Economic Consequences of Pollinator Declines: A Synthesis

Dana Marie Bauer and Ian Sue Wing

This paper surveys the literature on pollinator declines and related concerns regarding global food security. Methods for valuing the economic risks associated with pollinator declines are also reviewed. A computable general equilibrium (CGE) approach is introduced to assess the effects of a global catastrophic loss of pollinators. There appears to be evidence supporting a trend towards future pollinator shortages in the United States and other regions of the world. Results from the CGE model show economic risks to both direct crop sectors and indirect non-crop sectors in the economy, with some amount of regional heterogeneity.

Key Words: ecosystem services, pollinators, food security, valuation, computable general equilibrium modeling

This paper deals with the impacts on the economy of changes in the supply of the services provided by natural ecosystems. A key challenge for research on this topic is the multifaceted nature of ecosystem services, in terms of not only the scope of benefits they provide to society, but also their own characteristics and the channels through which their influence is felt. Even if we restrict the scope of our investigation to agriculture, the myriad ecosystem services provided to and generated by the sector (see, for example, Zhang et al. 2007) are too numerous to rigorously review in a single article-length manuscript. Thus, rather than give a broad and superficial overview of the topic, we focus in more depth on a single well-defined service: pollination, whose primary impact on the economy is through the productivity of a comparatively narrow slate of crops. We synthesize the literature on pollinator declines with the objective of characterizing the associated risks, and quantifying what those risks might mean in terms of adverse shocks to yields in different crop categories and regions. We then briefly review existing methods for valuing such shocks before introducing a novel general equilibrium assessment approach and highlighting a few of its preliminary results.

Pollination is a valuable ecosystem service, providing a variety of benefits including food and fiber, plant-derived medicines, ornamentals and other aesthetics, genetic diversity, and overall ecosystem resilience (Millennium Ecosystem Assessment 2003, Naban and Buchmann 1997). The issue of pollinator declines began to receive widespread attention in 2006 when the popular press reported on the mysterious disappearances of managed honey bee colonies across the United States. Bees were leaving their colonies in search of pollen and nectar—a typical day of work for a honey bee—but not returning to the hive. There does not appear to be any single pest or pathogen responsible for this phenomenon, which scientists have named Colony Collapse Disorder (CCD), and the United States is currently spending millions of dollars to investigate its potential causes and to develop management guidelines and mitigation strategies (Pettis and Delaplane 2010).

At the global scale, declines in pollinator populations and species diversity more broadly have raised concerns regarding 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, Potts, and Packer 2005, Allen-Wardell et al. 1998). From an ecological perspective, pollinator declines present additional risks to

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ecosystem stability and loss of biodiversity, not only of the pollinator species themselves but also the plants they pollinate (Biesmeijer et al. 2006, Kearns, Inouye, and Waser 1998). Evidence exists of local and regional declines of both managed and wild insect pollinators (vanEngelsdorp and Meixner 2010, NRC 2007, Potts et al. 2010), which appear to be a result of pests, diseases, pesticides, habitat destruction, and agricultural intensification (Le Feon et al. 2010, vanEngelsdorp and Meixner 2010, Winfree et al. 2009, Kremen, Williams, and Thorp 2002, Cunningham 2000).

Flowering plants require pollination to produce seed or fruit. Some plants are wind-pollinated and others are self-pollinated, but many plant species require animal-mediated cross-pollination (NRC 2007). Even in those plant species capable of self-pollination, animal pollination can increase the quantity and quality of production (Klein, Steffan-Dewenter, and Tshcarntke 2003, Roubik 2002). At the global level, 75 percent of primary crop species and 35 percent of crop production rely on some level of animal pollination (Klein et al. 2007). Gallai et al. (2009b) estimate the value of this pollination service to be €153 billion (~$200 billion). In the United States, more than half of primary crop species and 20 percent of primary crop production rely in part on animal pollination. A recent study estimates the value of honey bee pollination alone in the United States at $14.6 billion, which reflects both direct crop and indirect livestock feed values (Morse and Calderone 2000). Including the benefits of wild pollination services would increase the value further. The key issue addressed by the paper is the extent to which these figures fully capture the opportunity costs of pollination services, and in turn accurately account for the economic losses that would be experienced in the event of a sudden pollinator decline.

