The Macroeconomic Cost of Catastrophic Pollinator Declines

Dana Marie Bauer and Ian Sue Wing

Department of Geography and Environment, Boston University, Boston, MA 02215, USA

E-mail: bauer@bu.edu, isw@bu.edu

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ABSTRACT

A computable general equilibrium (CGE) approach is used to assess the macroeconomic effects of global and regional catastrophic losses of pollination ecosystem services. Results show economic risks to both direct crop sectors and indirect non-crop sectors in the economy, with a substantial amount of regional heterogeneity. In addition, there exists potential for winners, those regions with a comparative advantage in the production of non-pollinator dependent crops. Comparison to partial equilibrium analyses shows that, in general, the partial equilibrium approach overestimates the costs to agricultural producers, underestimates total economy-wide losses, and overestimates social welfare losses in most regions.

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

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, genetic diversity, and 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 have occurred in Europe and North America (Beismeijer et al. 2006; NRC 2007; vanEngelsdorp et al. 2008; Potts et al. 2010), and have 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; vanEngelsdorf and Meixner 2010). A particular worry is the confluence of these trends and 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]

These concerns have spurred efforts 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. Recent papers have sought to address the last question 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 surplus of a total loss of pollinator-dependent output (Losey and Vaughan 2006; Gallai

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[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).

et al. 2009a). This approach has been adopted by the U.N. Food and Agricultural Organization (FAO 2009; Gallai and Vaissiere 2009).

In the present paper, we extend this methodology to a general equilibrium setting with the aim of rigorously quantifying the macroeconomic consequences of catastrophic losses of pollination service inputs to agriculture. Our approach is to incorporate 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 and Vaissiere (2009), we simulate catastrophic pollinator declines as exogenous reductions in the productivity of crop sectors by the fraction of pollinator-dependent production. The resulting price and quantity adjustments across domestic and international markets for agricultural as well as non-agricultural commodities elucidate the true welfare impacts of pollinator declines and the economic channels through which they operate.

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 value pollination services and quantify the impacts of declines therein. Our own methodology is described in section 3, which outlines the construction of our scenarios of pollination service losses, gives an overview of the CGE 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 pollinator declines on the costs of production in agricultural and non-agricultural sectors, changes in the relative prices of commodities and factors, and changes in consumers' welfare. Section 5 concludes with a summary of our findings and suggestions for future research directions.

2. Methods of Valuing Pollination Services

Economic valuation of pollination services provides information on the economic consequences of potential pollination shortages to various sectors of the economy and contributes to the decision-making process regarding selection of alternative mitigation strategies. Economic valuation studies focused on pollination services supplied to agriculture have, until recently, fallen into one of four categories, each of which has its weaknesses.

The first set of studies values the pollination services provided by commercially available bee colonies. Because these pollination services are exchanged through markets, colony rental prices are used as a direct measure of value (Burgett 2009; Burgett et al. 2010; Caron 2010). The drawback of this approach is that rental fees are a poor indicator of the non-market value of pollination services provided by wild insects, which in most parts of the world are responsible for much of the pollination in agriculture.

The second category of valuation studies measures the portion of the total value of crop production that can be directly attributed to animal pollination, typically using the formula $D \times Q \times P$, where D is the share of the yield of a particular crop that depends on pollinators, Q is production of the crop, and P is its price. This approach has been used to value the services provided by both managed and wild pollinator species (Robinson et al. 1989; Morse and Calderone 2000; Losey and Vaughan 2006; Gallai et al. 2009a) and has been adopted by the FAO in a spreadsheet tool for assessing the value of pollination services and national vulnerabilities to pollinator declines (FAO 2009; Gallai and Vaissiere 2009). The limitations of this approach are its failure to account for the costs of other inputs such as labor, capital and fertilizer, its assumption of perfectly elastic demand that ignores the price impacts of crop supply shocks, and its lack of recognition of substitutes for animal pollination such as mechanized and hand pollination or shifts to less pollinator-dependent cultivars (Muth and Thurman 1995; Allsopp et al. 2008; Winfree et al. 2011).

Studies in the third category measure the economic value of pollination services as the sum of the changes to producer and consumer surplus induced by the decrease in production due to a loss of pollination services (Kevan and Phillips 2001). This approach has been applied to pollination services provided by managed bees in a developed country context (Southwick and Southwick 1992), by wild bees in a developing country context (Kasina et al. 2009), as well as for total pollination services globally (Gallai et al. 2009a). Partial equilibrium estimates of shocks to consumer and producer surplus consider the market for a single crop in isolation, ignoring potentially important adjustments in input and output markets across the rest of the economy. For example, processed food producers are affected by an adverse crop supply shock through the channel of higher intermediate raw material prices, which in turn leads to final consumers seeing increased prices of both processed and non-processed foods.

Technology substitution is the basis of the fourth valuation technique, which employs a replacement cost approach whereby non-animal pollination alternatives (e.g., hand pollination or mechanized pollen dusting) are considered viable substitutes that offset the lost quantity of pollinator-provided services (Allsopp et al. 2008). However, the fact that replacement options ignore individuals' preferences and behavior creates that problem that they are not appropriate for making welfare calculations (NRC 2005). In particular, it seems doubtful that farmers will simply continue to purchase the same amount of equivalent pollination services if they are more costly; rather, they will likely exploit other margins of adjustment such as altering their mix of crops.

The need to overcome the aforementioned problems has prompted recent interest in using multi-market general equilibrium simulations to assess the economic consequences of changes in environmental quality and ecosystem service supplies (Brower et al. 2008; Carbone and Smith 2008, 2010; Sue Wing 2009, 2011; Delink et al. 2011). The primary advantage of this approach is its ability to consistently track changes in prices and demands across multiple interrelated markets, to summarize the macroeconomic effects of shocks by utilizing theoretically consistent measures of the change in aggregate economic welfare, and to test the consequences of different possibilities to substitute other inputs for pollination services. Notwithstanding this, computable general equilibrium (CGE) approaches have seen only limited application to the issue of pollinator declines.

In a key paper, Monck et al. (2008) use a single-country CGE model to assess the economic impacts of a potential invasion of the *Varroa* mite—a major honey bee pest—into Australia, the only major developed economy that currently relies on its large feral honey bee population for the majority of its pollination services, but has not yet experienced *Varroa*'s destructive effects. The model divides the economy into multiple crop sectors and two pollination services sectors, one with honey production and one with pollination-only, and is used to simulate the market impacts of counterfactual scenarios of *Varroa* incursion with and without pollination industry preparation. The results suggest that while investment in the managed pollination services industry is costly, overall benefits can be gained by moderating the short-run impacts of incursion on the overall supply of pollination services.

