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The Macroeconomic Cost of Catastrophic Pollinator Declines

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ABSTRACT

We develop a computable general equilibrium (CGE) approach to assess the macroeconomic impacts of productivity shocks due to catastrophic losses of pollination ecosystem services at global and regional scales. In most regions, producers of pollinator dependent crops end up benefiting because direct output losses are outweighed by increased prices, while non-agricultural sectors experience large adverse indirect impacts, resulting in overall losses whose magnitudes vary substantially. By comparison, partial equilibrium analyses tend to overstate the costs to agricultural producers, understate aggregate economy-wide losses, and overstate the impacts on consumers' welfare. Our results suggest an upper bound on global willingness to pay for agricultural pollination services of \$127-\$152 billion.

Keywords: ecosystem services, pollination, valuation, agriculture, general equilibrium model

1. Introduction

Pollination is a valuable ecosystem service which provides a variety of benefits including food and fiber, plant-derived medicines, ornamentals and other aesthetics, and genetic diversity, as well as contributions to overall ecosystem resilience (Naban and Buchmann 1997; MEA 2003). Mounting evidence of long-run declines of both managed and wild insect pollinators at local and regional levels has raised concerns over potential risks to global food security and economic development, particularly in countries where agriculture is a large portion of the economy (Kluser and Peduzzi 2007; Steffan-Dewenter et al. 2005; Allen-Wardell et al. 1998). Acute declines in pollinator populations and species diversity have occurred in Europe and North America (Beismejjer et al. 2006; NRC 2007; vanEngelsdorp et al. 2008; Potts et al. 2010), and been linked to pests, diseases, habitat destruction, and agricultural intensification (Cunningham 2000; Kremen et al. 2002; Priess et al. 2007; Winfree et al. 2009; Le Feon et al. 2010; vanEngelsdorp and Meixner 2010). Of particular concern is the fact that these trends coincide with agriculture's increasing dependence on pollination services globally (Aizen et al. 2008, 2009; Aizen and Harder 2009; Garibaldi et al. 2009), which has fueled fears of a global pollinator crisis (Steffan-Dewenter et al. 2005).¹

There has been a flurry of recent effort to quantify the economic benefits of pollination as an ecosystem service, elucidate the implications of pollinator declines for the supply of this service, and assess the economic and broader societal impacts of adverse supply shocks. Studies have sought to address this last issue in the context of agriculture by estimating the proportions of crops in a specific region that depend on pollinators, and calculating losses in terms of the value of the corresponding production at risk and the partial equilibrium impact on consumer

¹ Globally, 75% of primary crop species and 35% of crop production rely on some level of animal pollination (Klein et al. 2007), while in the United States, more than half of primary crop species and 20% of primary crop production rely in part on animal pollination services (Bauer and Sue Wing 2010).

surplus (Losey and Vaughan 2006; Gallai et al. 2009a). This approach has been adopted by the United Nations Food and Agricultural Organization (FAO 2009; Gallai and Vaissiere 2009).

In the present paper, we highlight the implications of extending this economic valuation methodology to a general equilibrium (GE) setting. Specifically, we develop and test a novel approach that incorporates measures of the pollinator dependence of different crops into the sectoral production functions of a multi-region, multi-sector computable general equilibrium (CGE) model. Following Gallai et al. (2009a) and others (Barfield et al. 2012; Brading et al. 2009; Gallai and Vaissiere 2009; Losey and Vaughn 2006), we simulate catastrophic losses in both wild and managed pollinators implicitly as exogenous reductions in the productivity of crop sectors by the fraction of pollinator-dependent production.² The resulting price and quantity adjustments across domestic and international markets for crop as well as non-crop commodities elucidate the full welfare impacts of lost pollination services as well as the economic channels through which they operate. Our goals are fourfold: (1) provide a more robust upper-bound estimate of the global value of pollination services broadly defined; (2) examine both the direct (crop sector) and indirect (non-crop sector) impacts that could result from lost pollination services; (3) highlight the heterogeneity of potential economic losses among global regions, including the influence of global trade; and (4) compare and contrast our GE results to those provided by individual-market partial equilibrium (PE) approaches.

The remainder of the paper is organized as follows. In section 2, we begin with a brief survey of the methods used by previous studies to estimate the value of pollination services. Our own methodology is described in section 3, which outlines the construction of our scenarios of pollination service losses as crop sector productivity shocks, gives an overview of the CGE

² Because of the global scale of our analysis and a corresponding lack of detailed regional data, we are not able to explicitly model the ecological relationships between animal pollinators and crop production. The catastrophic loss of all pollination service inputs provides an upper bound on potential economic losses.

model's structure, database and calibration, and explains its relationship to the partial equilibrium analyses. Section 4 presents the results of our simulations, and draws comparisons with partial equilibrium assessments to yield insights into the potential spillover effects of lost pollination services on production in agricultural and non-agricultural sectors, relative price changes, and, ultimately, consumers' welfare. Section 5 concludes with a summary of our findings and suggestions for future research directions.

2. Background

To provide context for our analysis, it is useful to first consider the methods used by earlier economic valuation studies of pollination services supplied to agriculture. Three major approaches tend to be used: (1) calculation of the value of total annual crop production that can be directly attributed to animal-mediated pollination (e.g., Robinson et al. 1989; Morse and Calderone 2000; Losey and Vaughan 2006; Brading et al. 2009; Barfield et al. 2012), (2) estimation of the impacts on social welfare, in particular changes to consumer and producer surplus (e.g., Southwick and Southwick 1992; Kevan and Phillips 2001; Kasina et al. 2009), and (3) summation of replacement costs, whereby purchased inputs—including the rental of commercial bee colonies or the use of non-animal alternatives (e.g., hand pollination or mechanized pollen dusting)—substitute for natural (i.e., wild) pollination services (e.g., Allsopp et al. 2008; Burgett 2009; Burgett et al. 2010; Caron 2010).

The key characteristic of these methods is the partial equilibrium (PE) focus on individual markets with no accounting for the consequences of potential linkages among them, in either backward (effects on upstream sectors' revenue by changing demand for the use of their products as inputs) or forward (effects on downstream sectors' costs by changing the supply of the product used by them as an input) directions (Bauer 2014). This is evident from the

separable manner in which valuation approaches (1) and (2) above are calculated. Letting i and r index crops and regions, the potential value of production loss (VPL) is simply the pollinator-dependent share of agricultural revenue (Gallai et al. 2009a):

$$VPL_r = \sum_i (D_i \times P_{i,r} \times Q_{i,r}) \quad (1)$$

where D is the crop-specific pollinator “dependency ratio”—which measures the impact of a loss of animal pollination in terms of a fractional reduction in fruit set (and yield) of particular plant species, and P and Q are baseline levels of prices and production specific to each crop and region. Similarly, the loss of consumer surplus (CSL) in crop markets for the simple case of a constant price elasticity of demand, ε , and perfectly elastic supply is (Gallai et al. 2009a; FAO 2009):

$$CSL_r = \frac{1}{1+\varepsilon} \sum_i P_{i,r} Q_{i,r} [(1 - D_i)^{-(1+\varepsilon)} - 1]. \quad (2)$$

Recognition of the potential bias from ignoring multi-market interactions when valuing changes in environmental quality or ecosystem services has catalyzed recent applications of multi-market general equilibrium (GE) simulations of the kind we use in this paper (Brouwer et al. 2008; Carbone and Smith 2008, 2010; Delink et al. 2011; McDermott et al. 2013). The principal advantages of such approaches are their ability to: (1) consistently track changes in prices and demands across multiple interrelated markets, (2) summarize the macroeconomic effects of shocks by utilizing theoretically consistent measures of the change in aggregate economic welfare, and (3) test the consequences of different possibilities to substitute other inputs for ecosystem services. Even so, the application of GE approaches to the issue of pollinator declines is still in its infancy.

A recent study by Gallai et al. (2009b) analyzes the distributional consequences of pollinator declines when there are market interactions. They construct a stylized analytical

general equilibrium model with two firms—each of which produces a single good, but only one of which requires inputs of pollination services—and two consumers endowed with factors of production. Distributional impacts vary with property rights regimes: both consumers suffer and there is an unequivocal welfare loss under an equal distribution of property rights, while the consumer without the pollination endowment can experience a welfare gain under an asymmetric distribution of property rights.

In a key paper, Monck et al. (2008) use a CGE model of the Australian economy to assess the impact of an invasion of the *Varroa* mite—a major honey bee pest. Australia is the only major developed economy that remains able to rely on a large feral (i.e., wild) honey bee population for the majority of its pollination services because it has not yet experienced *Varroa*'s destructive effects. Their model divides the economy into multiple crop sectors and two pollination services sectors—one combined with honey production and one that is pollination-only—and simulates the market impacts of counterfactual scenarios of *Varroa* incursion with and without pollination industry preparation. Results suggest that while investment in a managed pollination services industry is costly, overall benefits can be gained by moderating the short-run impacts of a *Varroa* incursion on the overall supply of pollination services.

Our study extends Monck et al.'s approach to multiple pollinators and multiple regions. We develop a static multi-region, multi-sector CGE simulation of agricultural production and international trade. Catastrophic wild and managed pollinator declines are modeled as exogenous neutral shocks to the productivity of four key crop sectors, and the direct crop sector and indirect non-crop sector effects of global and localized pollination service losses are investigated. For the sake of transparency, our analysis is deliberately stylized with respect to the ecological underpinnings of pollinator declines. We do not inquire into their origins or how

they manifest themselves across pollinator species, nor do we capture local or regional pollination deficits or overabundance, but focus instead on what might happen to heterogeneous but interlinked agricultural-economic systems should such catastrophes reduce pollinator-dependent crop production capacity.