The remainder of this paper is organized as follows. The next section describes the role of managed and wild pollinators in crop production, and surveys our current understanding of the risks associated with pollinator declines and their dependence on key trends in agriculture. Drawing on these discussions, we offer an assessment of the potential effects of a sudden pollinator decline on global crop yields. In the section after that, we critically review the various approaches previously used for valuing pollination services, and, by extension, estimate the economic consequences of a reduction in their supply. Then we present a new approach to assessing the economy-wide effects of pollinator declines based on the application of computable general equilibrium (CGE) models, and discuss the insights it can provide into the spillover impacts of pollinator declines on the costs of production in agriculture and non-agricultural sectors, changes in the relative prices of commodities and factors, and consumers' welfare. In the final section, we summarize our findings and offer suggestions for future research.

Agriculture's Dependence on Pollinators

Animal pollinators include many insect species, as well as several species of birds and bats (Naban and Buchmann 1997). Animal pollination of agricultural crops is provided by both managed and wild pollinators. European honey bees (*Apis mellifera*) are the most common managed pollinator species, as they possess several characteristics that make them good pollinators (NRC 2007). First, they are generalist pollinators that are physically capable of pollinating many different plant species. Second, they exist in large, perennial colonies with up to 30,000 individuals that are available for crop pollination year-round. Third, they are able to forage over large distances, so that their placement within large monoculture fields allows them to provide pollination services over a wide area. Fourth, they communicate with other members of the hive regarding location of food sources, making them highly efficient pollinators. And, finally, honey bees produce honey, a valuable, commercially marketed product.

Wild pollinators are also important for agricultural production (Veddeler et al. 2008, Klein, Steffan-Dewenter, and Tshcarntke 2003). Although honey bees can pollinate many plant species, they are not always the most efficient pollinator on a bee-per-plant-visit basis. For example, yucca plants are highly dependent on yucca moths for their pollination (NRC 2007). Principal pollinators vary by plant species, geographical location, and time of year (NRC 2007, Kearns, Inouye, and Waser 1998). In many developing regions, wild pollinators are the sole provider of pollination services available to small-scale farmers because of the high costs associated with maintaining managed colonies (Kasina et al.

2009). Wild and managed pollinators can also have complementary behavioral relationships which increase the efficiency of pollination (Greenleaf and Kremen 2006, Klein, Steffan-Dewenter, and Tshcarntke 2003). And lastly, as discussed below, there are insufficient numbers of managed honey bees available to fully service all pollinator-dependent crops. Thus, both managed and wild pollinators contribute to the global production of agricultural crops, although the relative populations of the two categories and the mix of pollinator species vary substantially by crop and region.

Pollinator dependency is a measure of the level of impact that animal pollination has on the productivity of particular plant species. Klein et al. (2007) recently reviewed the literature on animal pollination and developed a classification system for animal pollinator dependency:

i. *essential* – production reduced by ≥ 90 percent without pollinators
ii. *great* – production reduced by 40 to < 90 percent
iii. *modest* – production reduced by 10 to < 40 percent
iv. *little* – production reduced by > 0 to < 10 percent
v. *none* – no reduction in production
vi. *unknown* – no literature available.

In their review, Klein et al. (2007) found that 87 out of 115 global primary food crops require some level of animal pollination. The level of pollinator dependency varies dramatically among crops, with the highest level of dependence found predominantly in fruits, vegetables, and nuts. Crops that are essentially dependent on animal pollination include Brazil nuts, cantaloupe, cocoa beans, kiwi fruit, pumpkins, squash, vanilla, and watermelon (Klein et al. 2007). Many crops have reduced production in the quantity or quality of the plant part consumed directly by humans, while other crops have reduced production of seeds that are used to produce the vegetative parts of plants that humans consume.

The Risk from Pollinator Declines

The potential adverse effects of pollinator declines include direct economic losses incurred by reduced crop yields as well as broader impacts on agricultural activity as a consequence of lower productivity in the ecosystems that sustain it (through, e.g., nutrient cycling). While there is concern that the magnitude of the latter effects may be very large, the relevant causal chains—from reduced animal pollination to the population dynamics of wild plant species to changes in the structure of food webs, the health of ecosystems, and the supplies of their services to agriculture—have yet to be systematically elaborated. Perhaps in recognition of the enormity of this task, the literature on the societal impacts of pollinator declines has tended to focus on the direct implications for crop production and global food security.

