is that it requires relatively little information about the economic system. However, it is built on the assumed existence of a horizontal long-run crop supply curve (Southwick and Southwick 1992 p. 622), which implies an unconstrained availability and mobility of the production factors. In contrast, assumed crop demand functions are kept constant.

Winfree et al. (2011) propose incorporating yield analyses into an approach that combines the production value and the replacement cost methods in order to discriminate contributions to crop pollination between pollinator taxa (or between wild and managed pollinators). Their approach, coined "attributable net income method", accounts for changes in production costs after pollinator loss induced yield declines, which are assumed to either fall (e.g., because of harvest costs saved) or increase (e.g., when hiring managed pollination services) proportionally to the change in pollination services. By incorporating yield analyses, Winfree et al.'s (2011) approach also accounts for the pollination level that actually contributes to fruit production, thus avoiding overestimating changes in pollinator populations past a crop's pollination requirement threshold. In an appendix (ibid, p. 85 f.), they generalize their approach by expressing prices as a function of total market production, thus further accounting for large-scale welfare changes, i.e., consumer surplus and net incomes of producers inside and outside of the large region affected by pollination deficits. However, the modelling features that make the "attributable net income" approach attractive are also limited to small-scale valuations due to the expensive experiments underlying corresponding yield analyses. Winfree et al. (2011) also criticize and briefly discuss the simplifying assumptions in the mentioned large-scale studies. Yet, we believe that the assumptions underlying corresponding welfare economics and their implications on the value estimates merit more elaborate considerations than they have received so far.

With respect to the agroecological system, the question is how yield and quality of the different insect pollinated crops depend on pollinator assemblage, and on pollination frequency and requirements. Though this implies the idea of a production function that relates yield quantities to different states of pollinator mix and abundance, the large-scale valuation approaches used in the following sections neglect the shape of this function. This means, we do not know whether this function is linear or non-linear. Non-linearity can involve tipping points, from which on further decreases of the number of pollinators would suddenly lead to very large yield reductions. Such analyses would need detailed ecosystem-, crop- and pollinator-specific agronomic investigations. In contrast, large-scale partial equilibrium valuations only rely upon two reference points of the production function: That is either full pollinator potential or its complete disappearance.

The crop yield difference between these two states is captured by *pollinator dependence ratios*, which express the proportion of the total annual production of a crop that is due to animal-mediated pollination. In practice, such ratios are obtained in field experiments by comparing yields after pollinators have had free access to the flowering crop with yields when pollinating animals were excluded (Melathopoulos et al. 2015 p.60 f.). Studies based on pollinator dependence ratios implicitly assume that any analyzed crop will homogenously replicate the pollination response of the original field experiments (i.e., underlying the corresponding dependence ratio) across varieties, locations and spatial scales. This simplifying assumption on the agroecological system allows for modelling the yield effects, with which one obtains large-scale estimates of pollination-dependent production values (e.g., Calderone 2012 for the USA and Leonhardt et al. 2013 for Europe) and of relevant consumer surplus changes (e.g., Gallai et al. 2009). Moreover, Barfield et al. (2015), Schulp et al. (2014) and Lautenbach et al. (2012) integrated pollinator dependence ratios with spatial analyses to plot production value estimates at local (i.e., in the US state of Georgia), regional (European Union) and global scales, respectively.

Detailed yield analyses, on the other hand, rely on experiments that seize each crop's field-specific agroecological conditions in order to obtain more accurate pollination-dependent production value estimates. Ricketts and Lonsdorf (2013), for instance, mapped marginal economic losses from simulated reductions in wild pollinator habitats bordering coffee fields in Costa Rica. For this purpose, they calibrated Lonsdorf et al.'s (2009) model with the economic value estimates that Ricketts et al. (2004) obtained through pollen limitation experiments along replicated distance gradients from the forest margin. Garratt et al. (2016), on the other hand, used field experiments to obtain taxa-specific value estimates for the per hectare contributions of four different pollinator guilds to the quantity and quality (i.e., accounting for different price classes) of four apple cultivars, which they extrapolated to these crops' entire cultivated area in the UK. Yield analyses, however, are limited to the estimation of local and crop-specific pollination-dependent production values, as their accuracy requires expensive experimental setups that hardly justify their application to large-scale crop-pollination related welfare effects.

Recently, in an extensive study covering 131 locations throughout the US, Reilly et al. (2020) analyzed whether pollination was a crop yield limiting factor and which crop-specific share of pollination was due to wild pollinators. They identified five crops showing pollinator limitation (e.g., apples in Michigan and Pennsylvania) and could establish that, for most of the investigated crops, the levels of pollination provided by honeybees and wild bees were similar. Based on their findings for the seven crops treated in their study, they also estimated a US-wide yearly production value of USD 1.5 billion owing to the activity of wild pollinators.

The countrywide and worldwide valuation performed below simply deals with either a full pollination potential scenario or that of a complete pollinator disappearance. The valuation methods estimating the welfare effects at such large-scale have either consisted of partial-equilibrium or general-equilibrium models. Southwick and Southwick (1992) for the U.S. and later Gallai et al. (2009) at the global level calculated the long-term changes in consumer surplus using a partial equilibrium approach subject to the previously mentioned assumptions. These analyses do not account for cross-price effects, but in return have a very high resolution of crop representation. Gallai et al. (2009) applied pollinator dependence ratios derived from the review article by Klein et al. (2007) to 100 crops directly used for human consumption. Bauer and Wing (2016) incorporated the pollination dependence ratio approach into a multi-region, multisector computable general equilibrium (CGE) model to estimate the impacts of a sudden disappearance of pollinators. The model allowed for product substitution on the consumer side and for intersectoral reallocation of production factors (e.g., labor, land) and intermediate inputs within agriculture and with non-agricultural sectors. However, such a model is subject to high complexity (Breeze et al. 2016, p. 929) and a high aggregation scale, particularly with regard to agricultural commodities. Moreover, the authors simulate the pollination loss within an unspecified “short timeframe” (ibid, p. 11), in which agents' ability to reallocate production factors, particularly land, remains unclear.

The problem common to all large-scale valuation approaches so far is that the reported and underlying dependence ratios are highly uncertain and in many cases derived from only few studies. They comprise broad ranges (for an overview see Gallai et al. 2009, p. 811) and were obtained under different experimental settings. The estimation of yield effects due to insect pollination is not only afflicted with uncertainty regarding these ratios (i.e, their variety-specificity and the agroecological conditions of the field experiments under which they were obtained), but also depends on the assumptions about the current state of the agroecological system. In other words, the experimental reference situation leading to the observed crop production (e.g., the pollinator potential when pollinators are not prevented from visiting the flowers) is not always clear (for an extensive discussion of this problem see Melathopoulos et al. 2015).

As will be illustrated below, it makes a substantial difference whether the assumed pollinator reference situation denotes a full pollinator potential or (complete) pollinator absence. Further, a common assumption of global partial equilibrium valuations is that current crop revenues are obtained without measures to mitigate pollinator loss, such as pollination by hand or placing bee hives in fruit plantations. In reality, in the case of global analyses, the true state of wild and managed pollinators is unknown, and it is unclear to what extent some regional status quos have already approached situations of complete degradation of insect pollination. Consequently, in the following not only do we examine the influence of the size of the dependence ratio but also illustrate the differences in the estimated welfare effects that result from assumptions on whether the reference situation is the state of the environment “before” or “after” a pollinator collapse.

3. Analytical framework for evaluating welfare effects of pollinator abundance

The long-term reactions of producers and consumers to a change in pollinator services and the resulting new market equilibria for pollinator-dependent crops involve a multitude of adaptations. These are difficult if not impossible to anticipate and therefore, one may renounce to the long-term perspective and only focus on the near future instead. Admittedly, the reference case of a complete disappearance of pollinators is a theoretical construct in both the long run and the short run. Hence, estimating long-term welfare effects has the same argumentative value as asking what society would lose in the short term when suddenly all pollinators disappeared. *Short-term* here refers to one year or cropping season after a pollinator collapse occurred and before significant adaptation can take place, whereas *long-term* refers to several years until a new (bioeconomic) equilibrium has been reached. Thus, in this section, we theoretically analyze both short-term and long-term welfare effects of a complete pollinator loss in a partial equilibrium setting before empirically applying the different approaches in Section 4. These welfare analyses are comparative static in the sense of economic theory. We compare momentary market equilibria before and after certain crop yield changes occurred. The diagrams of this section do not illustrate the dynamics that lead to the new equilibria.

Following Southwick and Southwick (1992), Gallai et al. (2009) used a convenient way to appraise welfare losses from a potential pollinator collapse. A major advantage of this approach is its reduced need for data regarding pollinator impact and demand response. For the latter, they renounced to estimate (a system of) demand functions and relied on assumed own-price elasticities of demand instead. However, their theoretical foundations for welfare analyses are difficult to retrace. Hence, before discussing the implications and possible biases of the different partial equilibrium approaches and the resulting welfare effects, in this section, we present the underlying economic theory.