3. Methods

3.1 The Numerical Model

As summarized in Table 1, our simulation model divides the world into 18 regions that mirror FAO's member country groupings. Production in each region is divided into 13 broad industry groupings, which are made up of four crop sectors, the major markets for their outputs (e.g., processed food products), and their inputs (e.g., fuels, and chemicals such as fertilizer and pesticides). Our structural specification of the world economy builds on the template developed by Rutherford and Paltsev (2000). Each regional consumer is modeled as a representative agent with nested constant elasticity of substitution (CES) preferences and endowments of three factors of production: labor, capital and arable land. Each industry sector is modeled as a representative producer of a single commodity with nested CES production technology. Regions are linked by bilateral trade in commodities, which is modeled using the Armington (1969) formulation in which goods are differentiated according to their region of production, and commodity uses in each region are a nested CES composite of domestic and imported varieties. The model is algebraically specified in the complementarity format of equilibrium (see, e.g., Sue Wing 2009, 2011), numerically calibrated using version 7.2 of the Global Trade Analysis Project (GTAP) database for the benchmark year 2004 (Narayanan and Walmsley 2008), formulated as a mixed

complementarity problem using the MPSGE subsystem (Rutherford 1995, 1999) for GAMS (Brooke et al. 2011), and solved using the PATH solver (Ferris and Munson 2000).

3.2 Modeling the Effects of Pollinator Declines

3.2.1 Pollination Service Losses as Agricultural Productivity Shocks

We model the impacts of changes in the regional supplies of pollination services in a deliberately simple way, by subjecting our four crop sectors to exogenous neutral productivity shocks that are calculated using ecologically-defined agricultural crop pollinator dependency ratios. These ratios vary dramatically among crops, with the highest level of pollinator dependence found predominantly in fruits, vegetables, and nuts. Even in those plant species capable of wind-pollination, animal-mediated pollination can increase the quantity and quality of seed and fruit production (Roubik 2002; Klein et al. 2003). We use Klein et al.'s (2007) animal pollinator dependency classification scheme (Table 2A), which quantifies for each FAO primary crop the yield reduction that would occur as a consequence of a complete absence of wild and managed pollinators.

A four-step procedure was used to calculate the proportion of crop production value that would be lost due to a complete loss of pollination services. We first calculated the value of production of every crop at the country level in the 2004 target year using FAOSTAT data on primary crop prices and production levels (FAO 2010). We then multiplied these values by the midpoints of the ranges of the crop-specific pollinator dependency ratios (baseline values in Table 2A) to obtain the value of production at risk from catastrophic pollination service losses for each primary crop in each country. Next, we aggregated the total value of production and the value of production at risk across countries and across crop types to match our 18 regional and

four crop sector groupings in Table 1. This is essentially the same as Gallai et al.'s (2009a) value of production loss given by equation (1) in Section 2. Our final step was to calculate a region-by-sector matrix of potential productivity losses by dividing the value of production at risk by the total value of production in each of our regional aggregate crop sectors.

We take pains to emphasize that these calculations produce the *ex ante* productivity shocks which in general diverge from the *ex post* change in the crop sector's output, whose magnitude is ultimately a function of supply- and demand-side adjustments. The affected sector's supply schedule will shift inward by an amount that is moderated by input substitution responses. In turn, this new supply curve will interact with the demand curve for the sector's output to determine the ultimate changes in price, output quantity and value of production.

3.2.2 Modeling Agricultural System Responses

To model the responses of producers of crops affected pollination service losses, the ideal place to begin would be accounts of the inputs of wild and managed pollinators to different crop sectors. Unfortunately, however, such data are not available. But if they were, we could model the economic impacts of pollinator shocks using a nested production structure of the kind shown in Fig. 1A. There, pollination services play the role of a quasi-market input to crop production, substituting for a composite of market inputs with elasticity of substitution, σ^{PY} . This parameter determines the extent to which an increase in the shadow price of pollination services induces compensating adjustments in the quantity of market inputs such as labor, capital or chemicals (e.g., fertilizer and pesticides). In turn, the availability of disaggregate data would allow us to model pollination inputs as a composite of the services of managed pollinators, a market input, and wild pollinators, a non-market fixed factor. (Note that in input-output economic accounts

the former are typically subsumed within livestock inputs to crop sectors, while the latter are imperfectly capitalized into returns to land.) The lower-level elasticity of substitution, σ^{PP} , is meant to capture the efficacy of using managed pollination services to replace wild pollinators, or vice versa, as the quantity of one or both declines.

With perfect information, cost-minimizing producers will know the marginal product of pollination services and set that equal to its shadow price by adjusting their demands for these services as well as other market inputs. Additionally, given a fixed endowment of wild pollination services, producers would adjust their demands for managed pollinator inputs to equalize the marginal productivities of the two kinds of pollinators. An adverse shock to managed pollinators such as colony collapse disorder (CCD) can be modeled as a secular decline in the productivity of that input, while a decline in wild pollinators simply shrinks the wild pollinator fixed factor endowment. Either shock would bid up the shadow price of pollination services, inducing substitution among market inputs and changes in the quantity of crop output, with follow-on GE impacts in other sectors.

The key challenge to this type of analysis is our limited understanding of pollinators' role in crop production technology, particularly across crops and regions at a global scale, which at present prohibits the use of this framework. To actually implement this model, it would be necessary to numerically calibrate the nested cost function represented in Fig. 1A, specifying values for the substitution elasticities, the technical coefficients on pollination services provided by wild and managed pollinators, and the quantity of the wild pollinator fixed factor in different crop sectors and world regions. Neither the ecology nor the agricultural economics literature yield useable estimates of these parameters at this time. Furthermore, underlying data that might be used to calculate them is only now being collected (e.g., Koh et al. in press). While Klein et

al.'s (2007) pollinator dependency ratios allow us to impute the share of the value of output made up by pollination services, how this input breaks down into wild and managed components is very much a measure of our ignorance, as economically-beneficial wild pollinator populations have not been quantified. Furthermore, many of the developing countries that utilize managed pollinators lack markets for their services in which the corresponding price and component of crop value might be observed. For these reasons we conclude that attempting to explicitly simulate the substitution among managed and wild pollinators, and between pollination services and market inputs, in pollinator-dependent crop production, is too difficult and speculative an undertaking at this time.

Our fallback strategy is therefore to pursue the alternative expedited approach summarized in Fig. 1B. Our radical simplification is to model pollination services, not as explicitly accounted-for inputs to production, but implicitly as productivity parameters which modulate the relationship between crop sectors' output and their marketed inputs. Collapsing all the substitutions within the dashed box in Fig. 1A into a single, pollinator-dependency parameter allows us to subsume the highly uncertain details of these processes, and focus squarely on assessing the economic consequences of their effects through sensitivity testing. The shocks themselves are modeled as fractions of the total value of production, based on the results of the procedure described in section 3.2.1. Thus, for example, in a sector where pollinator-dependent output accounts for 10% of production, a catastrophic loss of managed and/or wild pollinators that ends up reducing total pollination services by a half would be modeled as a 5% decrease in the productivity of market inputs. The advantage of this approach is its ease of implementation through the introduction of a neutral productivity shifter into crop producers' cost functions. Yet in so doing we are essentially making the assumption that there are no substitution possibilities

for lost pollination services (i.e., $\sigma^{PP} = \sigma^{PY} = 0$) including, for example, the use of manual hand pollination or mechanized pollen dusting. This approach is not without its own limitations, as we discuss below.

Our model structure is elaborated in Fig. 1C. In crop sectors, inputs to production (all of which are non-pollination marketed inputs, per the previous paragraph) are represented by a hierarchical constant elasticity of substitution (CES) production technology. At the top level, land (which is a sector-specific fixed factor) substitutes for an aggregation of capital, labor, energy and material (KLEM) inputs, with elasticity σ^Y . Within the KLEM composite, a CES aggregation of labor and capital, the value-added composite, substitutes for a CES composite of energy and materials with elasticity σ^{KLEM} . The labor-capital elasticity of substitution is σ^{VA} . The energy-materials composite is made up of intermediate inputs of energy and fuels (petroleum and electricity necessary to power machinery), intermediate inputs of chemicals (fertilizers and pesticides), and an aggregation of additional intermediate material inputs, X_m . Fuels, chemicals and materials are assumed to substitute for one another with elasticity σ^{INT} , while substitution among material inputs is determined by the elasticity σ^M . Individual intermediate inputs are each assumed to be CES composites of imported and domestic varieties, whose substitution for one another is governed by the vector of elasticities σ^{DM} .

The substitution possibilities embodied in Fig. 1A modulate the economic impact of pollination-loss driven productivity declines. That is, the ex-ante and ex post productivity losses will be identical only if there are no opportunities for producers to adjust through input substitution (such that the supply curve shifts inward by the full amount of the productivity shock) and demand is perfectly elastic, neither of which is likely to be the case. By using the

structure in Fig. 1B, the key concern is an upward bias in our simulated loss estimates if producers could in fact substitute marketed inputs for pollination services—or inputs of managed pollinators for their declining wild counterparts—at low cost, because the percentage of the value of production lost calculated in section 3.2.1 will then overstate the actual adverse shock to the productivity of marketed inputs.³ As insufficient data exist to enable us to rigorously quantify this error, we acknowledge that our economic loss estimates are upper bounds and further examine this potential problem through sensitivity analysis, discussed in section 3.5.

Despite the above caveat, our model’s ex ante and ex post productivity losses will not be the same. Recall that our regional crop sectors are aggregates of pollinator-dependent and non-dependent crops. Thus, there remains potential for substitution among the (non-pollination) market inputs (land, labor, capital, energy, and materials) from pollinator-dependent crops to non-dependent crops within each crop sector. We do not model this explicitly because we would need to make gross assumptions about the allocation of inputs between pollinator-dependent and non-dependent crops. In addition, it is worth noting that our GE modeling approach allows for movement of primary factors (i.e., labor and capital) among production sectors, which also mitigates economic losses.

Computational implementation of the structure in Fig. 1C requires us to overcome two further challenges. The first is simply the dearth of empirical estimates of the substitution elasticities at the various levels of the nesting hierarchy. The second is structural. Input-output (I-O) databases such as GTAP that are the backbone of multiregional economic models typically divide agricultural activity into coarse sectoral groupings, which aggregate together many crops with markedly different pollinator dependencies. Thus, although the parameterization of the

³ Indeed, the apparent negligible effects of colony collapse disorder on US agricultural production (see, e.g., Rucker et al., 2012) raises the possibility that the values of σ^{PY} and σ^{PP} are indeed large, even though data limitations do not allow us to track how much producers might be adjusting on each substitution margin.

production hierarchy should ideally vary by crop and region, data constraints force us to replicate the same production structure for different coarse agricultural sectors and regions at all but the lowest level of the nesting hierarchy.⁴ To mitigate the threat of aggregation bias, we employ FAO crop production statistics to disaggregate the GTAP “vegetables, fruits & nuts” aggregate sector with the greatest pollinator dependence into three separate production subsectors within each region.