But even the magnitude of the direct impact is the subject of controversy (Ghazoul 2005a, 2005b, Steffan-Dewenter, Potts, and Packer 2005). While Klein et al. (2007) found that 75 percent of primary global food crop species relies on some amount of animal pollination, only 35 percent of crop production is pollinator-dependent. At least 60 percent of global food crop production comes from plant species that do not require animal pollination (e.g., cereals and grains), while 5 percent of production comes from crops with unknown pollinator dependency. Comparing pollinator-dependent and non-dependent crop production at the global level suggests that all regions exhibit a consistently heavy reliance on non-dependent food crops (Figure 1). Aizen et al. (2009) found similar results when dividing the world into developed and developing countries, and Ashworth et al. (2009) found similar results for Mexico alone. Thus, from a total caloric perspective, there does not appear to be a current risk to food security from pollinator declines.

Some have argued, however, that there may be a global food security risk from a micro-nutrient perspective, as the majority of pollinator-dependent crops are fruits, vegetables, and nuts (Gallai et al. 2009b, Steffan-Dewenter, Potts, and Packer 2005). This raises the question of future trends in food consumption vis-à-vis nutritional content. Figure 2 shows an increase in the percentage of total harvested acreage due to pollinator-dependent crops, suggesting an increasing reliance on animal pollinators. Aizen et al. (2008, 2009) and Garibaldi et al. (2009) provide a more detailed discussion of this global trend.

U.S. crop production data also indicate an increase in the harvested acreage of pollinator-de-

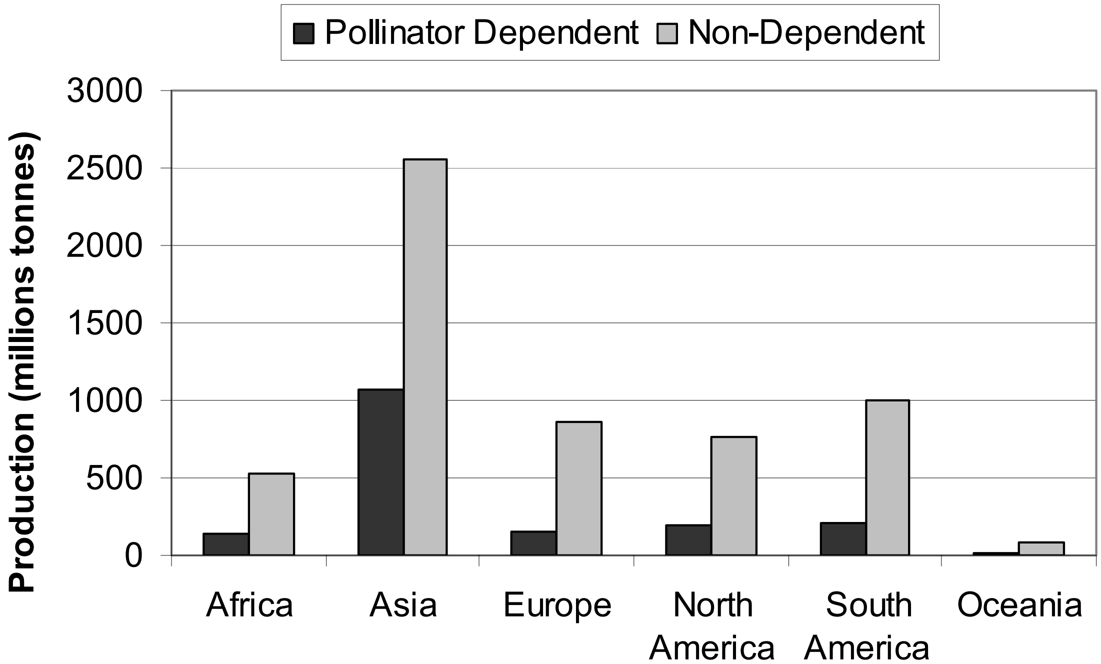

Figure 1. World Crop Production by Pollinator Dependency by Continent (2008)
Source: FAO (2010), Klein et al. (2007).