For simplicity and applicability reasons, and in accordance with Gallai et al. (2009), we assume isoelastic demand functions for all crops when modelling the interplay of supply and demand in our partial analyses as follows:

$$P(Q) = P_0\left(\frac{Q}{Q_0}\right)^{1/\varepsilon} \tag{1}$$

with

P = Price per unit of a certain crop.

Q = Crop quantity.

P_0 = Price at reference equilibrium.

Q_0 = Crop quantity at reference equilibrium.

ε = Own-price elasticity of demand.

Given perfect competition among the suppliers, the (long-term) equilibrium price P_0 just covers the full costs of the farmers. Hence, the long-term supply curve is horizontal, i.e., with a perfectly elastic own-price elasticity of supply. It should be noted that this zero-profit

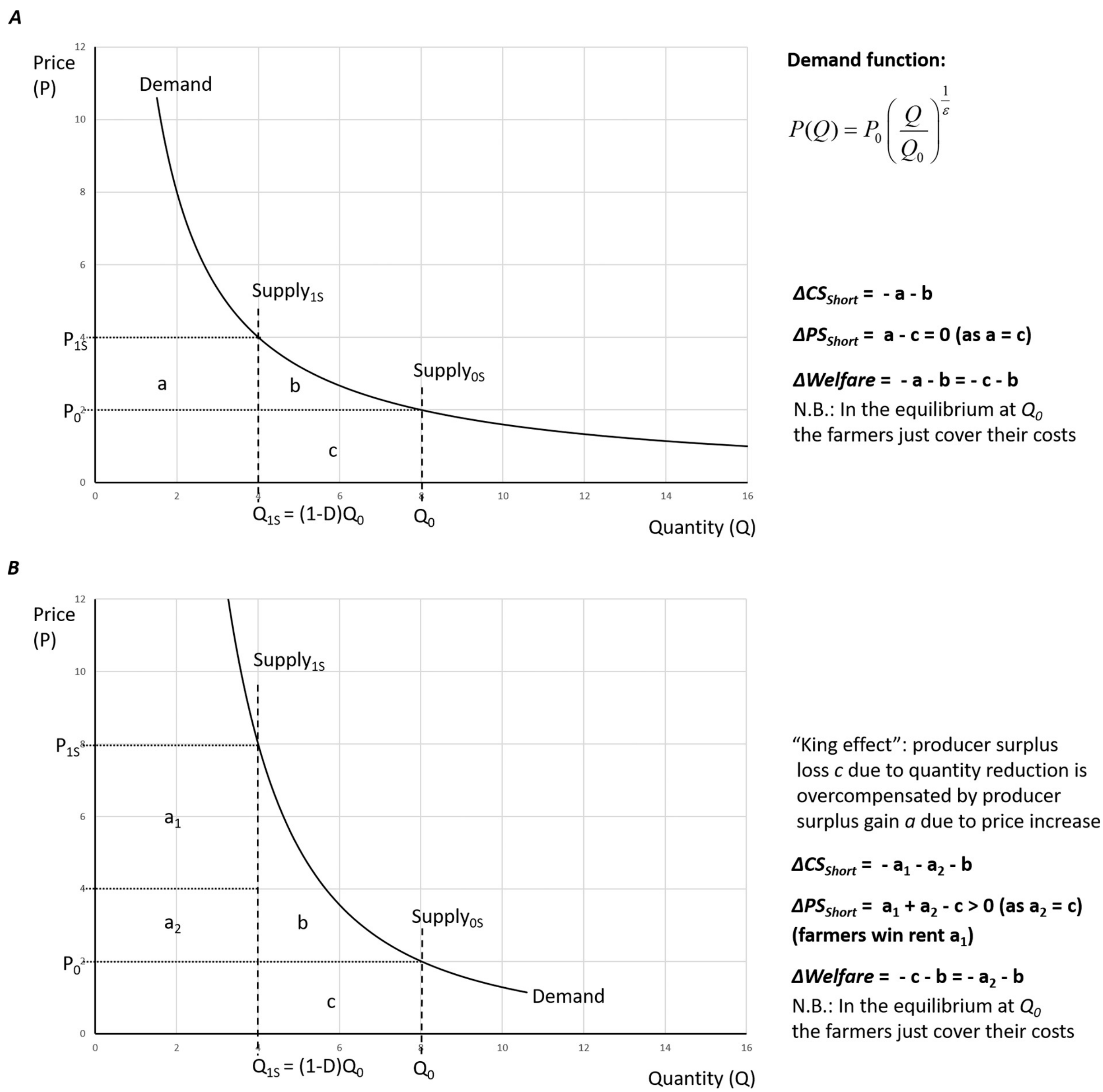

Fig. 1. A. Short-term welfare effects in the case of an elasticity of $\varepsilon = -1$. B. Short-term welfare effects in the case of an elasticity of $\varepsilon = -0.5$.

assumption disregards possible land rents due to beneficial agro-climatic conditions or other regional characteristics like positive agglomeration effects. Especially for high value crops, such site-specific land rents result in product revenues P_0Q_0 that exceed the opportunity cost of the common local farmland.

Another underlying assumption in Sections 3.1 and 3.2 is that the reference equilibrium (before a pollinator collapse) is always characterized by sound agroecological conditions with the full potential to sustain pollinating insects (i.e., Q_0 is the crop yield in the agroecological optimum). This assumption is removed in Section 3.3, where, in theory, we depart from a degraded pollinator situation and allow for pollinator recovery.

3.1. Short-term welfare effects of a sudden pollinator collapse

As in the short run farmers have almost no possibilities to mitigate abrupt changes of ecological conditions, the *short-term crop supply* is assumed to be perfectly inelastic. Using a crop price-quantity diagram, the short-term impacts of a sudden pollinator decline are illustrated in Fig. 1a and b. A sudden collapse of all pollinators would mean that harvest would drop from Q_0 to Q_{1S} (i.e., a shift from the curve $Supply_{0S}$ to the curve $Supply_{1S}$). This would lead to the short-term welfare effects illustrated in this section. Disregarding some short-term cost savings the resulting change in the producer surplus is written as follows:

$$\Delta PS_{Short} = P_{1S}Q_{1S} - P_0Q_0 = P_{1S}Q_0(1-D) - P_0Q_0 \tag{2}$$

where the additional symbols indicate the following:

Q_{1S} = Quantity produced and sold after a collapse of pollinating insect populations.

P_{1S} = Price reached in the short term after a collapse of pollinating insect populations.

D = Dependence ratio, i.e., the proportion of the total annual production of the crop that is due to animal-mediated pollination.[2]

Graphically, Eq. (2) is equal to subtracting area c (loss in producer surplus due to reduced output) in Fig. 1a and b from area a (gain in

[2] Here we follow the definition given in Gallai et al. (2009, p. 812). Notice that the ratio D only captures *quantitative yield* effects of insect pollination, whereas possible changes in crop *quality* (translating into price mark-ups) are not covered by this measure.