In interindustry accounts, disaggregating supply (industries’ uses of inputs down the columns of the I-O table) tends to be much easier than splitting demand (the disposition of industries’ outputs across the I-O table’s rows) for the simple reason that the ancillary economic data necessary to constrain the former procedure are more readily available. This is the case here, particularly for developing countries. Accordingly, we maintain GTAP’s “vegetables, fruits & nuts” aggregate as a single composite commodity on the demand side of our model, and on the supply side allow the outputs of the three constituent crop groups to substitute for one another within the aggregate. The choice of the corresponding elasticity of substitution, σ^{VFN} , is somewhat arbitrary. On one hand, inter-annual variation in output and acreage, particularly among vegetable crops, reflects farmers’ ability to adjust elastically to shifts in relative prices. But on the other hand, the fact that standing orchards and tree nut groves represent fixed factors of production—particularly in the short run—suggests technical limitations to reallocating production between tree crops and vegetables. As a compromise we select a benchmark value of unity (Table 2B).

⁴ The GTAP database tabulates Armington elasticities between domestic and imported varieties of 57 different goods. These vary by commodity but are the same for all regions. Note that even though the structure will be the same, interregional differences in interindustry structure mean that inputs’ shares of total cost in all sectors, the implied technical production coefficients, and the associated substitution possibilities will all vary across sectors and regions.

3.3 Global and Regional Pollination Service Loss Scenarios

We simulate a total of 19 scenarios: a worldwide collapse of pollination services, in which production of pollinator-dependent crops in all 18 regions are simultaneously impacted, and 18 region-specific shocks, in which the production of pollinator-dependent crops in a single region is impacted. Each of these scenarios is envisaged to be a catastrophic shock in which animal-mediated pollination services from both wild and managed pollinators are completely lost, triggering a decline in the productivity of pollinator-dependent crops in the amount of Klein et al.'s (2007) estimated mean value of the dependency ratio for each primary crop. We remind the reader how extreme such losses are. From an ecological standpoint, although different degrees of decline in pollinator populations can be triggered by various factors (e.g., disease outbreaks, habitat degradation or climate change), complete elimination of pollination services at broad spatial scales is highly unlikely. The implication is that our economic impact results should be interpreted as an extreme upper bound. But these caveats do not change the fact that the pivotal economic issue is the uncertain relationship between the extent of pollinator dependence and the magnitude of the potential shock to agricultural productivity. A range of assumptions can of course be made, but we deliberately strive for clarity by choosing to elucidate the consequences of the simplest possible one-to-one relationship.

In the region affected by the shock, there are direct impacts on pollinator-dependent crop sectors' production activity levels, input demands, and output prices. These in turn induce a plethora of indirect effects, in the form of price and quantity adjustments in upstream and downstream markets. For every region, the model computes new commodity and factor prices, sectoral activity levels, and household (i.e., representative agent) income levels necessary to re-

establish equilibrium in the markets for factors and domestic and internationally traded commodities. We focus our analyses on two economic valuation metrics. First, the concomitant changes in the prices and quantities of primary factors (labor and capital) allow us to distinguish direct impacts on value added in our four crop sectors from indirect impacts on value added for the rest of the economy.⁵ We compute real value added as the quantity of the labor-capital composite multiplied by its price and deflated by the consumer price index in each sector (j) and region (r):

$$RVA(j,r) = PVA(j,r) * QVA(j,r) / CPI(r). \quad (3)$$

We then sum these up among direct (crop) and indirect (non-crop) sectors. Second, the concomitant change in the total expenditure of each regional representative agent yields a theoretically consistent indicator of the change in aggregate economic welfare, in the form of equivalent variation.⁶ We compute this metric as the percentage change in the total expenditure on consumption of commodities by the regional representative agents.

3.4 Comparison with Partial Equilibrium Approaches

To clarify how our results differ from those of PE approaches, we identify the outputs of our CGE model that broadly correspond to the PE metrics defined in section 2, and provide a comparison by computing equations (1) and (2) based on the same set of FAOSTAT data for our 2004 target year. Our analogue of the loss of consumer surplus (*CSL*) is the change in equivalent variation, which captures both supply and demand impacts through the CGE model's ability to track, on one hand, the effects of the shock on factor remuneration and consumers' incomes, and

⁵ Value added is the return to primary factors of production.

⁶ Equivalent variation is defined as the change in an individual's income which, if the shock under consideration were to not occur, would leave that individual with the same level of utility if the shock did in fact occur (Just et al. 2004).

on the other hand, downstream industries' substitution of other inputs for pollinator-dependent crops. These effects are modulated by consumers' and producers' elasticity of substitution parameters, and by the model's structural representation of intersectoral capital mobility. By contrast, FAO (2009) collapses all these interactions into a single price elasticity on the demand side ($\varepsilon = -0.8$ or -1.2), while treating supply as perfectly elastic. The latter is particularly problematic because it ignores producer surplus as a component of welfare. Fig. 2 illustrates this point by adapting Gallai et al.'s figure (2009a, Figure 1) to include relatively price-inelastic and relatively price-elastic supply curves: S_0S_0' and S_1S_1' , respectively. The effect of a pollination service shock is to shift these curves inward to the dashed loci Z_0Z_0' and Z_1Z_1' . Even though in both cases the equilibrium quantity falls by the amount $Q_B - Q_A$, and the price increases by $P_B - P_A$, yielding the same consumer surplus loss, the more (less) elastic supply curve is associated with a smaller (larger) reduction in producer surplus, and welfare.⁷

Our counterpart to ex-ante valuation of production at risk (*VPL*) in absolute and percentage terms is the simulated change in value added in crop sectors—which we refer to as the direct effect—as well as in non-crop sectors—the indirect effect. While we acknowledge that this comparison is of an “apples versus oranges” nature, it does highlight the potential error in using *VPL* as a measure of the economic impact on farmers.

3.5 Parameter Sensitivity Analysis

Finally, we test the robustness of our findings by investigating the sensitivity of our model results to the values of key parameters. To assess the potential importance of the substantial uncertainties in, first, the magnitudes of pollination-driven productivity shocks, and, second,

⁷ The key condition is the relative differences in the producer surplus triangles: $S_0AP_A - Z_0BP_B > S_1AP_A - Z_1BP_B$. The aggregate (CS+PS) "error" can be shown in Fig. 2 as the trapezoid between S_1 and S_0 , between the origin and a point the same distance to the right of the origin as the distance $QA-QB$.

their effects on the productivity of marketed inputs to crop sectors, we re-run every one of our 19 simulations with shocks that correspond to Klein et al.'s (2007) pollinator dependency ratio upper and lower bounds. Likewise, we elucidate the effects of uncertainty in the various types of substitution responses by re-running our scenarios with high and low values of key elasticity parameters within the model. Baseline, lower-, and upper-bound parameter values are listed in Table 2.

4. Results

4.1 Crop Sector Production at Risk

Table 3 summarizes the fraction of the value of production at risk to lost pollination services as described in section 3.2.1, with vegetables, fruits and nuts disaggregated to better illustrate regional heterogeneity. Vulnerability to catastrophic pollination service loss ranges from 0% (i.e., no risk) for sugar and other crops in two European regions to 51.9% for fruit crops in Eastern Asia. In 11 of 18 regions, the fruit sector is the most vulnerable with greater than 30% of the value of output at risk in eight regions. In Northern America, the nut sector is the most vulnerable due to substantial production of almonds, a high-value but highly pollinator-dependent crop. Vegetables are generally much less vulnerable because even though animal pollination is necessary for seed production, this requires only a small portion of total output. Grains are the least vulnerable crop sector in most regions because the majority of cereal crops such as wheat and rice are wind pollinated. Oil seeds (e.g., rapeseed, sesame seed, soybeans and sunflowers) exhibit a modest degree of pollinator dependence, but are most vulnerable to lost pollination services in four regions. Sugar and other crops (which includes cocoa, coffee and

vanilla beans) is the most vulnerable sector in two regions. These results are comparable to those reported in Gallai et al. (2009a).⁸

4.2 Global and Regional Welfare Impacts

Table 4 summarizes the effects on consumers' expenditure, our measure of social welfare, due to global or regional losses of pollination services implemented as productivity shocks. The welfare loss due to a global pollination-driven productivity shock in equivalent variation terms is approximately \$140 billion or a 0.6% decrease from the 2004 baseline level (columns 2-3). Welfare impacts vary dramatically among the 18 regions, from a 0.1% loss in Eastern Africa to a loss of 4.2% in Western Africa. Eastern Asia and Northern America (which include the large economies of China and the US, respectively) experience the largest absolute losses, \$51 billion and \$31 billion respectively, and together make up more than half of the world total. Mean regional losses due to a global shock are \$7.8 billion or a 1.0% reduction in welfare.

Impacts of regional pollination-driven productivity shocks can be broken down into two basic components. *Own region welfare losses*—incurred in the region which is subject to the regional productivity shock—are of a similar magnitude to those in the global shock scenario, with a mean regional loss of \$7.7 billion and 1.3 % reduction in welfare from the baseline (columns 4-5). Similar to the global scenario, Western Africa is particularly vulnerable to losses of pollination-driven productivity shocks as a % welfare reduction, while Eastern Asia and Northern America suffer the largest absolute dollar losses. *Other region welfare changes*—incurred in regions other than the region experiencing the loss in pollination services—are, on a net basis, small and often positive (columns 5-7).

⁸ The minor variations between our results in Table 3 and those in Gallai et al.'s Table 4 stem from differences in the base year of FAO crop data (2004 versus 2005) and the mix of crops (all primary crops here versus only food crops in Gallai et al.).