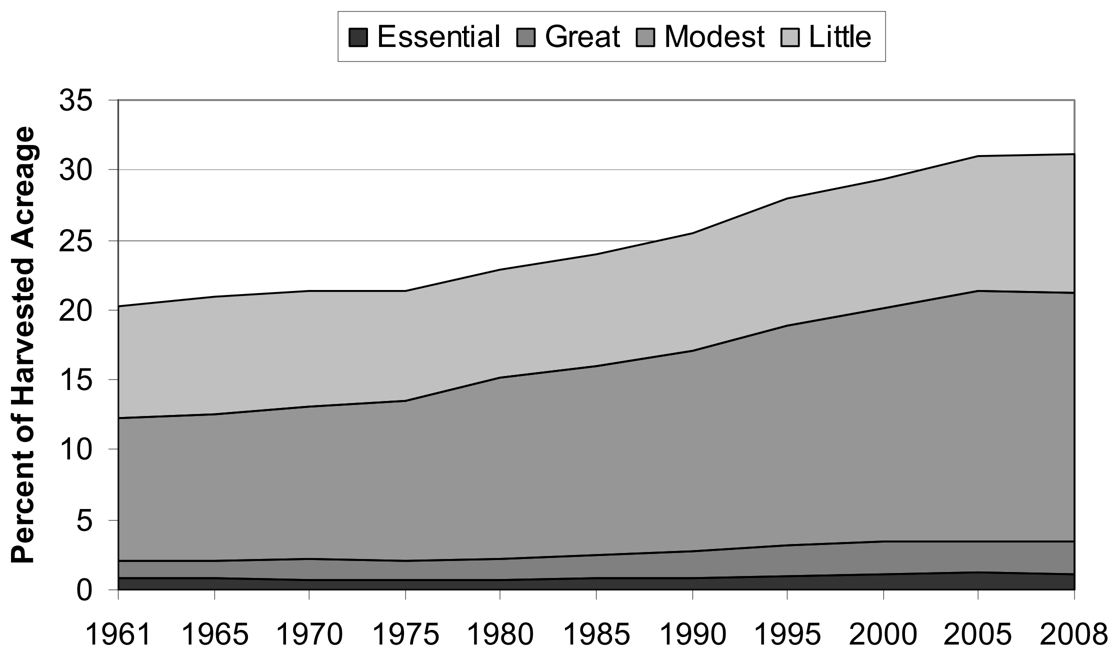

Figure 2. World Crop Pollinator Dependency (1961–2008)
Source: FAO (2010), Klein et al. (2007).

pendent crops, from less than 20 percent of total acres harvested in 1961 to greater than 25 percent in 2008 (Figure 3). The majority of this growth occurred in crops that are classified as modestly dependent on animal pollination (i.e., 10–40 percent of yields would be lost without pollination services). Particularly large increases in harvested acreage occurred for almonds, soybeans, and sunflower seeds.

It is difficult, if not impossible, to assess the status of wild pollinators on a global scale (Aizen and Harder 2009). However, studies have shown declines at the local and regional level, particularly in Europe and North America (Potts et al. 2010, Biesmeijer et al. 2006). In terms of managed pollinators, the number of colonies globally has steadily increased over the past 50 years (Figure 4) (Aizen and Harder 2009). However, similar to wild bees, managed bee colonies have declined on a regional scale, especially in Europe and North America (Figure 5) (Aizen and Harder 2009, vanEngelsdorp and Meixner 2010).

Figure 6 (solid line) shows a decline in U.S. honey-producing colonies over the past twenty years. While some of this decline can be explained by lower world prices for and increasing imports of honey causing beekeepers to leave the industry (vanEngelsdorp and Meixner 2010, Sumner and Borriss 2006), other bee colony losses are due to parasites, pathogens, and Colony Collapse Disorder (Johnson 2010, vanEngelsdorp et al. 2008, 2009). The trend for total honey bee colonies (square dots in Figure 6) is less obvious. There appears to have been a decline in the total number of colonies between 1987 and 2002; however, the recent sharp increase in 2007 provides circumstantial evidence that some beekeepers who exited the honey-producing market may have now entered the pollination market.

In attempting to address the food security question, it is important to distinguish between pollinator declines and pollinator shortages (Aizen et al. 2008, 2009). A pollinator decline is a reduction in population size (i.e., the number of individuals) or biodiversity (i.e., the number of species), while a pollinator shortage occurs when the demand for pollination services exceeds the available supply. Despite evidence of local and regional declines among managed and wild pollinators, little evidence of current pollinator shortages appears in the literature. However, we argue here that three current trends do indeed indicate the potential for future shortages both regionally and in the United States. First, the demand for pollination services, as indicated by acreage for pollinator-dependent crops, is increasing (Figures 2 and 3), while the supply of managed bees in some regions is declining (Figures 5 and 6). In addition, the rate of growth in the global supply of managed bees is less than the rate of growth in global demand for pollination services, as indicated by pollinator-dependent crop acreage, suggesting the potential for future shortages of pollination services on a global scale (Aizen and Harder 2009).