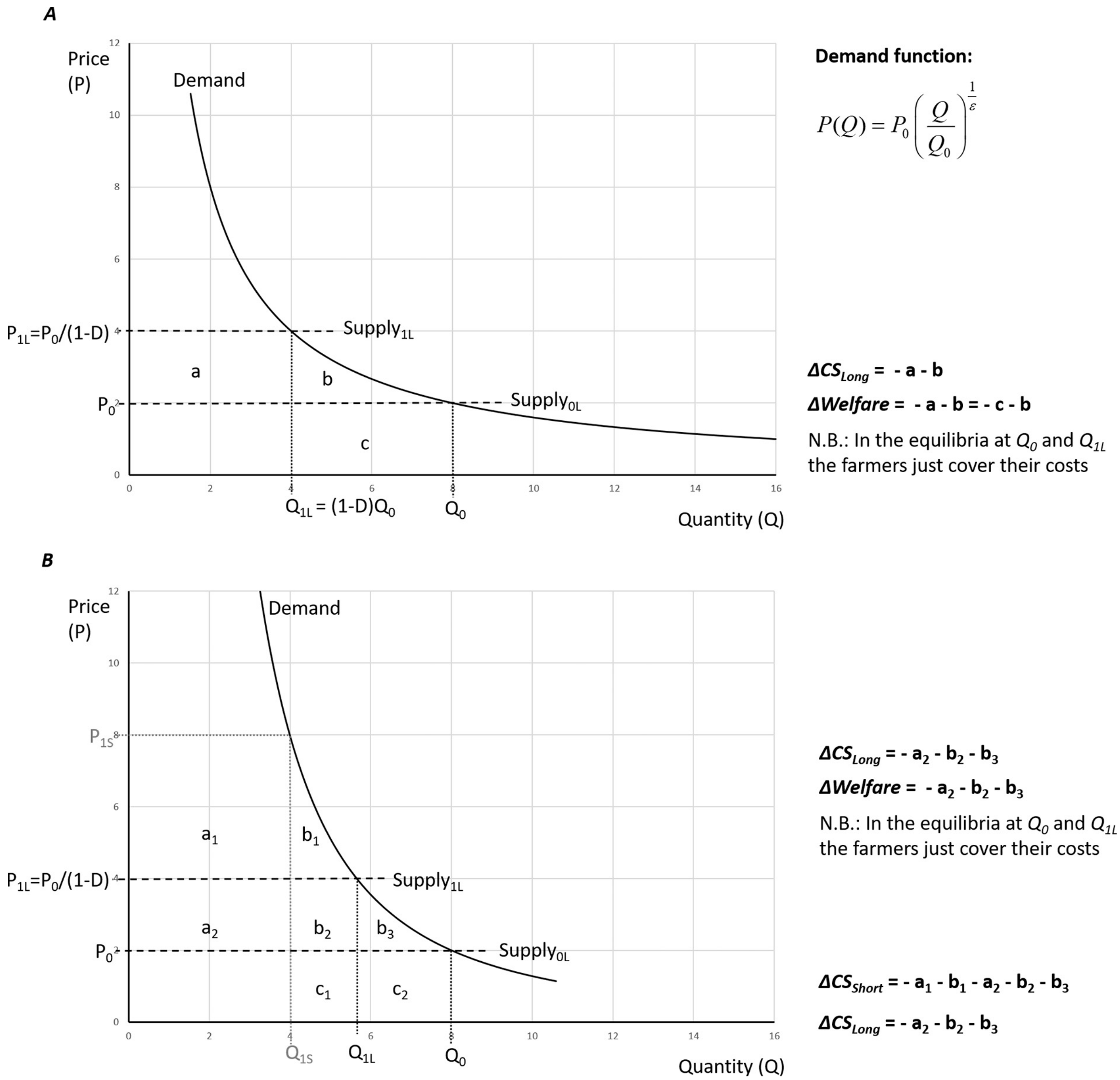

Fig. 2. A. Long-term welfare effects in the case of an elasticity of $\varepsilon = -1$. B. Long-term welfare effects in the case of an elasticity of $\varepsilon = -0.5$.

producer surplus from the price increase).[3] Hence, producers incur a loss if area *c* exceeds area *a*, and vice versa. Replacing P_{1S} with the demand function Eq. (1) thus yields the following equation:

$$\Delta PS_{Short} = P_0\left(\frac{Q_0(1-D)}{Q_0}\right)^{1/\varepsilon} Q_0(1-D) - P_0Q_0 = P_0Q_0\left[(1-D)^{\frac{1}{\varepsilon}+1} - 1\right]. \tag{3}$$

From Eq. (3), it follows that for any given dependence ratio *D*, the farmers' welfare changes strongly depend on the own-price elasticity of demand ε. For $\varepsilon = -1$, there is no change in the producer surplus ($\Delta PS_{Short} = 0$). In this case, the value lost from the decline in production (area *c*) is exactly offset by the change in revenue due to the price increase (area *a*). For an elastic demand (i.e., $|\varepsilon| > |-1|$), ΔPS_{Short} is negative; for an inelastic demand (i.e., $|\varepsilon| < |-1|$), the producers benefit, ΔPS_{Short}, is positive (see the example of Fig. 1b).

If not analyzing a simultaneous worldwide pollinator decline, but only a sudden and unexpected pollinator collapse in a small, price-taking region for which a constant crop price P_0 is given, ΔPS_{Short} would amount to P_0Q_0D (corresponding to area *c* in Fig. 1a and b), which is the production value due to (entomophilous) pollination. Thus, for local valuations of short-term benefits from insect pollinators in small regions, one could simply rely upon the expected decline in revenue that would result from a pollinator collapse. This revenue decline would then be a loss to local farmers who would not be compensated by increased market prices.

The short-term change of consumer surplus corresponds to areas *a* and *b* in Fig. 1a and b. It can be calculated as follows (see Appendix A1):

[3] Note: For the case treated here, area *c* is a loss in producer surplus as in the short run all relevant production costs are sunk costs (fixed costs) that farmers fully incurred before the sudden pollinator collapse occurred. Hence, in Fig. 1 the short-term supply curves start in the origin and are identical to the abscissa up to the vertical lines labelled *Supply*$_{\cdot S}$ (i.e. zero variable cost). In the real world, even in the very short run, this loss would be slightly reduced because of some cost savings, such as lower harvest and transportation costs, related to crop yield decreases. In regional crop-specific analyses, they can be accounted for as in the approach suggested by Winfree et al. (2011).

$$\Delta CS_{Short} = -a - b = -(P_{1S} - P_0)Q_{1S} - \int_{Q_{1S}}^{Q_0} P(Q)dQ + P_0(Q_0 - Q_{1S})$$

$$\Delta CS_{Short} = -\frac{P_0 Q_0}{1+\varepsilon}\left[(1-D)^{\frac{1}{\varepsilon}+1} - 1\right]. \tag{4}$$

For the special case of $\varepsilon = -1$, Eq. (4) reads (see Appendix A1):

$$\lim_{\varepsilon \to -1} \Delta CS_{Short} = \ln(1-D)P_0 Q_0. \tag{4a}$$

As for $\varepsilon = -1$, ΔPS_{Short} is equal to zero (see Eq. (3) above), in this case, the short-term welfare change corresponds to $\Delta CS_{Short} = \ln(1 - D) P_0Q_0$ (see Eq. (4a)). For all other elasticities ε from Eqs. (4) and (3), it follows that:

Welfare change (ΔW_{Short}) = ΔCS_{Short} + ΔPS_{Short} =

$$\Delta W_{Short} = -\frac{P_0 Q_0}{1+\varepsilon}\left[(1-D)^{\frac{1}{\varepsilon}+1} - 1\right] + P_0 Q_0\left[(1-D)^{\frac{1}{\varepsilon}+1} - 1\right] = \frac{\varepsilon}{1+\varepsilon}P_0 Q_0\left[(1-D)^{\frac{1}{\varepsilon}+1} - 1\right]. \tag{5}$$

3.2. Long-term welfare effects of a pollinator collapse

Compared to the reference long-term equilibrium at Q_0, there is no change in the producer surplus resulting from a pollinator decline, as in both cases (production before and after the collapse), the long-term revenues of the farmers are supposed to just cover their costs. A zero long-term change in producer surplus (ΔPS_{Long}) thus implies a welfare change (ΔW_{Long}) consisting solely of the long-term change in consumer surplus ($\Delta W_{Long} = \Delta CS_{Long}$).

The unit cost after a pollinator collapse at which farmers will operate in the new perfect competition equilibrium (realizing a price P_{1L} at which their costs are just covered) would equal $P_{1L} = P_0/(1 - D)$ (see Fig. 2a and b).

It should be noted that for an inelastic demand function ($|\varepsilon| < |-1|$; see Fig. 2b), this long-run equilibrium implies an expansion of the farmland used for the corresponding crop. The initially higher (short-run) price P_{1S} overcompensates for the crop revenue losses (see Fig. 1b) and thus creates an incentive for participating in the land rent before the price settles in the long-run equilibrium P_{1L} that is displayed in Fig. 2b. For an elastic demand function ($|\varepsilon| > |-1|$), on the other hand, long-term adaptation after pollinator collapse would lead to a release of farmland for other, more profitable agricultural or horticultural purposes. Entering P_{1L} into the demand function Eq. (1) and solving for Q yields the new long-term equilibrium quantity Q_{1L} as follows:

$$Q_{1L} = \frac{Q_0}{(1-D)^{\varepsilon}}. \tag{6}$$

The long-term consumer surplus (welfare) change (ΔCS_{Long}) is a loss that corresponds to area a plus b in Fig. 2a and correspondingly to area a_2 plus b_2 plus b_3 in Fig. 2b. It can be calculated as follows (see Appendix A2):

$$\Delta CS_{Long} = -P_{1L}Q_{1L} - \int_{Q_{1L}}^{Q_0} \frac{P_0}{Q_0^{1/\varepsilon}} Q^{1/\varepsilon} dQ + P_0 Q_0$$

$$\Delta CS_{Long} = -\frac{P_0 Q_0}{1+\varepsilon}\left[\left(\frac{1}{1-D}\right)^{1+\varepsilon} - 1\right]. \tag{7}$$

For the special case of $\varepsilon = -1$, Eq. (7) reads (see Appendix A2) as follows:

$$\lim_{\varepsilon \to -1} \Delta CS_{Long} = \ln(1-D)P_0 Q_0. \tag{7a}$$

Note that only in this special case of unit elastic demand ΔCS_{Long} equals the short-term change in consumer surplus ΔCS_{Short} (see Eq. (4a), above).