The key to the direction of these other-region impacts is the effect of the shock on comparative advantage in the affected region. By reducing the productivity and increasing the unit costs of pollinator-dependent crop production, the shock shifts agricultural comparative advantage toward unaffected, now relatively low-cost agricultural producers. Consequently, affected regions that are initially relatively specialized in agriculture see their pollinator-dependent exports supplanted by increased supply from competitors, who experience windfall gains. This effect is epitomized by Southern Europe, the third largest producer of vegetables, fruits and nuts (accounting for 9% of world production) and the world's largest exporter. Increased crop production and exports of competing unaffected regions enable them to experience the largest collective net welfare gain (\$4 billion).⁹

Accompanying the contraction in crop sectors is a decline in their demand for factors of production and a fall in their prices. In most affected regions, what results is a decline in the unit costs of non-agricultural production and a concomitant shift in comparative advantage toward manufacturing, service and other sectors. The upshot is that affected regions that are initially relatively specialized in the latter industries see their non-agricultural exports expand at the expense of their competitors. Epitomizing this effect is Northern America, the largest producer and third largest exporter of non-agricultural commodities, which experiences the biggest increase in exports of manufacturing and services. In turn, this is associated with the second largest decline in unaffected regions' non-agricultural exports, the biggest drop in their production, and their largest welfare loss (\$7.3 billion).¹⁰

⁹ Southern Europe's vegetable, fruit and nut production experiences a 23% decline, the second most severe after Northern Africa. Unaffected regions' total vegetable, fruit and nut exports jump by more than 1%, the largest increase out of the 18 regional shocks. Behind this shift in trade patterns is importer substitution away from Southern Europe's exports and toward those from unaffected regions, whose export revenues rise.

¹⁰ Northern America is unique in several respects. Its gross output of manufacturing, service and other sectors is the largest in the world, while that of pollinator-dependent crop production is the third largest. However, the ratio of crop to non-crop gross output is the smallest, which causes the input-shifting effect of the shock to be minimal in

Combining own-region and other-region impacts gives the total impact of regional pollination-driven productivity shocks at the global level, all of which are negative because own-region negative effects substantially outweigh their other-region positive counterparts (columns 8-9). At the mean of our 18 regional scenarios, global welfare losses of single-region pollination-driven productivity shocks amount to a \$7.5 billion or a 0.03% reduction in total consumer expenditure (i.e., welfare loss).

4.3 Direct and Indirect Impacts on Producers

Direct, indirect and total impacts of a global pollination-driven productivity shock on regional value added are shown in Table 5. A worldwide shock results in total value-added losses of \$420 billion, or 1.2% of the 2004 global baseline. All regions experience losses (columns 6-7), both in absolute and percent terms (mean = -\$23 billion, -2.3%), and are geographically concentrated in Eastern Asia and Northern America. A similar pattern is realized for losses aggregated across non-crop sectors (mean = -\$25 billion, -2.4%), with a global indirect loss of \$443 billion or 1.25% (columns 4-5).

Counterintuitively, crop producing sectors *gain* by \$23 billion globally, an increase of 4%, while at the regional level the mean effect on producers is a \$1.3 billion (3.4%) increase (columns 2-3). This result reflects the potential for farmers to benefit from adverse shocks to production when the concomitant increase in the prices of agricultural commodities outweighs the declines in output quantities. Fig. 3A demonstrates that this phenomenon is concentrated in oil seeds and vegetables, fruits and nuts. Thus, despite substantial declines in the quantity of

spite of the fact that pollinator-dependent agricultural output declines by 19%. The shift in comparative advantage manifests itself in declines in the domestic prices of manufactures and services which propagate to unaffected regions via the transmission effects of international trade. Since these commodities are such a substantial share of gross world product, such small but pervasive price changes are associated with substantial reductions in income. To put this effect in context, the declines in the prices of non-crop commodities triggered by a productivity shock to Northern America are an order of magnitude larger than those from the aforementioned shock to Southern Europe.

output of the highest-dependency crops, the direct impact in value added terms is negative in only three regions, Southern Asia and Middle and Western Africa, with the latter being particularly vulnerable. Because the shock is global, regions are unable to satisfy domestic demand through trade, as supplies from trade partners are also constrained. We therefore see *expansion* of production of high-value crops in these regions, facilitated by intrasectoral substitution toward non-pollinator dependent crops and intersectoral reallocation of land and marketed inputs.

When pollination service losses are localized in the form of regional productivity shocks, own-region direct, indirect, and total effects on producers are uniformly negative with two exceptions (Table 6A), with a mean loss of \$19 billion (2%). Absolute losses are largest in Eastern Asia, while percentage losses are greatest in Middle Africa and Southern Asia. Compared with the global shock, regions impacted by own-region shocks generally experience larger direct losses or smaller direct benefits, with the opposite being true for indirect losses in every region but one. As illustrated in Fig. 3B, this occurs because when regions are affected individually, their crop sectors exhibit larger reductions in output quantity and smaller increases in price. This latter effect is the key difference from a systemic shock: because there is an abundance of exports from unaffected regions which can substitute for relatively high-cost domestic supply, domestic crop producers have little incentive to expand output by purchasing additional inputs. The upshot is a shift in comparative advantage in pollinator-dependent crop production to unaffected regions which can amplify affected regions' total losses. We see this in five regions whose exports are most intensive in pollinator-dependent crops, three of which are in Africa. The positive direct effect in Eastern Asia is likely due to vegetable, fruit, and nut prices rising more than production falls, along with a shift in production from the highly

pollinator-dependent fruit sector to less pollinator-dependent vegetables and nuts. The positive indirect effect in Western Africa is likely due to a shift in labor and capital away from highly vulnerable pollinator-dependent export crops to non-crop sectors in the economy.

In the aggregate of unaffected regions (i.e., Rest of World), producers enjoy a mean net positive direct effect of \$1.8 billion, or 0.3% of baseline value-added (Table 6B, columns 2-3). However, the indirect effect in unaffected regions is uniformly negative, with a mean aggregate loss of \$4.9 billion, or 0.02% (Table 6B, columns 4-5). In all regions, the negative indirect effects outweigh the positive direct effects, with a mean total loss of \$3.1 billion or less than 0.01% (Table 6B, columns 6-7).

4.4 Western Africa's Economic Vulnerability to Lost Pollination Services

Western Africa's economy is particularly susceptible to the adverse effects of pollination-driven productivity shocks that occur both within its borders and globally. Several factors account for this. First, compared to other regions its economy is relatively intensive in agriculture, which together with processed food comprises more than 25% of gross output. Second, the composition of agricultural production is heavily pollinator dependent, with the four crop sectors making up 16% of total agricultural output, of which vegetables, fruits, and nuts comprise 10%. Third, consumption of vegetables, fruits, nuts and oil seeds is autarkic, with imports accounting for less than 1% of the benchmark value of household consumption. This sharply curtails consumers' ability to substitute toward foreign pollinator-dependent goods as a margin of adjustment to the shock, and exposes intermediate and final consumers to the full extent of domestic producer price changes. Lastly, Western Africa is a large producer of coffee and cocoa beans, stimulant crops for which insect pollination is essential, but 95% of whose

output is exported. The resulting contraction in foreign exchange earnings reduces imports of *non-agricultural* commodities, exacerbating losses in both value-added and welfare.

4.5 Comparison with Partial Equilibrium Impact Estimates

Table 7 summarizes the PE estimates of the changes in the values of firms' production and consumers' surplus, calculated using equations (1) and (2), respectively. Recall that these measures consider only losses that occur in pollinator-dependent crop sectors within the region experiencing the shock, and therefore cannot distinguish losses due to a global shock from those due to regional shocks.

Focusing first on changes in consumer surplus (Table 7, columns 2-3), all regions experience losses, as anticipated. Globally, consumer surplus loss ranges between \$206 billion ($\varepsilon = -0.8$) and \$279 billion ($\varepsilon = -1.2$). Regionally, when $\varepsilon = -0.8$ losses range between \$1.1 and \$94.6 billion, with a mean of \$11.5 billion, and when $\varepsilon = -1.2$ they range from \$839 million to \$68.7 billion, with a mean of \$15.5 billion. As with our GE estimates, the loss increases with the size of the affected economy. At the global level these figures exceed our GE welfare loss estimates (cf Table 4), with the exception of Northern America and Northern Europe, and the same is true for shocks at the regional level, with the exceptions of Northern America and Oceania (Fig. 4). The differences can be large, up to \$139 billion globally and \$45 billion regionally, and vary with the type of shock—global or regional—and the value of the price elasticity of demand parameter. This result reflects the fact that consumer surplus loss only captures the effect of price shifts that occur in the markets for pollinator-dependent crops, while neglecting adjustments in the much larger rest-of-economy aggregate that may serve to moderate crop price changes. FAO's elasticity values do not appear to adequately incorporate such

“offstage” substitution responses—or their interregional variation. Using price elasticities of larger absolute magnitude could generally bring consumer surplus losses into line with our equivalent variation estimates.

Turning now to the PE value of production lost (Table 7, columns 4 and 5), a global pollination-driven productivity shock incurs opportunity costs of \$138 billion or 11.3% of baseline value. Regionally, absolute losses range from \$580 million in Southern Africa to \$44.6 billion in Eastern Asia, with a mean of \$7.7 billion, while percentage losses range from 4.5% in Eastern Africa to 15.2% in Western Asia, with a mean of 10.3%. Comparison with Table 5 suggests that, for a global shock, value of production loss tends to (a) overestimate and misrepresent the sign of the direct impact on crop sectors by ignoring potential increases in the prices of crop producers’ outputs, and (b) underestimate the total impact on the economy by not accounting for concomitant changes in the value of non-crop sectors’ outputs. With localized regional shocks (cf Table 6A), the value of production loss consistently overestimates the direct effect on crop sectors in the region of impact, underestimates the total own-region effect in all but one region, and dramatically underestimates total world production losses (Table 6A and 6B, column 7 combined) for all regional shocks except that in Western Africa.

4.6 Sensitivity Analysis

Sensitivity tests of the CGE model’s key inputs and parameters corroborate our main findings. Table 8 summarizes the losses in welfare and total value added for the model’s elasticity of substitution parameters at their upper and lower bounds. A worldwide pollination-driven productivity shock triggers welfare losses of \$127-\$152 billion with a mean of \$140 billion, still well below the partial equilibrium consumer surplus estimate. The direct plus

indirect losses in value added range between \$375 and \$448 billion with a mean of \$418 billion, well above the corresponding partial equilibrium value of production lost estimate.