Gallai et al. (2009b) analyze the distributional consequences of pollinator declines using a stylized analytical general equilibrium model. Their model economy consists of two firms—each of which produces a single good, and one of which requires inputs of pollination services—

and two consumers endowed with factors of production. In this setting, pollinator declines have different distribution effects under different property rights regimes. They show that under an egalitarian distribution of property rights, both consumers suffer and there is an unequivocal loss in social welfare, while under a polarized structure of property rights the consumer without the pollination endowment can experience a welfare gain.

Our approach in this paper is a standard application of a static multi-region, multi-sector CGE model. We simulate agricultural production in, and trade among, 18 world regions, each of which resolves four broad crop sectors that exhibit varying degrees of pollinator dependency. Our model also includes detailed representations of nine additional sectors that demand the outputs of, or supply intermediate inputs to, pollinator-dependent agriculture. We simulate pollinator declines as exogenous neutral shocks to the productivity of the four key sectors, and examine the direct (crop sector) and indirect (non-crop sector) effects of a global and region-by-region loss of pollination services.

3. Methods

3.1 The Numerical Model

Our integrated ecological-economic CGE model of pollination services, agriculture, and global trade was developed using an updated version of the GTAPinGAMS package, originally developed by Rutherford and Paltsev (Rutherford 1999). As shown in Table 1, the model divides the world into 18 regions that mirror the 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., food products) which represent forward economic linkages, and their inputs (e.g., fuels, chemicals such as fertilizer and pesticides) which represent backward linkages.

Consumers in each region are modeled as a representative agent who has nested constant elasticity of substitution (CES) preferences and is endowed with the factors of production: labor and capital. Production in each region occurs in the 13 industry sectors, each of which is modeled as a representative producer of a single output commodity using nested CES production technology as shown in Fig. 1. Each region is treated as a small open economy linked to all other regions by trade in commodities. The latter is modeled using the Armington (1969) assumption that differentiates goods according to their region of production, and specifies a nested CES composite of imported and domestic varieties of each commodity that fulfills domestic final and intermediate demands.

The assumption of expenditure minimization by households yields final demands for final uses of commodities and allows unit expenditure on an aggregate consumption bundle to be expressed as a function of commodity prices. The assumption of cost minimization by firms yields demands for intermediate uses of commodities and factors and allows the unit cost of production to be expressed as a function of commodity and factor prices. The CGE model is constructed by algebraically combining the unit cost and expenditure functions and the commodity and factor demands with the Walrasian equilibrium conditions of market clearance (supply-demand balance) in goods and factors, zero profit (equality of price and marginal cost) in production, and income-expenditure balance for households (for details, see Sue Wing 2009, 2011). The resulting square system of nonlinear equations is numerically calibrated using version 7.2 of the Global Trade Analysis Project (GTAP) input-output database of global production and trade for the benchmark year 2004 (Narayanan and Walmsley 2008), formulated as a mixed complementarity problem using the MPSGE subsystem (Rutherford 1995) for the GAMS optimization package (Brooke et al. 2011), and solved using the PATH solver (Ferris and Munson 2000).

3.2 Simulating the Effects of Pollination Service Losses

The impacts of changes in the regional supplies of pollination services are modeled 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. Pollinator dependency is a measure of the level of impact that animal pollination has on the productivity of particular plant species. It varies dramatically among crops, with the highest level of dependence found predominantly in fruits, vegetables, and nuts. We use Klein et al.'s (2007) animal pollinator dependency classification scheme, which, based on a review of the literature on pollination requirements among primary crop species, quantifies the yield reduction as a consequence of an absence of pollinators:

1. *Essential*: > 90% [0.95] (e.g., cocoa beans, kiwi, pumpkins, watermelons)
2. *Great*: 40-90% [0.65] (e.g., almonds, apples, blueberries, cucumbers, pears)
3. *Modest*: 10-40% [0.25] (e.g., currants, sesame seeds, soybeans, strawberries)
4. *Little*: < 10% [0.05] (e.g., lemons, limes, oranges, tomatoes)
5. *None*: no reduction in production [0.0] (e.g., asparagus, maize, oats, wheat)
6. *Unknown*: no estimates available.

These ratios were used to calculate the proportion of crop production that would be lost due to a reduction in animal-mediated pollination services. Our first step was to calculate 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 (FAO 2010). Second, we multiplied these values by the midpoints of the ranges of the crop-specific pollinator dependency ratios shown in square braces above to obtain the value of production at risk from pollinator declines. Third, we aggregated the total value of production and the potential loss across countries and across crop types to match our 18 regional and four dependent sector groupings in Table 1. The final step was to calculate a region-by-sector matrix of potential productivity losses by dividing the total value of losses by the total value of production in each of our aggregate sectors.

We simulated a total of 19 scenarios: a global pollinator decline in which production of pollinator-dependent crops in all 18 regions were simultaneously impacted, and 18 region-specific shocks, each of which affected the production of pollinator-dependent crops in a single region. Every scenario was envisaged to be a catastrophic shock in which pollinator services were completely lost, triggering a decline in the productivity of pollinator-dependent crops in the amount of the mean fraction of the corresponding dependency category, indicated in square braces, above.

In the region where the shock manifests itself, it triggers direct impacts on pollinator-dependent crop sectors' input demands, production activity levels and output prices, which in turn induce a plethora of indirect effects, in the form of price and quantity adjustments in upstream and downstream markets. The model computes the new vectors of commodity and factor prices, sectoral activity levels, and household income levels necessary to re-establish equilibrium in the markets for factors and domestic and internationally traded commodities in every world region. The concomitant changes in the ruling prices and quantities demanded and supplied allow us to distinguish between the direct and indirect impacts, both of which will in general differ in magnitude from the initiating shock. Moreover, the resulting change in the aggregate expenditure of each regional representative agent yields a theoretically consistent indicator of the change in economic welfare, in the form of equivalent variation.[2]

3.3 Comparison with Partial Equilibrium Approaches

To highlight the ways in which our results differ from those of prior approaches, we compare them by juxtaposing the outputs of our simulations against three pollinator loss impact metrics used by Gallai et al. (2009a) and FAO's valuation tool (FAO 2009; Gallai and Vaissiere 2009), which we calculate using the FAOSTAT data for our 2004 target year. The economic value of insect pollination (EVIP) in each region *r* is calculated as the sum of the pollinator-dependent portion of production across all crops, *i*:

$$EVIP_r = \sum_i \left(D_i \times P_{i,r} \times Q_{i,r} \right) \tag{1}$$

where *D* is the crop-specific pollinator dependency ratio, and *P* and *Q* denote crop- and region-specific price and production levels. EVIP is the ex-ante valuation of production at risk, which we juxtapose with our simulated change in value of production in crop sectors—the direct effect—as well as non-crop sectors—the indirect effect. The vulnerability ratio (VR) expresses EVIP as a proportion of total value of crop production, i.e.,

$$VR_r = EVIP_r \div \sum_i \left(P_{i,r} \times Q_{i,r} \right) \tag{2}$$

Central to our comparison is the CGE model's ability to capture the fact that in reality both *P* and *Q* change simultaneously in response to substitution effects in the markets for crop sectors' inputs and outputs, causing the ex-ante and ex-post values of the metrics to diverge.