3.3. Partial welfare analysis for the case of crop yields recovering from reduced pollinator potential[4]

Because of the flaws linked to the long-term analysis discussed in Section 5, we only analyze the short-term effects associated with increasing crop yields when pollinators suddenly recover from hypothetical degradation. Keeping all other assumptions underlying Section 3.1, we assume the extreme case where, in the reference equilibrium, a pollinator collapse has already occurred and the benefits corresponding to a full insect pollination potential have already been lost and are to be assessed. In other words, the quantity $Q_{1S} = Q_0/(1 - D)$ is now greater than the observed reference crop production Q_0.[5]

Without accounting for additional harvest cost incurred due to an increased crop yield, the farmers will obtain the following change in producer surplus:

$$\Delta PS_{Short}^{+} = P_{1S}Q_{1S} - P_0 Q_0 = P_{1S}\frac{Q_0}{1-D} - P_0 Q_0$$

$$\Delta PS_{Short}^{+} = P_0\left(\frac{Q_0}{(1-D)Q_0}\right)^{1/\varepsilon}\frac{Q_0}{1-D} - P_0 Q_0 = P_0 Q_0\left[\left(\frac{1}{1-D}\right)^{\frac{1}{\varepsilon}+1} - 1\right]. \tag{8}$$

From Eq. (8), it follows that for $\varepsilon = -1$, the producer surplus gain of the farmers would equal zero. Notice that in the case of an inelastic demand ($|\varepsilon| < |-1|$), the farmers' gains would be negative (i.e., a yield increase would result in revenue losses due to an opposite “King effect”, see Section 5).

The short-term changes in consumer surplus because of a sudden worldwide pollinator switchover from complete degradation to the agroecological optimum can be expressed as follows (see Appendix A3):

$$\Delta CS_{Short}^{+} = P_0 Q_0 + \int_{Q_0}^{Q_{1S}} \frac{P_0}{Q_0^{1/\varepsilon}} Q^{1/\varepsilon} dQ - P_{1S}Q_{1S}$$

$$\Delta CS_{Short}^{+} = \frac{-P_0 Q_0}{1+\varepsilon}\left[\left(\frac{1}{1-D}\right)^{\frac{1}{\varepsilon}+1} - 1\right]. \tag{9}$$

For the special case of $\varepsilon = -1$, Eq. (9) is as follows (see Appendix A3):

$$\lim_{\varepsilon \to -1} \Delta CS_{Short}^{+} = -\ln(1-D)P_0 Q_0, \tag{9a}$$

for which the absolute value is equal to ΔCS_{Short} (see Eq. (4a)).

Hence, if $\varepsilon = -1$, ΔPS_{Short}^{+} will be equal to zero (see Eq. (8) above) and it will follow that the corresponding short-term welfare change is $\Delta W_{Short}^{+} = \Delta CS_{Short}^{+} = -\ln(1 - D)P_0Q_0$. For all other elasticities ε, it follows from Eqs. (8) and (9) that:

$$\Delta W_{Short}^{+} = \Delta PS_{Short}^{+} + \Delta CS_{Short}^{+} = P_0 Q_0\left[\left(\frac{1}{1-D}\right)^{\frac{1}{\varepsilon}+1} - 1\right] - \frac{P_0 Q_0}{1+\varepsilon}\left[\left(\frac{1}{1-D}\right)^{\frac{1}{\varepsilon}+1} - 1\right] = \frac{\varepsilon}{1+\varepsilon}P_0 Q_0\left[\left(\frac{1}{1-D}\right)^{\frac{1}{\varepsilon}+1} - 1\right]. \tag{10}$$

[4] In the following, welfare changes due to *recovery* from an assumed pollinator collapse are designated by a plus sign (e.g., ΔW_{Short}^{+}).

[5] In reality, the actual delivered crop pollination services may lie somewhere between their (unknown) full potential and the complete pollinator collapse situation. We call the situation where the full insect pollination potential is achieved (when all crop harvests contain the share D) the agroecological optimum.

Table 1
Worldwide welfare effects of global pollinator changes in billions of USD for the average agricultural production value 2016–18 (in current prices).

1	2	3	4	5	6	7	8
	Short-term effects of a pollinator decline in billions of USD			Long-term effects of a pollinator decline in billions of USD	Short-term effects of a pollinator recovery in billions of USD		
Own-price elasticity of demand ε	Producer surplus	Consumer surplus	Total welfare changes	Consumer surplus[a]	Producer surplus	Consumer surplus	Total welfare changes
	ΔPS acc. to Eq. (3)	ΔCS acc. to Eq. (4)	ΔW acc. to Eq. (5)	ΔCS acc. to Eq. (7)	ΔPS^+ acc. to Eq. (8)	ΔCS^+ acc. to Eq. (9)	ΔW^+ acc. to eq. (10)
−1.5	−211	−422	−634	−574	365	730	1095
−1.4	−186	−467	−654	−608	298	745	1043
−1.3	−156	−522	−678	−648	227	759	987
−1.2	−118	−591	−709	−693	155	775	930
−1.1	−68	−682	−750	−745	79	790	869
−1.0	0	−805	−805	−805	0	805	805
−0.9	98	−983	−884	−876	−82	821	739
−0.8	251	−1258	−1006	−959	−167	837	669
−0.7	520	−1734	−1214	−1058	−256	854	598
−0.6	1084	−2712	−1627	−1176	−349	874	524
−0.5[b]	2681	−5363	−2681	−1318	−449	898	449

Source: Authors' calculations based on average production value estimates 2016–2018 of pollination dependent crops (USDA, 2019; FAO 2020).
[a] Consumer surplus change here corresponds to the total welfare effects as the producer surplus does not change.
[b] Note: The large difference between long-term and short-term welfare losses in the case of inelastic demand is mainly due to highly pollination dependent crops with a dependence ratio of $D = 95\%$ (in particular melons and pumpkins).

4. Estimated welfare effects due to changes in insect pollination

The objectives of our empirical analyses are (i) to demonstrate the quantitative implications of the previously presented approaches, (ii) to produce corresponding value estimates based on most recent global data, and (iii) to perform a sensitivity analysis of the impact of own-price elasticities and of dependence ratios on the valuation results. To account for the uncertainty regarding demand, all global estimations are carried out for a set of different price elasticities. The influence of the highly uncertain dependence ratios is analyzed for the case of Germany by means of a Latin Hypercube Sampling experiment.

4.1. Worldwide welfare effects of global pollinator changes using 2016-18 data

In this section, for a range of own-price elasticities, we estimate the welfare implications ΔW caused by a hypothetical global insect pollinator collapse from short-term and long-term perspectives and by a hypothetical short-term global recovery of pollination services (Table 1). Unlike the collapse scenarios, the latter deviates from the implicit assumption that the reference situation is characterized by optimal agroecological conditions. In many parts of the world, insect populations and closely linked pollinator services have already substantially declined (cf. Sánchez-Bayo and Wyckhuys 2019), and the corresponding reference situation thus reflects suboptimal agroecological conditions. At the global level, we neither observe the full potential of pollinator services nor (fortunately) have we experienced a complete collapse. However, the simulation of a recovery scenario becomes increasingly relevant the more a current state is approaching a general degradation of pollinator services.

We use recent data (2016–2018) on agricultural production values aggregated for five world regions (Africa; Asia and Oceania; Europe; Northern America; and Latin America and the Caribbean). Crop specific pollination dependence ratio data for 63 crops are taken from Klein et al. (2007) and FAO (2008) (see Appendix B). The welfare effects are computed for each region and crop applying Eqs. (3) through (10) across a range of plausible own-price elasticities. The regional changes for consumer and producer surplus and total welfare are aggregated at the global level as reported in Table 1.

Notice that the welfare effects resulting from a pollinator decline have opposite signs than the corresponding effects due to a recovery. In the first case, less is produced and consumers lose, while in the latter case crop harvests increase and consumers win. The different absolute values of the short-term effects for both cases are due to the specific shape of the isoelastic demand functions and to the absolute values of assumed crop harvest changes (e.g., for $D = 0.5$ the assumed yield increase caused by recovery is twice as much as the respective loss because of a decline).

The relevance of the value of pollination services becomes clearer when expressing it in terms of world GDP, as reported in Table 2. In this table, the estimates from Table 1 for 2016–18 are also compared to the short-term and long-term welfare effects computed for the year 2005 using the production value data by Gallai et al. (2009). The absolute 2005 welfare effects (in billion EUR) are presented in Appendix C.

Table 2
Worldwide welfare effects of global pollinator changes in % of world GDP in 2005 and 2016–18.