Table 9 summarizes the effect of varying each crop's pollinator dependency ratio between its upper and lower bound. As these parameters are the key input to our partial equilibrium loss metrics, we recalculate the values of *VPL* and *CSL* as well. The range of values exhibited by both metrics is wider as a consequence, but the overall pattern of results is the same: the partial equilibrium approach overestimates welfare losses and underestimates total production sectoral losses. In addition, the baseline model results of positive direct crop-sector effects for global productivity shocks (Table 5) and positive rest-of-world effects for regional productivity shocks (Table 6B) are also robust.¹¹

5. Summary and Conclusion

Using a general equilibrium approach that simulates the full spectrum of price and quantity changes across sectors of the economy, we demonstrate that pollination service losses implemented as neutral productivity shocks affect both crop and non-crop sectors, often in non-intuitive ways, and that some regions of the world suffer much heavier burdens than others. Although the gains and losses presented here are necessarily impressionistic, they nonetheless allow us to draw several important insights.

Our principal finding concerns the value of pollination services to global economic activity. A systemic worldwide productivity shock at Klein et al.'s (2007) mean dependency ratios triggers reductions of global consumer expenditure (i.e., social welfare) of 0.5%-0.6%, or \$127-\$152 billion. Corresponding figures for pollination-driven productivity shocks in

¹¹ A full set of tabular results for each sensitivity analysis is available from the authors upon request.

individual regions vary markedly, but are highest in percentage terms for Middle and Western Africa, and in absolute terms for the large economies of Eastern Asia and Northern America.

Second, looking behind these numbers, the existence of interindustry linkages between crop and other sectors in the rest of the economy mean that catastrophic pollination service losses, in addition to directly affecting the value added of crop production, have indirect impacts on value added in non-crop sectors. We show that indirect impacts, despite being smaller in percentage terms, are liable to be substantially larger in absolute magnitude, owing to the fact that non-crop sectors make up a uniformly bigger share of regional economies.

Third, pollination-driven productivity shocks can induce modest increases in crop sector value added if the prices of agricultural commodities increase by an amount that exceeds the decreases in output and imports from other regions are constrained. Notwithstanding this, we find that the indirect effect is both uniformly negative and outweighs this positive direct effect.

Fourth, although the partial equilibrium pollination service loss valuation methods embodied in decision support tools are useful for identifying countries' susceptibility to pollinator declines, our results highlight key limitations in their application to economic impact assessment. We document a clear tendency for value of lost production and consumer surplus loss measures to not only overestimate the general equilibrium impacts on crop producers, but even misrepresent the sign of direct effects. Our hope is that by more fully elaborating both the range of economic outcomes and their driving forces, studies of this kind can catalyze improvements in the valuation methods used to assist decision makers.

Fifth, a caveat to our analysis is the low probability of large-scale catastrophic pollination service losses over broad geographic domains within the short timeframe of our static simulation. For this reason the magnitudes of our losses computed here should be considered an upper

bound. But even so, there appears to be substantial interregional heterogeneity in the burden of a localized pollination service loss, which greatly exceeds the variation predicted by value-of-production-at-risk metrics. The critical factor is the structure of the economy within which pollinator-dependent crop production is embedded. This point is epitomized by Western Africa, whose ex ante vulnerability due to its high-value, highly pollinator-dependent crop mix is amplified by the fact that pollinator-dependent crops account for a relatively large proportion of its gross output, satisfy a substantial share of its food and aggregate consumption, and bring in a large fraction of its export revenues.

Sixth, there is a pressing need to enhance the precision and robustness of our estimates. However, this must await improved understanding of the role played by managed and wild pollination services in the production of crops with different degrees of dependency, especially the development of crop production datasets that resolve pollination services as distinct inputs. Our discussion highlighted key modifications to the structure and parameterization of our model's representation of the production process that might enable us to better capture the broad range of substitution and mitigation strategies available to producers. The main obstacle to implementation is the dearth of empirical estimates quantifying the substitutability among managed and wild pollinators (Klein et al. 2003; Greenleaf and Kremen 2006), the substitutability of humans and/or machines for animals in the pollination process, and the opportunities faced by producers to substitute non-pollinator dependent for pollinator-dependent crop varieties. The data necessary to construct such estimates are only now being gathered (Koh et al. in press). In the meantime, a priority is the development of more realistic scenarios that are capable of focusing more specifically on the roles of various crop types, pollinator species, and policies or mitigation strategies.

Seventh, characterization of more radical margins of adjustment available to farmers requires investigation of the performance and potential roles of technology-based and conservation-based mitigation strategies. The former include the development of management regimes for more effective pollinator pest and pathogen control, more efficient mechanized pollen dusters, and plant cultivars that are less dependent on animal pollination, while the latter include both on-farm and off-farm habitat protection through policies such as the USDA's Conservation Reserve Program (Morandin and Winston 2006). A more nuanced understanding of the relative cost and efficacy of these alternatives will greatly improve our understanding of producer decision-making in response to pollinator declines and enhance our ability to characterize associated economic vulnerability.

Finally, pollination is only one of several ecosystem services of importance to agriculture (Zhang et al. 2007). The modeling framework developed here could be extended to include other ecosystem services such as natural pest control, as well as account for future shocks to the provision of ecosystem services due to climate change.

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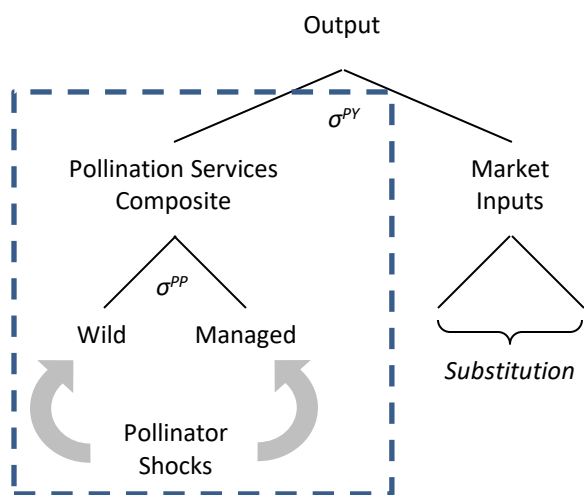
Figure Captions

Fig. 1. Representations of the contribution of pollination services to agriculture.

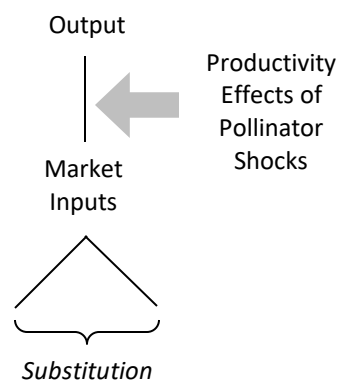
Fig. 2. Partial equilibrium impacts of pollination service losses on the market for a pollinator-dependent crop. Impact of pollination shock on quantity produced/consumed: $Q_A - Q_B$; consumer surplus loss: $DAP_A - DBP_B$; producer surplus loss with relatively inelastic supply: $S_0AP_A - Z_0BP_B$; and producer surplus loss with relatively elastic supply: $S_1AP_A - Z_1BP_B$.

Fig. 3. Price and quantity impacts on four crop sectors due to global (A) or regional (B) loss of pollination-driven productivity shocks in 2004. The dashed gray line indicates the locus of no net direct impact on sectoral revenue: producer gains increase further northeast while losses increase further southwest. Figures in parentheses indicate crops' importance, expressing the baseline revenue for an individual crop sector as a percentage of the region's total baseline crop revenue.

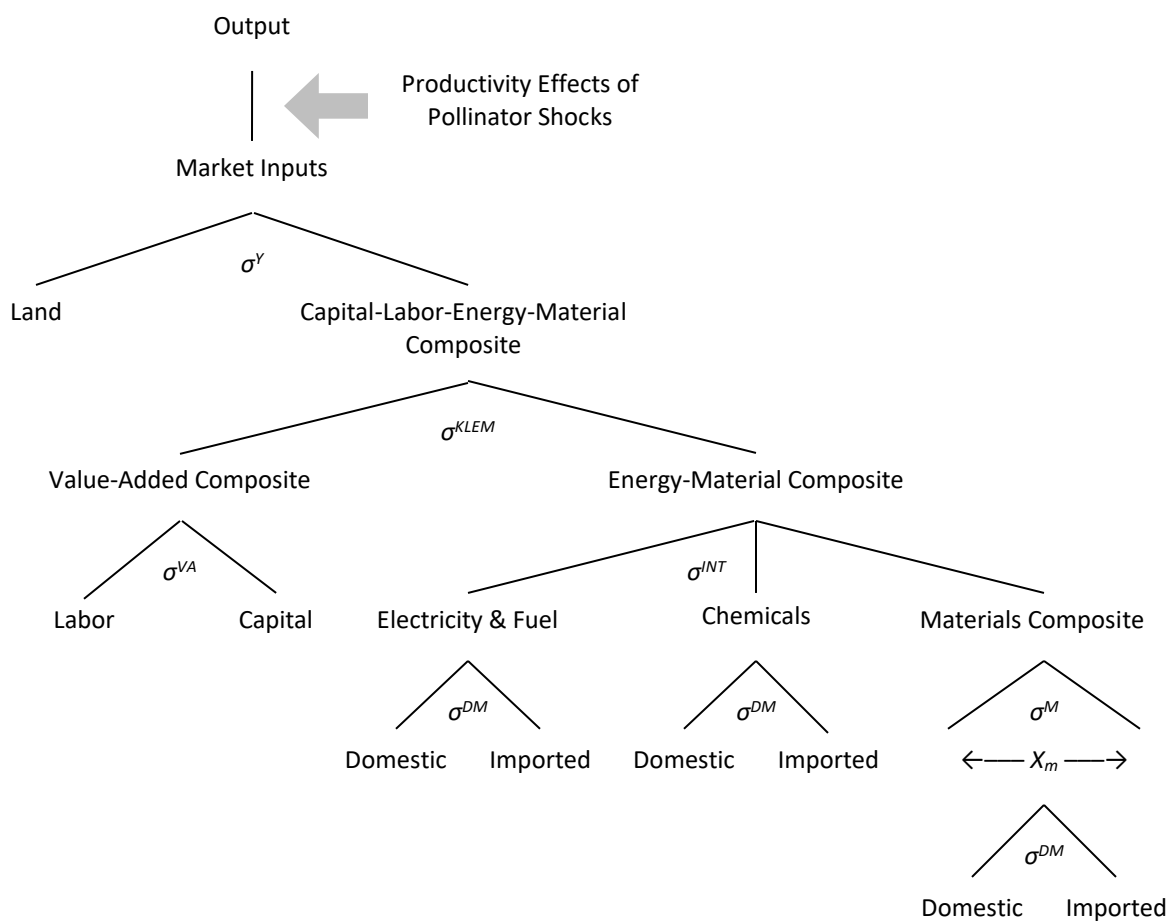
Fig. 4. Reduction in welfare due to global or regional loss of pollination services in 2004 (GE = General Equilibrium, PE = Partial Equilibrium). Partial equilibrium impacts are the same for both global and regional pollination-driven shocks. Welfare is measured as equivalent variation in general equilibrium and consumer surplus in partial equilibrium ($\epsilon = -1.2$).