Second, prices for managed honey bee colony rentals in California, the Pacific Northwest, and the mid-Atlantic have increased dramatically over the past few years (Burgett et al. 2010, Caron 2010, Sumner and Borriss 2006), reflecting both the increase in demand for pollination services, particularly from almond growers in California, and declines in the supply of honey bee colonies (Sumner and Borriss 2006). The average bee colony rental fee in the Pacific Northwest has risen from $19.25 per colony in 1992 to $89.90 in 2009 (Burgett 2009). In addition, an insufficient supply of honey bee colonies for almond growers in 2007, due to a high rate of CCD winter kills, resulted in the loosening of trade restrictions on the import of honey bee queens (vanEngelsdorp and Meixner 2010). The California almond industry currently accounts for 66 percent of California and 34 percent of Pacific Northwest honey bee colony rentals (Burgett et al. 2010). Many of these colonies travel to a second crop field later in the growing season, but this level of almond pollination services does suggest the potential for a shortage of managed bees for other pollinator-dependent crops.

Third, the number of managed honey bee colonies available per hectare of pollinator-dependent harvested crop acreage over the past 47 years has declined both globally and for the United States (Figure 7). By way of comparison, recommended managed honey-bee colony densities range between 0.5 and 2.5 colonies per acre (1.2 to 6.2 colonies per hectare) for various pollinator-dependent crops (Burgett et al. 2010).

All three of these trends suggest an increasingly heavy reliance on wild pollinators for agricultural production both globally and in the United States and that this reliance on non-marketed ecosystem services is increasing. As a non-

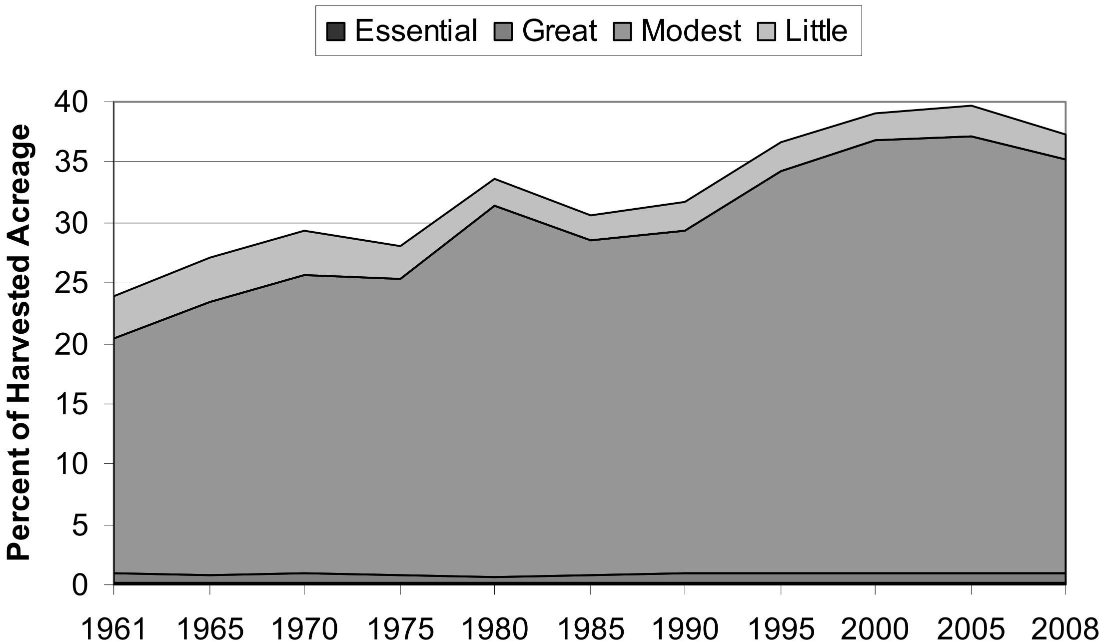

Figure 3. U.S. Crop Pollinator Dependency (1961–2008)
Source: FAO (2010).