Own-price elasticity of demand ε	Short-term welfare changes		Long-term welfare changes	
	2005	2016–18	2005	2016–18
−1.5	**−0.5%**	−0.8%	**−0.5%**	−0.7%
−1.4	**−0.6%**	−0.8%	**−0.5%**	−0.7%
−1.3	**−0.6%**	−0.8%	**−0.6%**	−0.8%
−1.2	**−0.6%**	−0.9%	**−0.6%**	−0.9%
−1.1	**−0.6%**	−0.9%	**−0.6%**	−0.9%
−1.0	**−0.7%**	**−1.0%**	**−0.7%**	**−1.0%**
−0.9	**−0.8%**	**−1.1%**	**−0.7%**	**−1.1%**
−0.8	**−0.9%**	**−1.2%**	**−0.8%**	**−1.2%**
−0.7	−1.0%	**−1.5%**	−0.9%	**−1.3%**
−0.6	−1.4%	**−2.0%**	−1.0%	**−1.4%**
−0.5	−2.2%	−3.3%	−1.1%	−1.6%

Note: The world GDP data (in current prices) for 2005 and 2016–18 is taken from the World Development Indicators database (World Bank 2020). The bold printed values denote the plausible range of shares in 2005 according to the reasoning of Gallai et al. (2009) and in 2016–18 the range considered adequate by the authors (see Section 5.1).
Source: Authors' calculations based on Klein et al. 2007; USDA, 2019; FAO 2020; World Bank 2020

Table 3
Pollinator-dependent crops and their average production values in Germany from 2006 to 2016.

Crop i	Average production value in 10^6 EUR P_0Q_0	% Share	Average prod. value due to pollination in 10^6 EUR P_0Q_0D	Dependence ratios D			Own price elasticity of demand ε	Sources for ε
				Min	Max	Mean		
Apple	872.3	22.4%	567.0	0.40	0.90	0.65	−0.57	a,b,c
Cherries	134.4	3.5%	87.4	0.40	0.90	0.65	−0.41	d
Plums and sloes	61.2	1.6%	39.8	0.40	0.90	0.65	−0.92	a
Pears and quinces	39.4	1.0%	25.6	0.40	0.90	0.65	−1.16	a,b
Sour cherry	30.1	0.8%	19.6	0.40	0.90	0.65	−0.41	d
Cranberries and blueberries	55.2	1.4%	35.9	0.40	0.90	0.65	−1.49	e
Raspberries and other berries	29.9	0.8%	19.4	0.40	0.90	0.65	−1.66	e
Currants and gooseberries	41.0	1.1%	10.3	0.10	0.40	0.25	−1.50	f
Blackberries	3.4	0.1%	2.2	0.40	0.90	0.65	−1.88	e
Cucumbers and gherkins	312.9	8.0%	203.4	0.40	0.90	0.65	−0.51	a
Pumpkins, squash and gourds	86.2	2.2%	81.9	0.90	1.00	0.95	−1.20	f
Zucchini	37.7	1.0%	35.8	0.90	1.00	0.95	−1.20	f
Beans, green	202.2	5.2%	10.1	0.00	0.10	0.05	−0.59	a
Tomatoes	153.6	3.9%	7.7	0.00	0.10	0.05	−0.45	a
Chilies and peppers, green	12.0	0.3%	0.6	0.00	0.10	0.05	−0.25	a
Strawberries	618.5	15.9%	154.6	0.10	0.40	0.25	−0.60	a,c,e
Broad beans, dry	10.1	0.3%	2.5	0.10	0.40	0.25	−1.20	f
Soybeans	1.3	0.0%	0.3	0.10	0.40	0.25	−0.37	g,h
Aggregate of fruits, vegetables and legumes	*2701.4*	*69.4%*	*1304.1*	*0.29*	*0.67*	*0.48*	*−0.50*	i
Rapeseed	1178.8	30.3%	294.7	0.10	0.40	0.25	−0.81	g,h
Sunflower seeds	11.0	0.3%	2.7	0.10	0.40	0.25	−0.77	g,h
Aggregate of oilseed crops	*1189.8*	*30.6%*	*297.4*	*0.10*	*0.40*	*0.25*	*−0.36*	i
Total	**3891.1**	**100.0%**	**1601.5**	**0.23**	**0.59**	**0.41**		

Note: In the case of available multiple estimates per crop, the simple average was computed. The dependence ratios of the aggregate categories and of the total are the weighted averages (weighted by the production values).
Source: Authors' calculations based on dependence ratios from Klein et al. 2007; Oré Barrios et al. 2017

[a] Simple average of demand elasticities reported in the USDA (2006) database. Only studies conducted in high-income countries using data from 1990 and sooner were considered.
[b] Durham and Eales (2010)
[c] Lin et al. (2009).
[d] Florkowski and Carew (2011).
[e] Sobekova et al. (2013).
[f] No studies were found, instead author assumptions were used
[g] Kojima et al. (2016).
[h] Kojima et al. (2014).
[i] Femenia (2019).

4.2. Case study for Germany

In this section, we focus on Germany as an illustrative case study for which the different estimation approaches presented above are applied to important pollination-dependent crops of a single country. Taking the average output values P_0Q_0 from 2006 through 2016 and the crop-specific demand elasticities derived from the available literature (see Table 3), we perform a Latin Hypercube Sampling experiment to calculate likely distributions of the welfare effects. For each crop, we randomly draw 10,000 dependence ratios D from the triangular distribution represented by the parameters for D in Table 3.[6]

In Germany, an average EUR 3.9 billion of crop production value (Table 3) was dependent on insect pollination between 2006 and 2016 (Oré Barrios et al. 2017). The production value weighted-average dependence ratio of the pollinator-dependent crops is 41%, which corresponds to an at-risk production value of EUR 1.6 billion. The production values P_0Q_0 given in Table 3 are used for the following estimations. Note that the displayed values P_0Q_0 are production values averaged over several years to avoid over- or underestimations due to single harvests.

Again, a partial equilibrium approach is applied, which does not account for any cross-price relationships or for possible intercountry adjustments via trade mechanisms. The latter is due to the assumption of identical consumer preferences across countries. In reality, consumers from Germany (and other high-income countries) with high purchasing power may exhibit rather inelastic demand behavior, leading to a relative high consumption of pollinator-dependent crops vis-à-vis low-income countries where price increases in common agricultural goods are likely to result in a diminished consumption.

Applying Eqs. (3) through (10), the welfare effects are computed with 10,000 draws from the dependence ratio distributions using the Latin Hypercube Sampling package *lhs* of the statistical software package *R* (v4.0.0) (Carnell 2020). We assume that the crop specific dependence ratios are statistically independent from one another, i.e. their parameters are uncorrelated.[7] The resulting distributions of consumer and producer surplus are shown in Fig. 3 as boxplot graphs of the short-term and long-term welfare effects. The results can be interpreted as the German part of the overall welfare impact following a global pollinator decline or recovery (i.e., supposing that the German yield changes are not compensated by trade[8]).

Overall, the welfare effects in the case of a pollinator collapse scenario vary strongly when accounting for the uncertainty in the

[6] The number of iterations was tested for convergence by running the experiment with also 9,000 and 11,000 iterations. The results of these experiments did not differ from the core experiment within a 1% threshold.

[7] Animal-pollinated crops with similar plant physiology may exhibit a positive correlation of variance in dependence ratio. However, there is (yet) no sufficient data to quantify this, which is why we assume no correlation.

[8] This assumption implies that the yield losses are entirely borne by (domestic) consumers whose preferences are correctly captured by the applied demand elasticities.