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[2] Equivalent variation is defined as the change in income of an individual 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). Equivalent variation and its companion metric, compensating variation, are considered more accurate measures of social welfare than the more often used—and easier to compute—consumer and producer surplus.

The potential for input and crop substitutability to moderate the impacts of pollinator shocks is an issue that is thrown into sharp relief by our final comparison between Gallai et al.'s (2009a) and FAO's (2009) partial equilibrium change in consumer surplus in crop output markets and our own general equilibrium change in the aggregate expenditure of consumers in each region. The former metric is calculated assuming constant elasticity demand curves and perfectly elastic supply curves in all crop markets:

$$CSloss_r = \sum_i \frac{P_{i,r} Q_{i,r}}{1+\varepsilon} \left(\left(\frac{1}{1-D_i} \right)^{1+\varepsilon} - 1 \right) \tag{3}$$

where ε is the price elasticity of demand, for which FAO (2009) assumes values of -0.8 or -1.2.

Although FAO's choice to model supply as perfectly elastic is understandable given the effort needed to specify regional crop supply functions, it gives short shrift to the impacts wrought by pollinator declines on exposed sectors' supply curves that reduce yields in the first place. The fewer possibilities to substitute other inputs for pollination, the less elastic the supply curve, and the higher the short run transition costs associated with the shock. Fig. 2 illustrates this by adapting Gallai et al.'s figure (2009, Figure 1) to include a relatively price-inelastic and a relatively price-elastic supply curve: S_0S_0' and S_1S_1', respectively. The effect of a pollinator shock is to shift these curves upward to the dashed loci Z_0Z_0' and Z_1Z_1', reducing the equilibrium quantity by the identical amount $Q_B - Q_A$ and generating identical consumer surplus losses. Additionally, a more elastic (inelastic) supply curve is associated with a smaller (larger) reduction in producer surplus and welfare.

Our general equilibrium welfare measure captures both supply and demand impacts through the CGE model's ability to track, on one hand, the productivity shock's effects on factor remuneration and consumers' incomes, and on the other hand, downstream industries' substitution of other inputs for pollinator-dependent crops. These effects are modulated parametrically by consumers' and producers' elasticities of substitution, and structurally by the model's treatment of intersectoral capital mobility.

4. Results

4.1 Crop Sector Production at Risk

Table 2 summarizes the fraction of the value of production at risk to pollinator declines in our 18 regions and six crop sectors, with vegetables, fruits and nuts disaggregated here to provide more details on regional heterogeneity. Vulnerability to 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, which are both high value and greatly pollinator dependent. Vegetables are generally much less vulnerable because even though animal pollination is necessary for seed production, only a small portion of the total of the crop is used to produce seeds. As expected, the least vulnerable crop sector for most regions is cereals 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 pollinator declines in four regions. The sugar and other crops sector, 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, Table 4).[3]

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[3] There are minor variations due to differences in the base year of FAO crop data (2004 here versus 2005 in Gallai et al.) and the selection of crops (all primary crops here versus only food crops in Gallai et al.).

4.2 General Equilibrium Direct and Indirect Effects on Producers

The direct, indirect and total effects of pollinator shocks on producers are shown in Table 3. A global loss of pollination services results in a \$302 billion reduction in the value of production across all sectors and regions representing a 0.39% decrease from the 2004 baseline (Table 3A). Crop sectors incur losses of \$23.7 billion globally, a 1.88% decline, while the remainder of the world economy incurs losses of \$278 billion, a 0.36% decline. Thus, less than 8% of the total loss in production value due to a global pollinator shock is sustained directly by farmers, while 92% of the loss occurs in other related markets. Every region experiences a loss in the aggregate value of gross output, both in absolute dollars (mean = -\$16.8 billion) and as a percent change from the baseline (mean = -0.7%). Similarly, every region experiences an aggregate loss across non-crop sectors (mean = -\$15.5 billion, -0.6%), a negative indirect effect. Overall, the direct crop effect in most regions is negative (mean = -\$1.3 billion, -1.6%). Counterintuitively, however, five regions experience increases in the value of production across the four crop sectors, a positive direct effect, representing a comparative advantage for some regions in non-pollinator dependent crops. Direct effects are larger than indirect effects in percentage terms in all but three regions, while indirect effects are larger than direct effects in absolute dollar terms with the exception of Western Africa. This makes sense because in most regions crop sector output is a small portion of the overall economy. Eastern Asia and Northern America incur the biggest losses in absolute dollar terms which together encompass more than 50% of the total decline in the value of global production, an unsurprising result because these two regions include the two largest country-level economies, China and the United States respectively. Western Africa is the most vulnerable region with 2.6% of total aggregate output and 12.8% of crop sector output at risk to a global loss in pollination services.

Table 3B shows the effects of regional pollinator shock scenarios on producers within the region of the shock. As expected, all own-region effects are negative because there is no opportunity for comparative advantage within the region experiencing the pollinator shock. Total losses in value of production vary dramatically among regions from \$1 to \$61 billion (mean = \$12.5 billion) in absolute dollars and from 0.02% to 2.83% (mean = 0.7%) as a percent change from the baseline. Direct crop-sector effects measured as percent change from baseline consistently outweigh indirect effects in all regions (mean = -5.9% versus -0.4%), while indirect effects outweigh direct effects in absolute dollar terms in all but three regions (mean = -\$8.7 billion versus -\$3.8 billion). Once again, the most vulnerable region is Western Africa.

Comparing results of regional shocks against those of a global shock shows direct crop sector losses within the region of impact to be greater in the regional scenarios than in the global scenario, while the opposite is true for indirect losses in all but one region, Oceania, in which the losses are of comparable magnitude. This is not surprising as regional shocks create comparative advantages in pollinator-dependent crop sectors in other regions not impacted by the shock. In addition, impacts in indirect upstream and downstream sectors are less rigid than in the global scenario such that prices in these sectors will not increase as much as they would if all regions experienced the shock. Interestingly, five of the eighteen regions—three of which are in Africa—experience a greater total loss with a regional pollinator shock, indicating a relatively large portion of aggregate output comes from pollinator-dependent crop sectors.