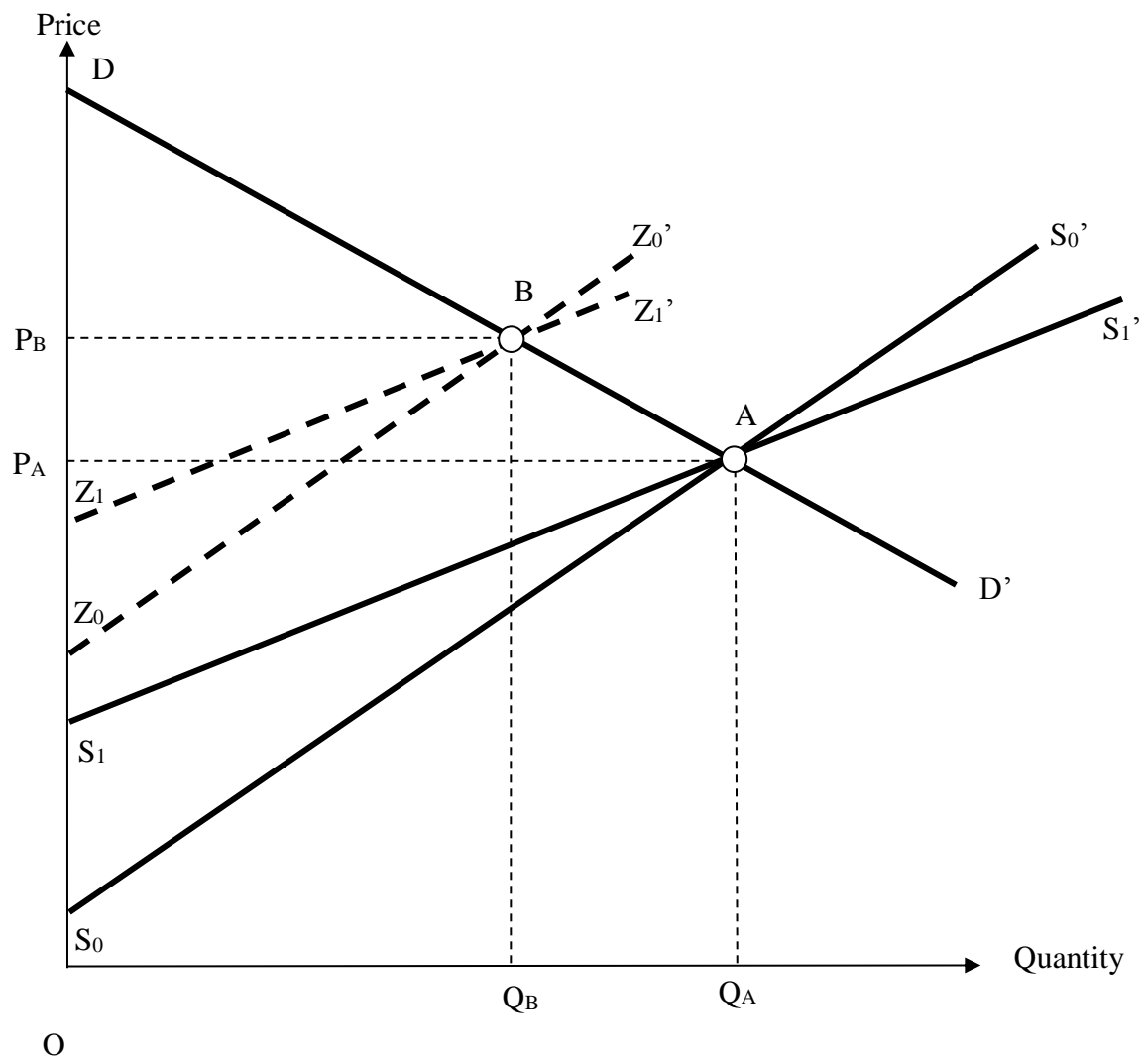
A. Pollinators as an input to production