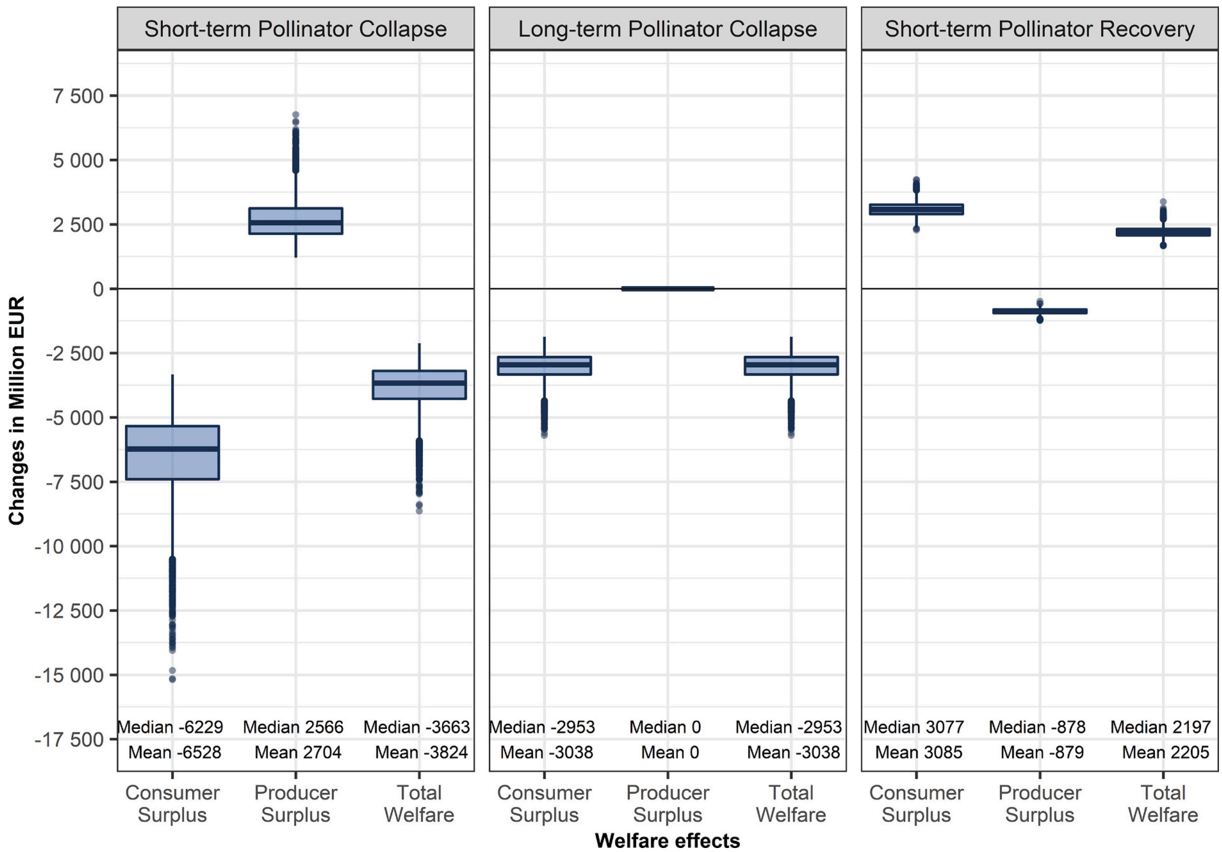

Fig. 3. Box plots showing the short- and long-term welfare effects for Germany of the pollinator collapse and recovery scenarios using crop-specific production values and dependence ratios varied in a Latin Hypercube Sampling (LHS) experiment with 10,000 iterations.
The boxes show the interquartile range (IQR) of the results (between the 25% and 75% quantile), and the whisker length is at most 1.5 times the IQR (beyond which the outliers are plotted).

dependence ratios. The highest variance of the possible welfare effects is reported for the short-term welfare effects of a pollinator collapse, with an interquartile range (IQR) of EUR 1.1 billion. For the long term, the IQR is EUR 0.7 billion. On the other hand, the welfare effects of an assumed pollinator recovery are less sensitive to changes in the dependence ratios. Moreover, the magnitude of the welfare gains in the case of pollinator recovery is also substantially lower compared to the negative welfare effects in the case of a decline.

The amount of total welfare changes is, at the mean, 26% greater in the short term than in the long term. This difference is particularly striking when comparing the extent of the consumer surplus losses, which on average were approximately only EUR 3.0 billion when using the long-term approach compared to EUR 6.5 billion with the short-term approach. The higher short-term consumer surplus losses are, however, partly offset by an increase in the producer surplus (EUR 2.7 billion).

The stochastic analysis with varying dependence ratios reports different mean welfare effects when compared to a static computation. This is due to the hyperbolic shape of the demand functions, which results in an amplification of dependence ratio increases compared to computation runs where dependence ratios are decreased by the same percentage. The difference for the welfare effects in the case of the recovery scenario are negligible, but the total welfare effects in the short-term and long-term pollinator collapse differ by 10.6% and 6.1%, respectively between static and stochastic computations (see Appendix D).

5. Discussion

The long-term partial equilibrium approach introduced by Southwick and Southwick (1992) and applied to worldwide crop production by Gallai et al. (2009) is contingent upon several strong assumptions that limit its applicability. We therefore compare it to an approach that simply estimates the short-term welfare effects, which are valid only for the year after a theoretical collapse (or recovery) of pollinators. In this section, we first discuss our results from applying both approaches and then debate the implications of the underlying model representation of the economic and the ecological systems, which need to be considered when interpreting estimation results.

5.1. Impact of demand elasticities on the estimation results

The differences between the short-term and long-term total welfare effects of a pollinator collapse (see Table 1) depend on the magnitude of each affected crop's own-price elasticity of demand. Demand elasticities are a common source of uncertainty when estimating market and welfare effects. Consumer demand is more elastic at the product level due to the many substitution possibilities, whereas at the aggregate commodity group level, e.g., fruits or stimulant crops as a whole, substitution possibilities are limited. This is also reflected in a recent meta-analysis of the price and income elasticities of food demand (Femenia 2019), which inter alia aimed to improve the parametrization of long-term food projections. For fruits and vegetables, for instance, the study reported an ε of -0.7 at the product level, but of -0.5 at the aggregate level.

Accordingly, since the production of a wide set of crops is affected, an elastic demand behavior (at least for major fruits and vegetables, and especially in the short run) is unlikely. Moreover, at the crop level, the illustrative example from Germany suggests that the production value weighted average of demand elasticities equals -0.65 and -0.81 for the categories “fruits and vegetables” and “oilseed crops”, respectively. Hence, even at the individual crop level empirical estimates point towards a moderately inelastic demand for pollination dependent food crops. Therefore, it is plausible that own-price elasticities ε range between -0.5 and -1.0. This stands in contrast to Gallai et al. (2009), who argued that “long-term elasticities [are] traditionally higher [than unity]” and therefore chose to predominantly communicate welfare losses corresponding to a range of ε between -0.8 to -1.5.

At the upper end of the suggested plausible range ($\varepsilon = -1$), the welfare losses of USD 805 billion are equal in the short and long terms (and also in the recovery scenario, yet with opposite sign), which is in conformity with Eqs. (4a), (7a) and (9a). At the lower end ($\varepsilon = -0.5$), the short-term welfare losses amount to USD 2681 billion, which is about twice as much as in the long-term (USD 1318 billion).[9] This makes sense because, when assuming the same demand elasticities for the short-term as for the long-term (i.e., keeping the demand function constant over time), the consumers will suffer less losses once the producers will have adapted to the new situation (i.e., once the economic system will have switched from inelastic to elastic supply). The short-term approach also allows highlighting the distributional implications that a global crop-pollination deficit would entail. Consumers and producers suffer both from welfare losses when $|\varepsilon| > 1$. However, consumers suffer substantially higher economic losses in the short term if $|\varepsilon| < 1$, which on the whole is partly offset by the gains in producer surplus due to the “King-Davenant law” (see below).

Considering the range of ε between -0.6 and -1.0, the value of pollination services in 2016–18 as a share in world GDP may range between 1.0% and 2.0% in the short-term and between 1.0% and 1.4% in the long-term (Table 2). According to the widely cited and communicated estimates from Gallai et al. (2009), for the elasticities shown in Table 2 the welfare effects of a collapse in pollination services (in the long-term) in 2005 comprised between 0.5% and 1.1% of world GDP. These shares are markedly higher under the short-term perspective, ranging from 0.5% to 2.2%. Contrasting the 2005 and 2016–18 estimates, it seems as though the economic relevance of pollination services has increased across the range of own-price elasticities and time horizons. Reasons for this increase could be changes in consumer preferences (e.g., a shift towards pollination-dependent crops) or disproportionately high increases in the prices of pollination dependent crops between 2005 and 2016–18, which could be due to higher production cost or to the mentioned shift in preferences. This trend seems at least corroborated by Aizen and Harder (2009), who claimed that the share of agricultural output that requires animal pollination increased more than 300% (in response to increasing demand per capita) during the half century preceding their study. However, the high difference in estimated GDP changes may also stem from the data used by Gallai et al. (2009). As they rely on production data from one year, this makes their analysis susceptible to extraordinary effects that may have occurred in that year. Moreover, for many pollination dependent crops, they probably underestimated the production value by averaging producer prices over 11 years (1991–2002) without adjusting for inflation.

There are two major differences between the estimation approach of the global analysis conducted in Section 4.1 and the case study in Section 4.2. First, the country-specific analysis relies on empirical point estimates for the parametrization of the own-price elasticities of demand (see second to last column in Table 3). While there are many studies estimating own-price elasticities of demand, there is a scarcity of estimates for most countries, particularly at the product level. The point estimates presented in Table 3 are from a range of studies conducted in high-income countries using different data sources and methods. In an ideal world, elasticity estimates would be available from studies conducted in the case study country using consistent data and methods. Even so, we preferred to use the above presented estimates as “best guesses”. On balance, these estimates reflect plausible consumer preferences. Commonly consumed fruits and vegetables (e.g., apples and tomatoes) face quite inelastic demand, while a higher elasticity is reported for niche goods (e.g., blackberries).