4.3 Global and Regional Welfare Impacts

The general equilibrium impacts on consumers' expenditure due to global or regional loss of pollination services are shown in Table 4. The welfare loss due to a global pollinator shock, measured in terms of equivalent variation across the global economy, is approximately $143 billion or a 0.6% decrease from the 2004 baseline level. Welfare impacts vary dramatically among the 18 regions from a 0.1% loss in Western Europe to a 4.4% loss in Western Africa, with a mean regional loss of 1.2%. Middle Africa and Northern Africa also experience relatively large welfare losses of 2.8% and 2.2%, respectively. As was the case with value of production impacts, Eastern Asia and Northern America incur the biggest losses in absolute dollars, $46.4 billion and $29.2 billion respectively, which together make up more than half of the world total.

Impacts of regional pollinator shocks can be broken down into two basic components. Own region welfare losses—incurred in the region which is subject to the regional pollinator shock—are of a similar magnitude to those in the global shock scenario, with a mean regional loss of $8 billion and 1.2 % reduction in welfare from the baseline. Similar to the global scenario, sub-Saharan Africa is particularly vulnerable to losses of pollination services in its own region, while Eastern Asia and Northern America suffer the largest absolute dollar losses. Other region welfare losses—incurred in regions other than the region experiencing a loss in pollination services—are, in contrast, quite small. That is, the largest impacts associated with regional pollinator shocks are sustained within the region experiencing the pollination service loss. Interestingly, 11 of the 18 regions experience positive welfare effects, on average, in response to pollinator losses in other regions, likely due to a newly realized comparative advantage in pollinator-dependent crops. An alternative approach to examining other region impacts of regional pollinator shocks is to sum up the impacts incurred in all regions other than that region experiencing the pollinator shock (i.e., rest of world effects). These impacts are also quite small, with rest of world effects being negative in only five regions. While still small, a regional pollinator shock in Northern America results in an $11 billion loss in welfare across the rest of world likely due to widespread reliance among other regions for its exports. At the other end of the spectrum, a regional pollinator shock in Southern Europe results in a $2.9 billion gain in welfare across the rest of the world. Combining own region and rest-of-world impacts gives the total world effect of regional pollinator shocks, all of which are negative because own region effects dramatically outweigh their corresponding rest of world effects. On average, total world effects of regional pollinator declines amount to a $7.8 billion welfare loss, a 0.03% reduction in global welfare from the baseline.

4.4 Western Africa Case Study

The interesting case of Western Africa highlights the power of our general equilibrium approach. Western Africa's apparent vulnerability to a decline in pollination services, both within its borders and globally, turns on a number of factors. First, its economy is relatively agriculture intensive in comparison to both developed and other developing regions, with agriculture and processed food comprising more than 25% of gross output. Second, agriculture is itself heavily dependent on pollination, with the four crop sectors making up 16% of the total agricultural output, 10% of which is dedicated to highly pollinator-dependent vegetables, fruits, and nuts. Third, as imports of vegetables, fruits, nuts and oil seeds account for less than 1% of the benchmark value of household consumption, the domestic market for these products is relatively autarkic, circumscribing consumer substitution toward foreign pollinator-dependent goods as a margin of adjustment to the shock. This suggests that intermediate and final consumers will be exposed to the full extent of domestic producer price changes. Moreover, Western Africa is a large producer of coffee and cocoa beans, stimulant crops for which insect pollination is essential. These crops are contained in the CGE model's sugar and other crops sector and nearly all (95%) of Western Africa's benchmark output in this sector is exported. The resulting contraction in foreign exchange earnings reduces the region's ability to import *non*-agricultural commodities, further impacting both production and welfare.

4.5 Partial Equilibrium Estimates of Economic Impacts

Table 5 summarizes the partial equilibrium estimates of the changes in the values of firms' production and consumers' surplus as a consequence of pollinator shocks, which by definition consider only losses that occur in pollinator-dependent crop sectors within the region experiencing the shock. Thus, the regional losses due to a global pollinator shock are the same as the losses incurred through regional shocks. With a global pollinator shock, the partial equilibrium value of lost production, EVIP, is $138.3 billion and the vulnerability ratio (VR), or percent decrease from the baseline, is 11.3%. In the case of regional pollinator shocks, the partial equilibrium losses range from $580 million to $44.6 billion, with a mean regional loss of $7.7 billion. In percentage terms, losses range from 4.5% to 15.2%, with a mean of 10.3% regional decrease from the baseline value.

A comparison of these partial equilibrium estimates to the direct and total effects from the general equilibrium global scenario analysis (Table 3A) shows the partial equilibrium analysis dramatically overestimates the direct impact on crop sectors ($138 billion versus $24 billion) and underestimates the total impact on the economy ($138 billion versus $302 billion) by not accounting for the effects on related sectors and households. In percentage terms, the partial equilibrium analysis overestimates both direct crop impacts and total impacts (11.3% versus 0.4% and 1.9%, respectively). Regionally, the partial equilibrium analysis overestimates the loss in value of crop production (direct effects) and underestimates the loss in value of total production (total effect) in all but a few regions. Recall from earlier, that five regions report positive direct effects due to global pollination service loss. Thus, not only does the partial equilibrium analysis overestimate the impact on farmers, it misrepresents the type of impact—negative versus positive—that would result from a global loss in pollination services.

Because the partial equilibrium analysis is restricted to a single region, a more viable comparison would be across regional pollinator shocks (Table 3B and Table 5). Once again, the partial equilibrium analysis overestimates the direct impact on crop sectors and underestimates the total impact on the economy in absolute dollars and overestimates both effects in percent change from the baseline, in all but a few regions. Fig. 3 visually compares the two approaches, showing not only magnitude and sign differences but also differences in heterogeneity among regions. That is, the general equilibrium analysis results in greater variability among regions. Here it becomes obvious that the partial equilibrium model is not detecting the extreme vulnerability of Western Africa.

Changes in consumer surplus are reported in Table 5. As expected, all regions experience a loss in consumer surplus due to pollinator shocks. Globally, the loss in consumer surplus is \$279 billion using a demand elasticity of -0.8 and \$206 billion using a demand elasticity of -1.2, the upper and lower bounds on the elasticity parameter used in the FAO tool. Regionally, the estimated loss in consumer surplus ranges from \$1.1 billion to \$94.6 billion, with a mean loss among regions of \$11.5 billion, using an elasticity of -0.8, and ranges from \$839 million to \$68.7 billion, with a mean loss among regions of \$15.5 billion, using an elasticity of -1.2. The large variability among regions is due in large part to differences in the size of regional economies. For example, the largest loss in consumer surplus occurs in Eastern Asia, the region that includes China.