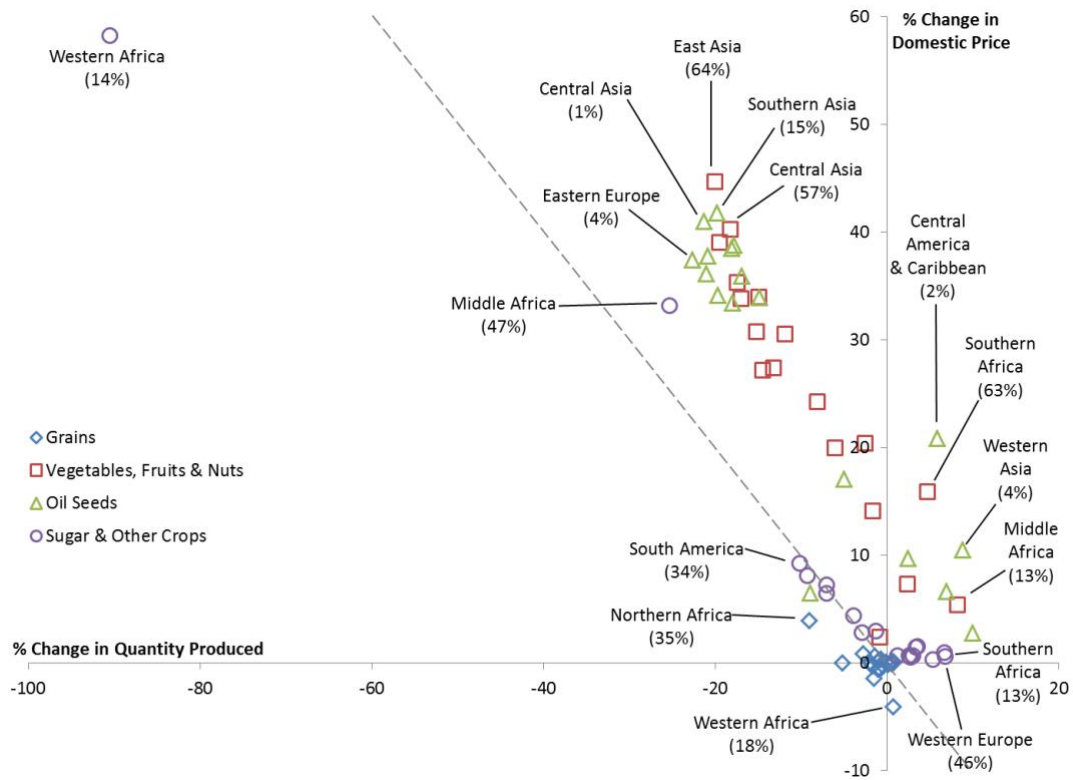


B. Pollinators as modulators of productivity

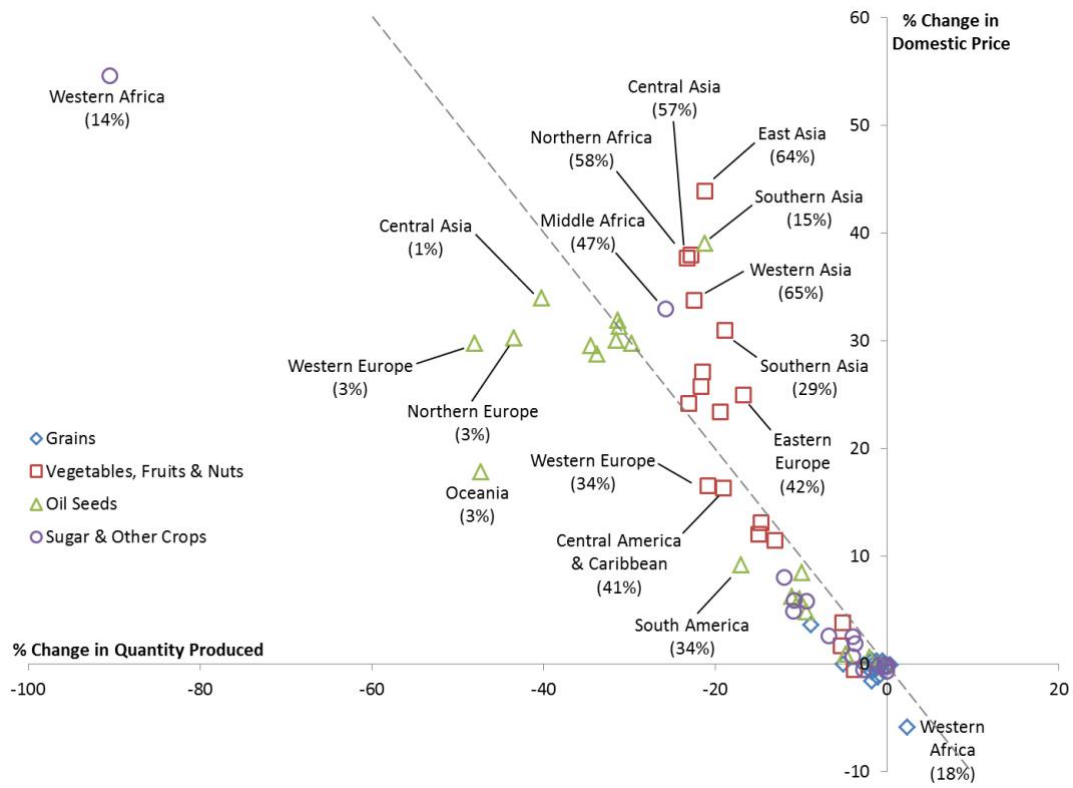


C. CGE model production structure in crop sectors





A. Global Pollinator Shock



B. Regional Pollinator Shocks

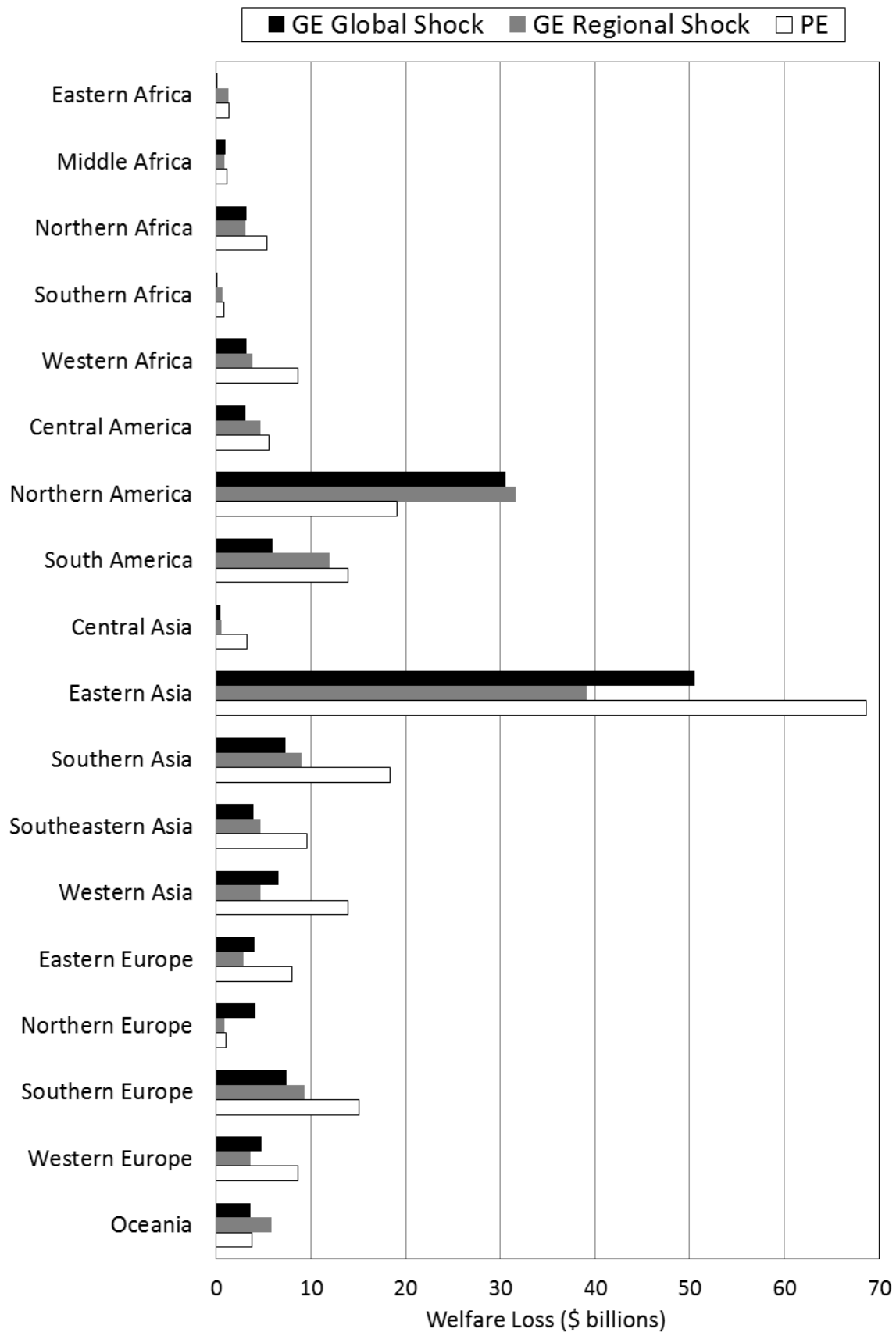


Table 1

Regional and sectoral structure of the numerical model.

Model regions	Major countries in GTAP database
Eastern Africa	Ethiopia, Madagascar, Malawi, Mauritius, Mozambique, Tanzania, Uganda, Zambia, Zimbabwe
Middle Africa	
Northern Africa	Egypt, Morocco, Tunisia
Southern Africa	Botswana, South Africa
Western Africa	Nigeria, Senegal
Central America & Caribbean	Mexico, Costa Rica, Guatemala, Nicaragua, Panama, CARICOM
Northern America	Canada, USA
South America	Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela
Central Asia	Kazakhstan, Kyrgyzstan
Eastern Asia	China, Hong Kong, Japan, Korea, Taiwan
Southern Asia	Bangladesh, India, Pakistan, Sri Lanka
Southeastern Asia	Cambodia, Indonesia, Laos, Myanmar, Malaysia, Philippines, Singapore, Thailand, Viet Nam
Western Asia	Armenia, Azerbaijan, Georgia, Turkey
Eastern Europe	Czech Republic, Hungary, Poland, Slovakia, Bulgaria, Belarus, Romania, Russia, Ukraine
Northern Europe	Denmark, Estonia, Finland, Ireland, Latvia, Lithuania, Sweden, UK, Norway
Southern Europe	Cyprus, Greece, Italy, Malta, Portugal, Slovenia, Spain, Albania, Croatia
Western Europe	Austria, Belgium, France, Germany, Luxembourg, Netherlands, Switzerland
Oceania	Australia, New Zealand
Model sectors	Major sectors in GTAP database
Grains	Paddy rice, Wheat
Vegetables, fruit, nuts	
Oil seeds	
Other crops, beet & cane	Sugar cane & beet, Plant-based fibers
Livestock	Cattle, sheep, goats, horses
Forestry	
Other agriculture	Raw milk, Wool, Silk, Fisheries
Processed food	Meat, Vegetable oils & fats, Dairy prod., Processed rice, Sugar, Beverages & tobacco
Fuels & electricity	Coal, Crude oil & gas, Natural gas, Electric power, Refineries
Chemicals, rubber, plastics	
Manufacturing	Textiles, Apparel, Leather prod., Wood prod., Paper prod., Ferrous metals, Metal prod., Motor vehicles & parts, Electronic equip.
Services	Communications, Finance, Insurance, Public admin/Health/Educ.
Rest of economy	Water utilities, Trade, Construction

Table 2

Key model parameter descriptions and values for baseline, upper, and lower sensitivity analyses.

Parameter	Description	Baseline	Lower	Upper
<i>A. Pollinator Dependency Ratios</i>				
Essential	> 90% yield reduction	0.95	0.90	0.99
Great	40-90% yield reduction	0.65	0.40	0.90
Modest	10-40% yield reduction	0.25	0.10	0.40
Little	< 10% yield reduction	0.05	0.01	0.10
None	No reduction in production	0.00	0.00	0.00
Unknown	No estimates available	0.00	0.00	0.00
<i>B. Elasticity of Substitution</i>				
σ^Y	between land and reproducible inputs ^a	0.5	0.25	1.0
σ^{KLEM}	between value-added and intermediate inputs ^a	0.8	0.4	1.6
σ^{VA}	between capital and labor ^b	1.0	0.5	2.0
σ^{VFN}	between fruits, vegetables, and nuts ^a	1.0	0.5	2.0
σ^{INT}	among intermediate inputs ^a	0.6	0.3	1.0
σ^M	among inputs to the material composite ^a	2.0	1.0	4.0
σ^{DM}	between domestic and imported varieties of each good (varies by commodity) ^c	0.77- 1.82	0.39- 0.91	1.54- 3.64
σ^{HH}	among inputs to household consumption ^a	0.5	0.25	1.0

^aAuthors' assumptions; ^bBalistreri et al. (2003); ^cGTAP database.

Table 3

Percent of crop sector production value in year 2004 at risk to pollination service loss (shaded cells indicate greater than 30% at risk; bold numbering indicates greater than 50% at risk).

Region	Vegetables	Fruits	Nuts	Grains	Oil Seeds	Sugar & Other Crops
Eastern Africa	1.50	8.64	17.08	1.35	22.96	4.30
Middle Africa	2.13	8.19	5.32	1.56	6.64	24.82
Northern Africa	8.73	35.75	21.62	0.95	7.00	0.37
Southern Africa	4.78	13.61	12.87	0.23	25.00	0.05
Western Africa	1.06	13.45	25.45	0.70	7.12	51.04
Central America & Caribbean	8.50	22.72	15.77	1.15	10.08	6.86
Northern America	5.04	35.78	43.66	0.08	24.69	0.10
South America	3.33	15.26	23.50	0.41	24.30	8.29
Central Asia	7.15	44.55	42.86	0.16	20.96	0.08
Eastern Asia	5.95	51.88	7.11	0.30	24.63	0.16
Southern Asia	7.86	34.49	12.90	0.27	24.41	2.91
Southeastern Asia	4.99	27.08	25.48	0.16	8.77	8.51
Western Asia	11.67	34.81	12.82	0.23	4.89	1.12
Eastern Europe	8.89	45.77	8.28	0.47	24.66	0.09
Northern Europe	3.18	47.70	0.00	0.35	24.51	0.00
Southern Europe	7.79	26.67	24.22	0.23	1.13	3.04
Western Europe	5.15	22.72	1.60	0.21	24.49	0.00
Oceania	4.21	29.02	26.12	0.16	21.90	5.53

Table 4

General equilibrium welfare effects (measured as change in equivalent variation) of productivity shocks due to global or regional loss of pollination services in 2004 (most at-risk regions in bold and positive effects shaded in grey).