Second, in contrast to previous studies that applied mean dependence ratios, our analysis accounts for the uncertainty about the effects of pollinator presence on the crop yields. Applying the constant elasticities displayed in Table 3, we treat the dependence ratios as a stochastic parameter, which is assumed to follow a triangular distribution along the minimum, mean and maximum values of the dependence ratios presented in Table 3.

It should also be noted that in the German case study, the magnitude and the range of the simulated short-term welfare effects of an assumed pollinator recovery are much smaller than the corresponding values in the case of a collapse (see Fig. 3). This effect can be explained by the inelastic demand of the crops with a high share in consumers' expenses (see Table 3 and the shape of the inelastic demand function in Fig. 1b).

5.2. *Impact of the representation of the economic system on the results*

5.2.1. *Adaptations in the short-term versus long-term changes*

We applied partial equilibrium approaches using a short-term and a long-term perspective. Both perspectives are based on a simple model representation of the economic system, e.g., there are no cross-price relationships and factor markets as well as sectors other than agriculture are excluded. While these are limitations when estimating how the economic system would adapt to a pollinator change scenario, they are of less concern in the short-term. The lack of cross-price relationships is of less relevance in the short-term, as then anyhow farmers cannot adapt to shocks immediately (i.e., no perfectly elastic supply response) and consumers only gradually change their consumption patterns (i.e., no change in demand elasticities). However, as outlined below, estimating the long-term welfare effects is problematic, as adjustments in the long run are highly uncertain and difficult to anticipate. This is also reflected in recent empirical research on adaptation towards climate change (D'Agostino and Schlenker 2016). Such adjustments could also consist of mitigating measures at the field level, such as the reallocation of farmland and labor to higher priced crops after a change in pollinator incidence.

In the long-term perspective, substantial changes in relative prices result in changes in consumption and production patterns and substitution effects via cross-price relationships that are then of much greater relevance. Over the long run, farmers can adjust to the decline in crop yields by either reallocating more (or less) land to pollination dependent crops or by relying on alternative mitigation measures such as self-fertile crop varieties or technical substitution of pollination services. However, the availability and ease of reallocation of land is constrained, among other factors, by the agroclimatic conditions of each site and the agronomic requirements of each crop. In this regard, estimating the effects of a pollinator decline with the long-term partial equilibrium approach is based on very questionable assumptions, as already remarked by Melathopoulos et al. (2015, p.66f.). Perfectly elastic supply of pollinator-dependent crops with zero producer surplus (*PS*), inherently assumes land homogeneity and unconstrained availability, thus allowing for perfect land reallocation for crops with

[9] It should be noted, however, that this large difference between short-term and long-term welfare losses is to a large extent due to some important crops with a dependence ratio of 95%. For these crops, the price increase resulting from the simulated 95% short-term decline in production is immense at $\varepsilon = -0.5$. Hence, one has to be careful when applying isoelastic demand functions over a wide range of crop harvests whenever an inelastic demand response is combined with high dependence ratios.

$|\varepsilon| \neq 1$. This clearly deviates from the real-world restrictions of the agricultural sector.

The long-term partial equilibrium approach only results in no change in farmland supply and no reallocation of crops (e.g., away from pollination dependent crops) when $|\varepsilon| = 1$, as reduced crop production on a given land area would automatically result in a new zero producer rent equilibrium. However, the own-price elasticities of the demand surveyed from the literature (Section 4.2) are either inelastic in the case of commonly consumed vegetables and fruits (e.g., tomatoes and apples) or elastic in the case of "luxury" goods, such as most berries. Moreover, it is likely that the production of high-value crops on a limited supply of land (with the required agroclimatic conditions) will generate rents[10] that violate the assumption of zero producer surplus. Only in the case of an own-price elasticity of $|\varepsilon| = 1$ would the long-term and short-term consumer surplus losses be identical and respectively correspond to overall average yearly welfare losses (see Figs. 1a and 2a). In other words, only in the rather special case of unit elastic demand do $Q_{1S} = Q_{1L}$ and $P_{1S} = P_{1L}$ simultaneously hold. In this case, there would be no need for land and labor reallocation after a harvest loss and the induced price change.

The assumption of long-term adaptation implies that (in the case of $|\varepsilon| < 1$) farmers will have an incentive to devote more land to pollinator-dependent crops until the crop prices decrease from P_{1S} to $P_{1L} = P_0/(1 - D)$ (see Fig. 2b), where, finally, a new zero farm profit market equilibrium is reached. This, however, would in reality increase the cost of the land required to produce Q_{1L}, consequently driving up price P_{1L}. This dynamic effect is not reflected in the long-term equilibrium analysis in Section 3.2 (and illustrated in Fig. 2b) also because of the doubtful assumption of an unconstrained supply of land, which furthermore requires the assumption of land homogeneity. The assumption of a horizontal long-term supply curve may make sense for a ceteris paribus analysis of one single crop with a low share in overall agricultural land. But this is not the case when many important crops are affected simultaneously. Also for this reason, the long-term partial equilibrium perspective is inappropriate.

Beyond the reallocation of land, long-term adaptations to pollinator declines may involve technological changes, such as the replacement of pollination services or the adoption of self-fertile crop varieties. At any rate, it is likely that the long-run price consequences of a pollinator deficit (i.e., once a new market equilibrium has been reached) would be weaker than those in the short run, as in the long run, consumer and producer adaptation possibilities are less constrained. Indeed, according to an economic interpretation of Le Chatelier's principle (Samuelson 1983), the absolute values of the long-term demand and supply elasticities tend to be greater than those in the short run. In the very long run and as a result of improved production technologies–induced by the disturbance of the bioeconomic system–, one may even expect no differences in the crop yields due to the presence or absence of insect-mediated pollination.

For short-term price and welfare reactions to a sudden change in pollinator abundance, however, the corresponding partial equilibrium analysis presented above seems appropriate, as it is not possible for the farm sector to adapt immediately (i.e., which would translate into elastic supply functions) and for consumers to quickly change consumption patterns (i.e., which would translate into changed demand elasticities). The short-term consumer and producer surplus changes presented in Section 4 can be seen as one-year welfare contributions of the available pollinators and as the amount of money that, in the present year, society owes to the existence of wild and managed pollinators.

[10] It is nevertheless conceivable that a pollinator collapse would be followed by a higher relative profitability of wind-pollinated crops, with a corresponding increase in land rental prices, which in turn could erode the rents that had been realized with pollinator-dependent fruit production before such a collapse.

Both approaches outlined in this article yield somehow artificial figures. The short-term approach gives an estimate for the loss incurred when suddenly all pollinators disappeared. The long-term approach produces an estimate for the corresponding loss once the economy has perfectly adapted to the disappearance of pollinators, which is subject to the aforementioned uncertainties. High uncertainty is also inherent to the time horizon that a long-term adaptation would take.

5.2.2. Parametrization of the economic system

In the worldwide valuations that we present, welfare estimates also rely on uniform, own-price elasticities ε that are broadly applied to all crops, thus attributing them to identically shaped demand curves. We make up for this approach by conducting a sensitivity analysis in which we calculate welfare changes with a range of values of ε that illustrate that the crops present lower and higher price elasticities. Gallai et al. (2009) argued that the choice of a single ε for each calculation was as arbitrary as if they had chosen distinct elasticity values, reasoning that there were no sound econometric foundations for the latter. We nevertheless contend that this choice entails a strong simplification, as in contrast to the worldwide analyses presented above, it is unlikely that all crops show the same demand elasticity, especially on a global scale. The assumption of a single elasticity coefficient neglects the multiplicity of the consumer preferences, constraints and behaviors that shape the demands for the different agricultural products, further disregarding the substitution possibilities between different crops and crop bundles.

Arguably, product-specific point estimates of demand elasticities are a reasonable choice for a ceteris paribus scenario, in which only the yield of one specific crop is affected. In the case of a global pollinator collapse, however, a large range of crops would be affected simultaneously. This also begs the question of whether the welfare effects should instead be estimated at aggregate levels–with relatively certain estimates for the elasticities but losses of information due to the weighted average calculations of the production values and dependence ratios–or at the product levels, which entails the above-mentioned drawbacks. Anyway, for a global valuation, we would appeal to choose low elasticities of demand because of the simultaneous reduction of harvests for many major fruits and vegetables, which means that consumers would have fewer opportunities to buy cheaper alternative crops.