Globally, the partial equilibrium estimate of welfare loss (Table 5) is greater than the general equilibrium estimate (Table 4) for both elasticity of demand parameter values used in FAO's tool. Regionally, the estimated loss in consumer surplus exceeds the estimated loss in equivalent variation for both global and regional pollinator shocks in all but three regions (Fig. 4). The differences between the two welfare measures range dramatically from \$20 million to \$56 billion depending on the type of shock—global or regional—and the value of the elasticity parameter. There are two possible explanations for these differences. First, while consumer surplus accounts for price changes in the markets for pollinator-dependent crops, it does not account for adjustments in the other crop markets or in non-crop sectors. Second, the partial equilibrium analysis presented here uses a single elasticity measure for all crops in all regions. In reality, one would expect greater variability among markets and regions. In general, it appears that the use of smaller elasticities (larger negative numbers) would result in consumer surplus losses more in line with estimates of equivalent variation. However, in those regions where consumer surplus underestimates equivalent variation, a larger elasticity would be in order.

5. Conclusions and Future Work

Although the precise values of gains and losses presented here are intended to be illustrative, three important insights emerge. The first is that the general equilibrium model captures both direct and indirect effects of pollination service loss. While the indirect effects are substantially larger than the direct effects in absolute dollar value, when viewed as percent changes from their baseline values, the direct effects outweigh both the indirect and the total effects. Second, the interregional distribution of the burden of pollination service losses is more heterogeneous in the general equilibrium framework. Although the partial equilibrium calculations indicate that a number of developed and developing regions are economically vulnerable, our general equilibrium analysis helps put these shocks in context. Thus, for example, Western Africa appears to be particularly vulnerable because pollinator-dependent crops make up a relatively large share of that region's agricultural output, agricultural sectors account for a substantial proportion of aggregate income, domestic consumption of agricultural crops relies heavily on domestic production, and a large portion of exports comes from pollinator-dependent crops. Third, in some regions it is possible for pollinator declines to have a positive direct impact on the value of crop production because agricultural products experience increases in their prices which outweigh the decreases in their yields. For example, agricultural producers in Southern Africa appear to benefit despite the fact that the region's economy as a whole suffers a loss.

In comparing partial equilibrium and general equilibrium approaches to valuing pollination services, our intent was not to criticize FAO's valuation tool. We believe that simple tools provided to decision makers are important and can be quite useful. Rather, our intent here was to investigate and report on the differences between the two approaches such that users of the tool can be aware of its potential limitations. In general, the partial equilibrium approach overestimates the costs to agricultural producers, underestimates total economy-wide losses, and overestimates social welfare losses in most regions while underestimating it in a few. In addition, it fails to recognize the potential for winners, those regions with a comparative advantage in the production of non-pollinator dependent crops.

Improving the precision and establishing the robustness of our results will likely necessitate modifications to the structure and parameterization of our nested CES representation of the crop production process. In particular, the extent to which our current implementation is able to capture the full range of substitution and mitigation strategies available to crop producers is not clear. The principal reason is our incomplete understanding of the role played by pollination services in the production of crops with different degrees of dependency, especially quantifying the degree to which managed pollinators can substitute for wild species (Klein et al. 2003; Greenleaf and Kremen 2006) and mechanized or hand pollination can substitute for pollination by animals, as well as the degree to which producers will convert to production of non-pollinator dependent crops. Remedying these gaps in our knowledge will likely entail a separate, complementary program of empirical research, which in turn must await the development of datasets on pollinator-dependent crop production that resolve pollination services as a separate input from the livestock sector.

In terms of characterizing more radical margins of adjustment, future research could also explore the role of technology-based and conservation-based mitigation strategies. Technology-based strategies 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 conservation-based mitigation strategies include both on-farm and off-farm habitat conservation through programs like the U.S. Department of Agriculture's Conservation Reserve Program (Morandin and Winston 2006). A more sophisticated understanding of substitution and mitigation alternatives will greatly improve our understanding of producer decision-making and enhance our ability to characterize the risks associated with pollinator declines.

Finally, pollination is only one of several ecosystem services of importance to agriculture (Zhang et al. 2007). The modeling framework introduced 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.

Using a general equilibrium approach that simulates the full spectrum of price and quantity changes across agricultural and non-agricultural sectors of the economy, we show that pollinator declines affect both sets of sectors, that the effects on downstream industries can be quite large, and that some regions of the world (e.g., Africa) suffer much heavier burdens than others.

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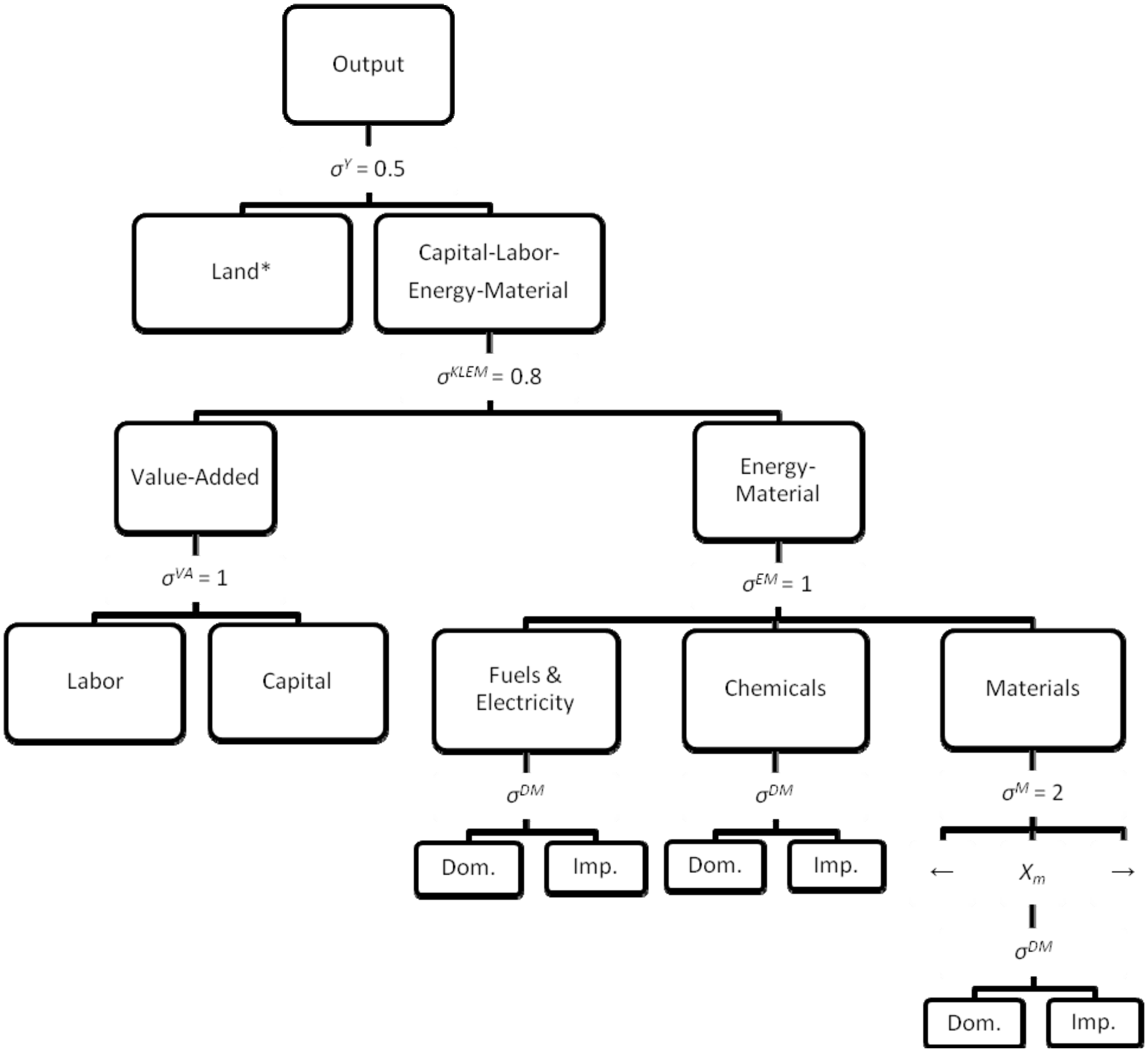