Region	Global Scenario		Regional Scenarios					
	%	Bn \$	Own Region		Rest of World [†]		World Total	
	%	Bn \$	%	Bn \$	%	Bn \$	%	Bn \$
Eastern Africa	-0.10	-0.08	-1.68	-1.31	0.000	0.08	-0.005	-1.22
Middle Africa	-2.86	-0.93	-2.62	-0.85	0.001	0.27	-0.002	-0.58
Northern Africa	-2.05	-3.22	-1.95	-3.06	0.002	0.57	-0.010	-2.49
Southern Africa	-0.12	-0.17	-0.45	-0.63	0.001	0.32	-0.001	-0.31
Western Africa	-4.23	-3.16	-5.15	-3.84	0.006	1.43	-0.010	-2.42
Central America & Caribbean	-0.46	-3.11	-0.70	-4.67	-0.007	-1.78	-0.026	-6.45
Northern America	-0.35	-30.60	-0.36	-31.66	-0.045	-7.32	-0.155	-38.98
South America	-0.85	-5.93	-1.72	-11.93	0.000	-0.10	-0.048	-12.02
Central Asia	-1.23	-0.47	-1.39	-0.53	0.000	0.02	-0.002	-0.52
Eastern Asia	-1.28	-50.54	-0.99	-39.09	0.009	1.99	-0.147	-37.10
Southern Asia	-1.11	-7.30	-1.36	-8.99	-0.001	-0.35	-0.037	-9.35
Southeastern Asia	-0.87	-3.96	-1.03	-4.66	0.001	0.24	-0.018	-4.42
Western Asia	-1.20	-6.61	-0.85	-4.71	0.005	1.30	-0.014	-3.41
Eastern Europe	-0.55	-4.00	-0.40	-2.89	0.003	0.81	-0.008	-2.07
Northern Europe	-0.20	-4.09	-0.04	-0.82	0.002	0.58	-0.001	-0.25
Southern Europe	-0.38	-7.45	-0.47	-9.31	0.017	4.04	-0.021	-5.27
Western Europe	-0.13	-4.80	-0.10	-3.59	0.012	2.49	-0.004	-1.10
Oceania	-0.81	-3.66	-1.28	-5.80	-0.002	-0.57	-0.025	-6.36
World Total	-0.56	-140.07						

[†]Total impact experienced by all other regions due to a regional productivity shock incurred by region listed in first column.

Table 5

General equilibrium direct, indirect, and total impact on the value added of crop, non-crop, and aggregate production, respectively, due to productivity shocks associated with a global loss of pollination services in 2004 (positive effects shaded in grey).

Region	Direct		Indirect		Total	
	%	Bn \$	%	Bn \$	%	Bn \$
Eastern Africa	0.02	0.00	-4.07	-2.99	-3.29	-2.99
Middle Africa	-4.27	-0.21	-5.55	-2.83	-5.43	-3.05
Northern Africa	0.72	0.14	-5.17	-11.48	-4.71	-11.35
Southern Africa	13.76	0.45	-0.86	-1.77	-0.63	-1.32
Western Africa	-13.15	-2.55	-0.26	-0.24	-2.55	-2.79
Central America & Caribbean	5.20	1.12	-1.49	-7.72	-1.22	-6.61
Northern America	6.87	4.15	-0.46	-53.82	-0.42	-49.67
South America	4.04	1.77	-2.10	-20.71	-1.84	-18.94
Central Asia	4.63	0.06	-4.61	-2.16	-4.34	-2.10
Eastern Asia	6.87	8.68	-2.48	-162.95	-2.31	-154.27
Southern Asia	-0.85	-0.58	-5.91	-44.98	-5.49	-45.57
Southeastern Asia	2.19	0.53	-2.20	-14.53	-2.04	-14.01
Western Asia	5.60	1.73	-3.27	-27.21	-2.95	-25.48
Eastern Europe	3.32	0.95	-1.54	-15.69	-1.41	-14.73
Northern Europe	6.94	0.56	-0.30	-8.49	-0.28	-7.93
Southern Europe	4.70	2.75	-1.24	-34.75	-1.12	-31.99
Western Europe	8.27	3.13	-0.44	-23.37	-0.38	-20.24
Oceania	6.40	0.49	-1.13	-7.61	-1.05	-7.11
World	3.98	23.16	-1.25	-443.31	-1.17	-420.15

Table 6

General equilibrium direct, indirect, and total impact on the value added of crop, non-crop, and aggregate production, respectively, due to productivity shocks associated with a regional loss of pollination services in 2004 (positive effects shaded in grey).

Region	Direct		Indirect		Total	
	%	Bn \$	%	Bn \$	%	Bn \$
<i>A. Own Region</i>						
Eastern Africa	-5.00	-0.87	-2.63	-1.93	-3.09	-2.81
Middle Africa	-7.02	-0.35	-4.76	-2.43	-4.96	-2.78
Northern Africa	-3.43	-0.65	-4.30	-9.55	-4.23	-10.20
Southern Africa	-3.51	-0.11	-0.47	-0.97	-0.52	-1.08
Western Africa	-16.72	-3.25	1.16	1.05	-2.01	-2.20
Central America & Caribbean	-3.70	-0.80	-0.78	-4.04	-0.89	-4.84
Northern America	-1.47	-0.89	-0.35	-40.89	-0.36	-41.78
South America	-5.44	-2.38	-1.44	-14.23	-1.61	-16.61
Central Asia	-0.44	-0.01	-4.06	-1.91	-3.96	-1.91
Eastern Asia	4.61	5.83	-2.18	-143.00	-2.05	-137.17
Southern Asia	-2.46	-1.68	-5.18	-39.42	-4.95	-41.10
Southeastern Asia	-2.82	-0.67	-1.24	-8.23	-1.30	-8.91
Western Asia	-0.91	-0.28	-2.51	-20.94	-2.46	-21.22
Eastern Europe	-0.41	-0.12	-1.01	-10.29	-0.99	-10.41
Northern Europe	-1.91	-0.15	-0.07	-1.99	-0.08	-2.14
Southern Europe	-3.60	-2.11	-0.89	-24.80	-0.94	-26.91
Western Europe	-3.32	-1.26	-0.12	-6.53	-0.14	-7.79
Oceania	-3.16	-0.24	-0.97	-6.54	-1.00	-6.78
<i>B. Rest of World</i>						
Eastern Africa	0.07	0.38	-0.00	-1.17	-0.00	-0.80
Middle Africa	0.03	0.19	-0.00	-0.41	-0.00	-0.22
Northern Africa	0.14	0.76	-0.01	-1.92	-0.00	-1.16
Southern Africa	0.05	0.31	-0.00	-0.95	-0.00	-0.64
Western Africa	0.28	1.59	-0.01	-3.59	-0.01	-2.00
Central America & Caribbean	0.30	1.70	-0.01	-4.99	-0.01	-3.29
Northern America	0.99	5.17	-0.07	-16.15	-0.05	-10.98
South America	0.87	4.67	-0.04	-14.77	-0.03	-10.10
Central Asia	0.03	0.15	-0.00	-0.82	-0.00	-0.66
Eastern Asia	0.71	3.24	-0.03	-8.35	-0.02	-5.10
Southern Asia	0.29	1.50	-0.01	-3.55	-0.01	-2.04
Southeastern Asia	0.27	1.52	-0.01	-4.54	-0.01	-3.03
Western Asia	0.29	1.60	-0.01	-4.15	-0.01	-2.55
Eastern Europe	0.21	1.16	-0.01	-2.35	-0.00	-1.18
Northern Europe	0.10	0.56	-0.00	-0.88	-0.00	-0.33
Southern Europe	0.64	3.35	-0.03	-9.65	-0.02	-6.30
Western Europe	0.51	2.76	-0.02	-5.18	-0.01	-2.41
Oceania	0.15	0.86	-0.01	-4.04	-0.01	-3.17

Table 7

Partial equilibrium estimates of losses in consumer surplus (\$ billions) and the value of crop production.

Region	Consumer Surplus Loss		Value of Production Loss	
	$\epsilon = -0.8$	$\epsilon = -1.2$	(Bn \$)	(%)
Eastern Africa	-1.59	-1.32	-1.04	-4.53
Middle Africa	-1.78	-1.14	-0.66	-5.63
Northern Africa	-8.04	-5.33	-3.12	-13.72
Southern Africa	-1.07	-0.84	-0.58	-8.05
Western Africa	-13.45	-8.67	-4.95	-7.57
Central America & Caribbean	-8.07	-5.56	-3.45	-10.32
Northern America	-23.26	-19.12	-14.44	-12.77
South America	-17.07	-13.95	-10.76	-12.17
Central Asia	-3.96	-3.20	-2.43	-15.11
Eastern Asia	-94.64	-68.70	-44.59	-12.76
Southern Asia	-23.00	-18.34	-13.26	-10.69
Southeastern Asia	-12.79	-9.60	-6.61	-8.48
Western Asia	-20.58	-13.90	-8.31	-15.22
Eastern Europe	-10.34	-7.98	-5.49	-8.87
Northern Europe	-1.21	-1.03	-0.79	-4.86
Southern Europe	-21.48	-15.08	-9.35	-11.81
Western Europe	-11.16	-8.67	-6.02	-9.19
Oceania	-5.07	-3.74	-2.51	-13.60
World	-278.55	-206.17	-138.33	-11.26

Table 8

Results of parameter sensitivity analysis showing the loss in welfare (measured as equivalent variation) and loss in value added due to productivity shocks associated with a global loss of pollination services for each elasticity of substitution model parameter at its upper and lower bound from Table 2.

Parameter	Welfare Loss (\$ billions)		Value Added Loss (\$ billions)	
	Lower Bound	Upper Bound	Lower Bound	Upper Bound
σ^Y	-127	-147	-448	-402
σ^{KLEM}	-141	-138	-421	-419
σ^{VA}	-141	-140	-420	-420
σ^{VFN}	-143	-135	-434	-395
σ^{INT}	-138	-142	-446	-379
σ^M	-146	-135	-425	-413
σ^{DM}	-140	-140	-422	-417
σ^{HH}	-132	-152	-448	-375

Table 9

Results of parameter sensitivity analysis showing the impacts on welfare and value of production due to productivity shocks associated with a global loss of pollination services for each pollinator dependency ratio at its upper and lower bound from Table 2. GE = General Equilibrium, PE = Partial Equilibrium. Note GE Crop Sector Value Added are gains rather than losses. All values in \$ billions.

Metric	Lower Bound	Upper Bound
<i>A. Welfare Measures</i>		
GE Equivalent Variation	-63	-240
PE Consumer Surplus ($\epsilon = -0.8$)	-148	-589
PE Consumer Surplus ($\epsilon = -1.2$)	-114	-357
<i>B. Value of Production Measures</i>		
GE Total Value Added	-205	-701
GE Crop Sector Value Added	13	36
PE Total Value of Production	-81	-198