5.2.3. Relevance for distributional and policy implications

In the context of important changes in food prices, also the *distribution* of welfare changes would be relevant and should be considered in the analysis. The long-run perspective neglects important short-run distributional aspects. Again, especially in the case that *all* pollinator-dependent crops were simultaneously affected by a sudden pollinator catastrophe, one would expect an inelastic demand response, which would endow farmers with an (additional) rent. Such additional rent (corresponding to area a_1 in Fig. 1b, the whole area a being an income transfer from consumers to farmers, with area a_2 offsetting the loss of area c by the farmers) is due to the "King-Davenant law"[11] (Creedy 1986). This effect of an inelastic demand, i.e., a price increase overcompensating the yield reduction, was also mentioned by Gallai et al. (2009) in this context. It is also not an unlikely scenario, as similar effects are reported in the context of climate change (D'Agostino and Schlenker 2016). Thus, in the short run, pollination-deficient crops with elastic demands (i.e., $|\varepsilon| > 1$) will generate surplus losses for producers, whereas $|\varepsilon| < 1$ will signify surplus gains at the expense of consumers, who then would instantly lose more than in the long run. Hence, particularly in the context of crops facing inelastic demand, the long-run perspective may substantially underestimate the highly

[11] Also known as the "King effect" named after Gregory King, a statistician living in 18th century England.

relevant short-term distributional aspects of an abrupt pollination collapse.

In this regard, better-informed policy recommendations could be made if they took into consideration the disaggregated short-run welfare effects (ΔCS and ΔPS) of pollinator deficit occurrences and the corresponding adjustments and adjustment costs, which in the end may lead to a new long-term equilibrium.

A pollinator collapse always entails welfare losses even if in the short-term farmers could temporarily benefit from an overcompensation of yield declines by price increases. As economic theory outlined in Section 3 and our empirical analyses in Section 4 clearly show, the consumers of marketed crops will always lose more than producers can win. From a distributive perspective, this is all the more detrimental as there are many poor consumers in the world, whose livelihoods are put at risk when food prices increase. Further, even in the case of producers temporarily benefiting, the respective annual profits will erode over time when more and more farmers adapt to the changed situation. Finally, one should also be aware of the lost production of pollination dependent crops, which are not recorded in agricultural statistics (e.g., crops not covered by the FAOSTAT commodity list). In the case of unknown household production, producers and consumers are the same individuals, who will definitely lose and whose losses–in the absence of market transactions–are not accounted for by our above value estimates.

5.3. Impact of the representation of the ecological system on the results

Despite the diversity and ecological complexity of pollination, the ecological system must also be modeled with simplified assumptions, such as the extent to which crop production depends upon insect-mediated pollination. Applying pollinator dependence ratios it is assumed that each crop has a common, global production function regardless of differences in crop varieties, production regions and farming systems. Valuation approaches applying dependence ratios also generally disregard the (unknown) shape of the production function, which may be nonlinear with yields remaining unchanged past a certain pollinator buildup threshold (Winfree et al. 2011). An exception is the recent study by Reilly et al. (2020), who identify corresponding "breakpoints" for selected crops in the US. Furthermore, the assumption of a common ecological reference equilibrium for a worldwide abundance (or scarcity) of pollinators is very strong. Hence, the "true" representation of the (potential) pollinator impact on crop harvest is very likely somewhere in between the "collapse assumption" (ecological reference: ideal sound environment, a collapse resulting in $|\Delta W|$; see Table 1) and the "recovery assumption" (ecological reference: completely degraded environment, a recovery resulting in $|\Delta W^{+}|$; see Table 1).

Furthermore, it is unknown to what extent a harmful change in the ecological system that loses all "wild" pollinators may be compensated by mitigation measures such as pollination by hand or–if still possible–managed crop-pollination activities.[12] If in some regions such measures, which may also comprise costly reallocation of labor between the different regions of the world, were worthwhile in the long run, the welfare effects of a pollinator collapse would only amount to the related pollination replacement costs. The above long-term partial equilibrium measures would then overestimate the contribution of wild pollinators to welfare from agricultural productivity. Mitigation measures are unlikely to be implemented within the same growing season, which also speaks in favor of taking the short-term perspective when assessing the impacts of pollinator degradation scenarios. Conversely, in the situation of an already experienced degradation, the monetary value of a pollinator recovery could also be overestimated if mitigation measures were (partially) effective. In the latter case, this may also overestimate the short-run potential of welfare gains due to an ecological recovery.

The above-illustrated partial analyses have the advantage that only little information (about production values, dependence ratios and own-price elasticities of demand) is needed to obtain rough value estimates of pollination services. However, due to the very restrictive assumptions regarding an ecologically and economically static world, we argue that short-term estimates should be considered when applying such partial analyses.[13] Moreover, the fact that the scenario of an entire worldwide pollinator collapse (or recovery) is relatively unrealistic further appeals for estimates of welfare changes at the local or regional scales.

Juxtaposing the estimated short-term welfare losses against the yearly cost of pollinator maintaining measures could guide policy decisions. For policymakers, a yearly effort to avoid a pollinator collapse by incentivizing tailored farm management practices like those analyzed in Cole et al. (2020) would then be worthwhile as long as its annual costs were less than this estimated short-term welfare impact. Such efforts could consist in schemes for changing farming practices and/or measures to increase landscape diversity.

For instance, departing from an assumed full pollinator potential, one could relate the hypothetical short-term welfare loss for Germany of approximately EUR 3.8 billion (see Fig. 3) to the yearly cost of broadly implementing insect-friendly, low-input farming practices. Insect declines in cultivated landscapes are, to a large extent, ascribed to highly intensive agricultural practices as characterized by "[…] genetically-uniform monocultures, the recurrent use of synthetic fertilisers and pesticides, the removal of hedgerows and trees in order to facilitate mechanization, and the modification of surface waterways to improve irrigation and drainage" (Sánchez-Bayo and Wyckhuys 2019). Hence, to stop or to revert insect declines involves convincing farmers to change such practices by granting them compensation payments. Assuming a yearly cost to the state budget of EUR 300 per hectare of farmland–which is above most payments for low-input farming practices under the current agro-environmental scheme in southwestern Germany (MLR 2017)–one could cover half of the farmland in Germany (16.65 million hectares) with such schemes at a yearly budgetary cost of EUR 2.5 billion. This amount of money corresponds to the lower bound of the hypothetical welfare changes shown in Fig. 3.

5.4. Concluding comments

In this article, we scrutinized different partial equilibrium valuation approaches of global changes in pollinator populations. We conclude that, in consideration of the highly speculative nature of the corresponding long-term assumptions and simulations, these approaches should be better restricted to the short-term perspective. For the global long-term perspective, at least with regard to theoretical consistency, sophisticated partial or general equilibrium models with a reasonably high crop resolution and incorporation of cross-price relationships may be more suitable to quantify the effects of strong changes in pollinator populations. Effects of marginal changes in pollinator abundance cannot be assessed by means of large-scale valuations like the approaches analyzed in this article. Such valuations need to be based on

[12] Notice that anyway the present (worldwide) share of pollination services due to wild pollinators and the share due to managed honey bees remains largely uncertain and in many cases impossible to disentangle (Melathopoulos et al. 2015, p. 65).

[13] Given the high uncertainty regarding global demand elasticities, one may also opt for an–however, overall not very realistic–general demand elasticity of minus one when carrying out simple partial equilibrium analyses. One advantage of this choice would be that then (as shown in Section 3 and illustrated in Section 4.1) the estimated welfare impact would not depend on the time horizon of the partial equilibrium analysis but would only be sensitive to the assumed dependence ratios.

small-scale bioeconomic models calibrated for the different regions of the world.

The above large-scale valuation approaches are comparative-static and are neither suitable for illustrating the dynamics of an adaptation of the economic and the ecological systems after a pollinator collapse, nor can they produce sensible value estimates for the case of a slow continuous decline of pollinator abundance. The long-term partial equilibrium approach is based on strong assumptions regarding the unknown adaptation reactions of consumers, producers and ecosystems that render it an inappropriate source of reliable valuation results. In contrast, the short-term approach gives "before adaptation" value estimates of the bioeconomic system and therefore needs less assumptions. Relying on best guess values or estimates drawn from the literature for elasticities and dependence ratios, it can produce realistic value estimates for the pollination ecosystem services provided by insects and other pollinating animals. It is of interest for the general public and for policymakers that the corresponding annual values are substantial at a global scale and for Germany. Since these values even disregard other pollinator-related ecosystem services they by far justify efforts to preserve or improve the situation of pollinators in our agroecological systems.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2020.106860.

Dataset 1: Average 2016-2018 production values of pollination dependent crops for different world regions http://dx.doi.org/10.17632/v2vf37kmxj.1

Dataset 2: 2006 to 2016 average production values and dependency ratios for Germany http://dx.doi.org/10.17632/wfcf2f6mmf.1

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