Fig. 1. Model nested CES production structure showing key elasticity of substitution parameters.

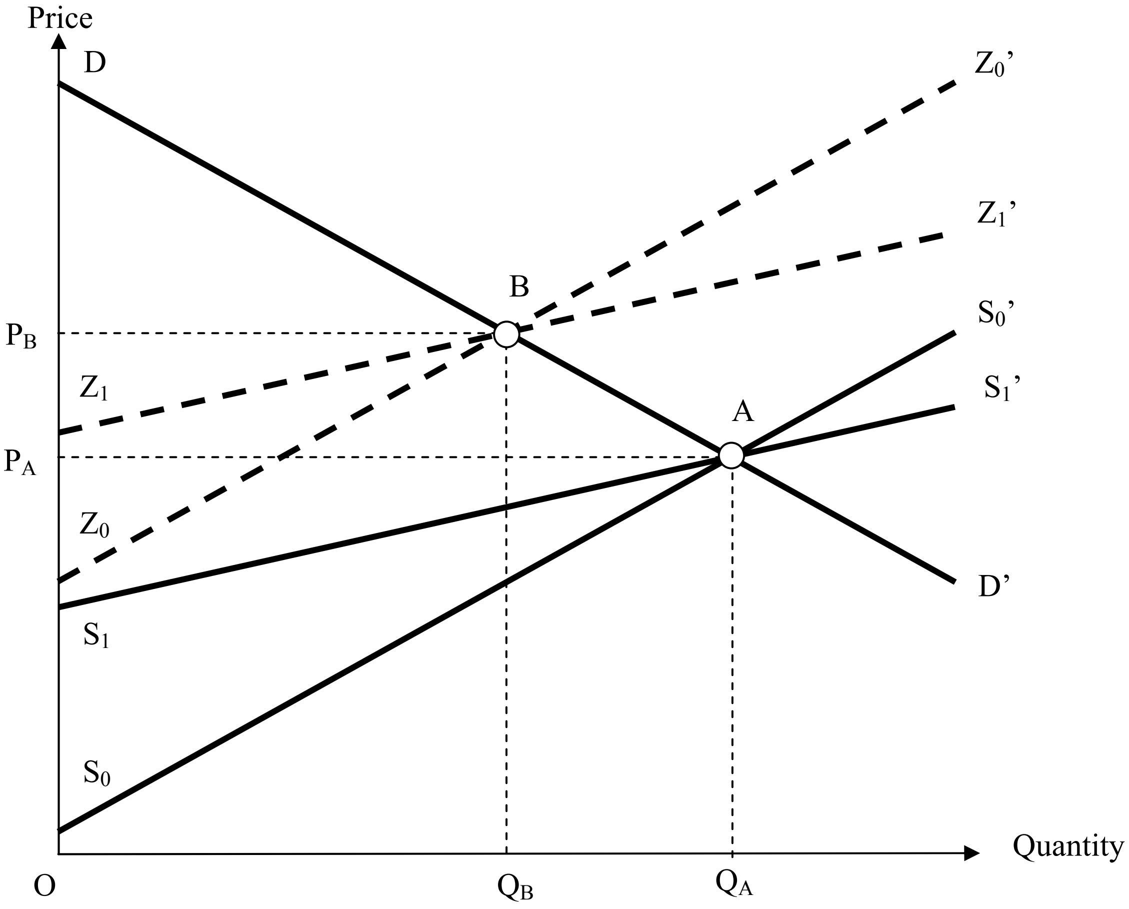

Fig. 2. Partial equilibrium impacts of pollinator declines on the market for a pollinator-dependent crop. Impact of pollinator shock on quantity produced/consumed: $Q_A - Q_B$; consumer surplus loss: $DAP_A - DBP_B$; producer surplus loss with relatively inelastic supply: $S_0AP_A - Z_0BP_B$; and producer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

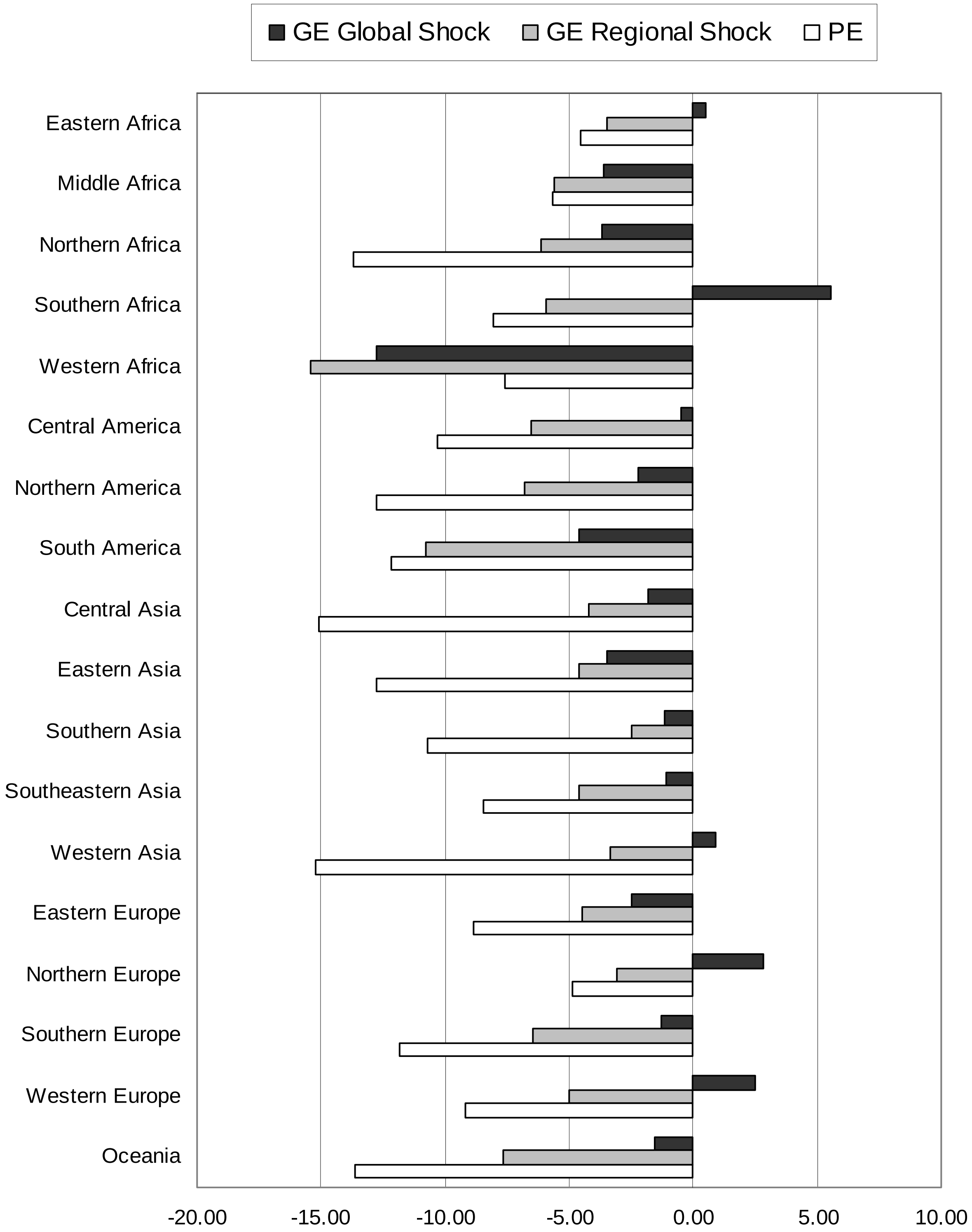

Fig. 3. Percent change in value of crop sector production due to global or regional loss of pollination services in 2004 (GE = General Equilibrium, PE = Partial Equilibrium). Regional partial equilibrium impacts are the same for both global and regional pollinator shocks. General equilibrium regional effects are own region impacts only.

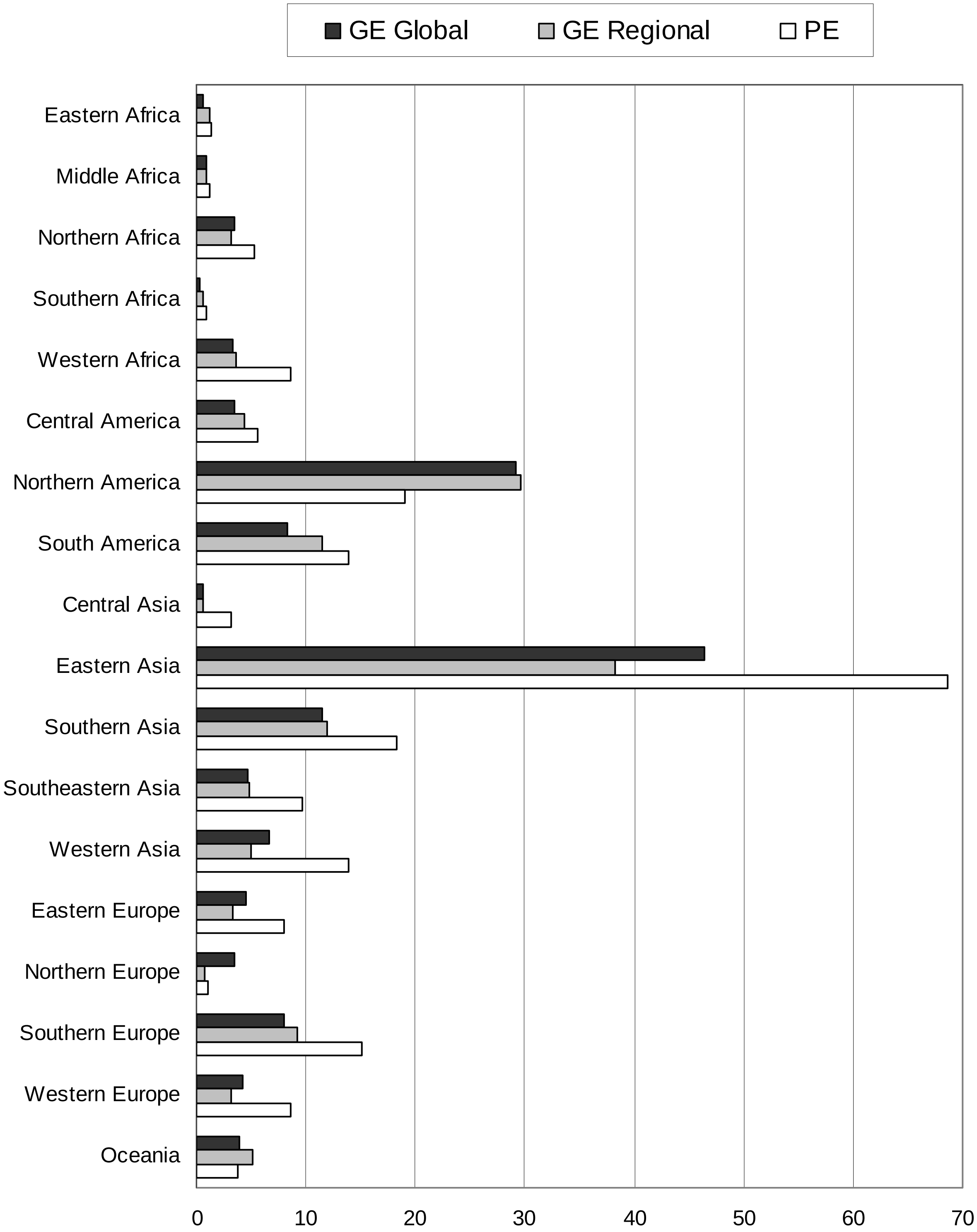

Fig. 4. Reduction in welfare (in $ billions) due to regional loss of pollination services in 2004; welfare measured as equivalent variation in general equilibrium and consumer surplus in partial equilibrium (ε = -1.2).

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
Percent of crop sector production value in year 2004 at risk to pollinator 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 3
General equilibrium direct, indirect, and total impact on the value of crop, non-crop, and aggregate production, respectively, due to a loss of pollination services in 2004 (positive effects shaded in grey).

Region	**Direct**		**Indirect**		**Total**	
	%	Bn $	%	Bn $	%	Bn $
A. Global Pollinator Loss Scenario						
Eastern Africa	0.48	0.13	-1.02	-1.69	-0.81	-1.57
Middle Africa	-3.57	-0.27	-0.94	-0.97	-1.12	-1.25
Northern Africa	-3.64	-1.18	-0.86	-4.10	-1.04	-5.28
Southern Africa	5.58	0.44	-0.26	-1.32	-0.17	-0.88
Western Africa	-12.75	-3.32	-0.62	-0.84	-2.55	-4.16
Central America & Caribbean	-0.48	-0.20	-0.51	-7.94	-0.51	-8.14
Northern America	-2.21	-3.12	-0.29	-63.84	-0.30	-66.96
South America	-4.60	-4.43	-0.58	-11.65	-0.76	-16.08
Central Asia	-1.79	-0.10	-1.10	-1.68	-1.12	-1.78
Eastern Asia	-3.49	-9.43	-0.48	-75.93	-0.53	-85.36
Southern Asia	-1.14	-1.85	-1.21	-20.11	-1.21	-21.96
Southeastern Asia	-1.09	-0.67	-0.49	-8.32	-0.51	-8.99
Western Asia	0.88	0.46	-0.59	-9.52	-0.54	-9.06
Eastern Europe	-2.51	-2.01	-0.31	-8.12	-0.37	-10.13
Northern Europe	2.82	0.87	-0.19	-11.99	-0.17	-11.12
Southern Europe	-1.27	-1.26	-0.33	-18.74	-0.34	-20.00
Western Europe	2.47	2.51	-0.20	-23.59	-0.17	-21.08
Oceania	-1.55	-0.25	-0.58	-7.97	-0.59	-8.22
World	**-1.88**	**-23.68**	**-0.36**	**-278.33**	**-0.39**	**-302.01**
B. Regional Pollinator Loss Scenarios						
Eastern Africa	-3.48	-0.91	-0.76	-1.26	-1.13	-2.17
Middle Africa	-5.62	-0.43	-0.61	-0.63	-0.95	-1.06
Northern Africa	-6.12	-1.98	-0.54	-2.55	-0.89	-4.53
Southern Africa	-5.95	-0.47	-0.13	-0.63	-0.22	-1.10
Western Africa	-15.40	-4.01	-0.44	-0.60	-2.83	-4.61
Central America & Caribbean	-6.52	-2.73	-0.21	-3.27	-0.38	-6.01
Northern America	-6.78	-9.60	-0.23	-51.19	-0.27	-60.79
South America	-10.81	-10.41	-0.54	-11.02	-1.01	-21.43
Central Asia	-4.23	-0.23	-0.86	-1.32	-0.98	-1.55
Eastern Asia	-4.60	-12.44	-0.25	-39.71	-0.32	-52.15
Southern Asia	-2.48	-4.02	-0.97	-16.02	-1.10	-20.04
Southeastern Asia	-4.62	-2.83	-0.17	-2.91	-0.32	-5.75
Western Asia	-3.37	-1.76	-0.19	-3.03	-0.29	-4.78
Eastern Europe	-4.48	-3.60	-0.07	-1.76	-0.20	-5.35
Northern Europe	-3.11	-0.96	-0.01	-0.58	-0.02	-1.54
Southern Europe	-6.43	-6.36	-0.16	-9.07	-0.26	-15.43
Western Europe	-5.01	-5.09	-0.01	-1.15	-0.05	-6.24
Oceania	-7.65	-1.24	-0.68	-9.41	-0.76	-10.65

Table 4

Welfare effects (measured as change in equivalent variation) due to global or regional loss of pollination services in 2004 (most at-risk regions shaded in grey).

	Global Scenario		Regional Scenarios							
			Own Region		Other Region†		Rest of World‡		World Total	
Region	**%**	**Bn $**	**%**	**Bn $**	**%**	**Bn $**	**%**	**Bn $**	**%**	**Bn $**
Eastern Africa	-0.68	-0.53	-1.60	-1.25	0.057	0.04	0.000	0.05	-0.005	-1.19
Middle Africa	-2.83	-0.92	-2.58	-0.83	-0.010	0.00	0.001	0.21	-0.002	-0.62
Northern Africa	-2.19	-3.42	-2.04	-3.20	-0.003	-0.01	0.002	0.44	-0.011	-2.75
Southern Africa	-0.21	-0.29	-0.41	-0.58	0.011	0.02	0.001	0.22	-0.001	-0.36
Western Africa	-4.40	-3.28	-4.76	-3.56	0.030	0.02	0.004	1.07	-0.010	-2.49
Central America & Caribbean	-0.52	-3.47	-0.64	-4.33	0.008	0.05	-0.006	-1.57	-0.023	-5.90
Northern America	-0.33	-29.24	-0.34	-29.59	0.001	0.07	-0.044	-11.12	-0.162	-40.71
South America	-1.19	-8.28	-1.65	-11.48	0.029	0.20	0.002	0.49	-0.044	-10.99
Central Asia	-1.62	-0.62	-1.56	-0.60	0.008	0.00	0.000	-0.07	-0.003	-0.67
Eastern Asia	-1.18	-46.40	-0.97	-38.27	-0.012	-0.45	0.003	0.66	-0.149	-37.61
Southern Asia	-1.73	-11.44	-1.81	-11.95	0.006	0.04	-0.002	-0.44	-0.049	-12.39
Southeastern Asia	-1.03	-4.69	-1.06	-4.80	0.003	0.01	0.000	0.05	-0.019	-4.75
Western Asia	-1.21	-6.70	-0.91	-5.04	-0.016	-0.09	0.004	1.06	-0.016	-3.98
Eastern Europe	-0.63	-4.54	-0.46	-3.28	-0.010	-0.07	0.001	0.37	-0.012	-2.91
Northern Europe	-0.17	-3.48	-0.04	-0.81	-0.008	-0.17	0.002	0.41	-0.002	-0.40
Southern Europe	-0.41	-8.06	-0.46	-9.16	0.003	0.07	0.011	2.89	-0.025	-6.26
Western Europe	-0.11	-4.18	-0.09	-3.23	-0.002	-0.07	0.007	1.74	-0.006	-1.49
Oceania	-0.87	-3.94	-1.13	-5.10	0.020	0.09	-0.002	-0.62	-0.023	-5.71
World	-0.57	-143.49								

†Average of impacts experienced by region listed in first column due to regional pollinator shock in one of the other regions.

‡Total impact experienced by all other regions due to regional pollinator shock incurred by region listed in first column.

Table 5
Partial equilibrium estimates of losses in the value of crop sector production and consumer surplus.

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