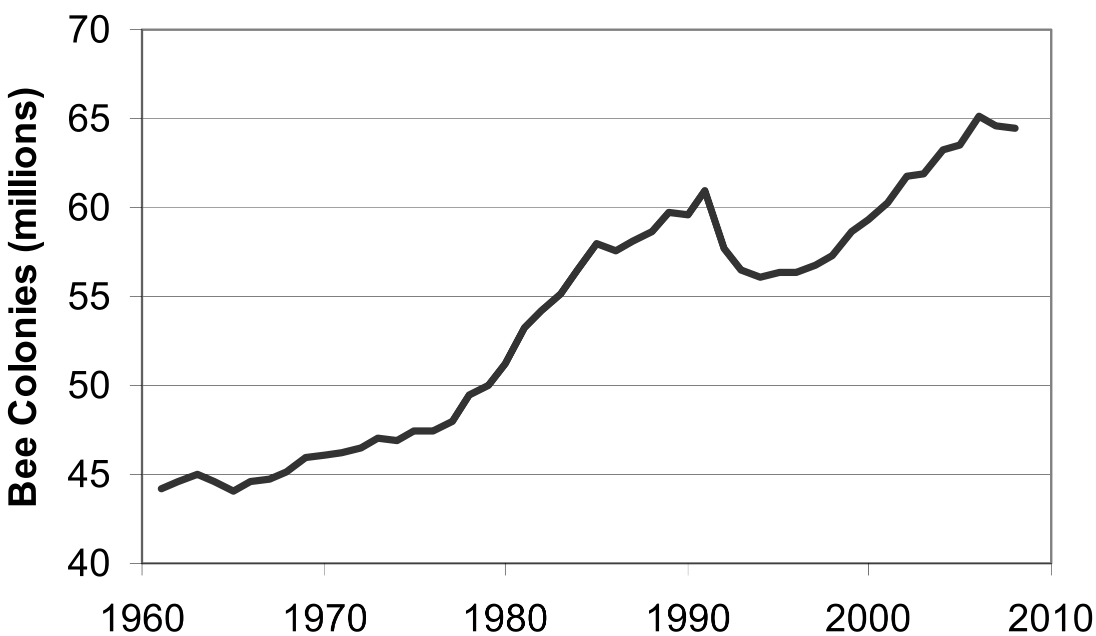

Figure 4. World Bee Colonies (1961–2008)
Source: FAO (2010).

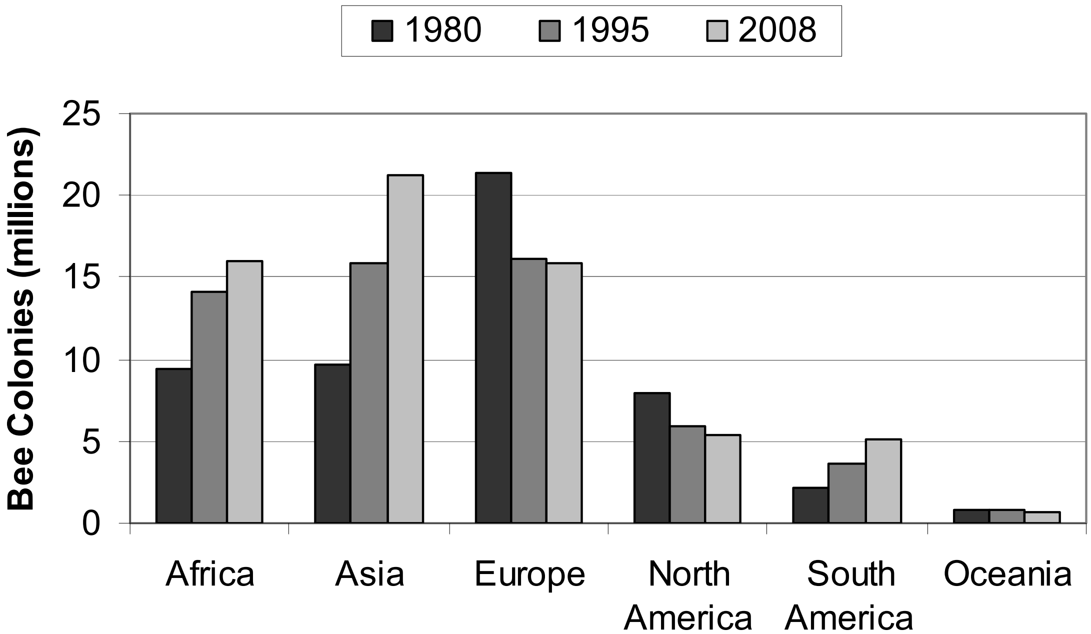

Figure 5. World Bee Colonies by Continent (1980, 1995, and 2008)
Source: FAO (2010).

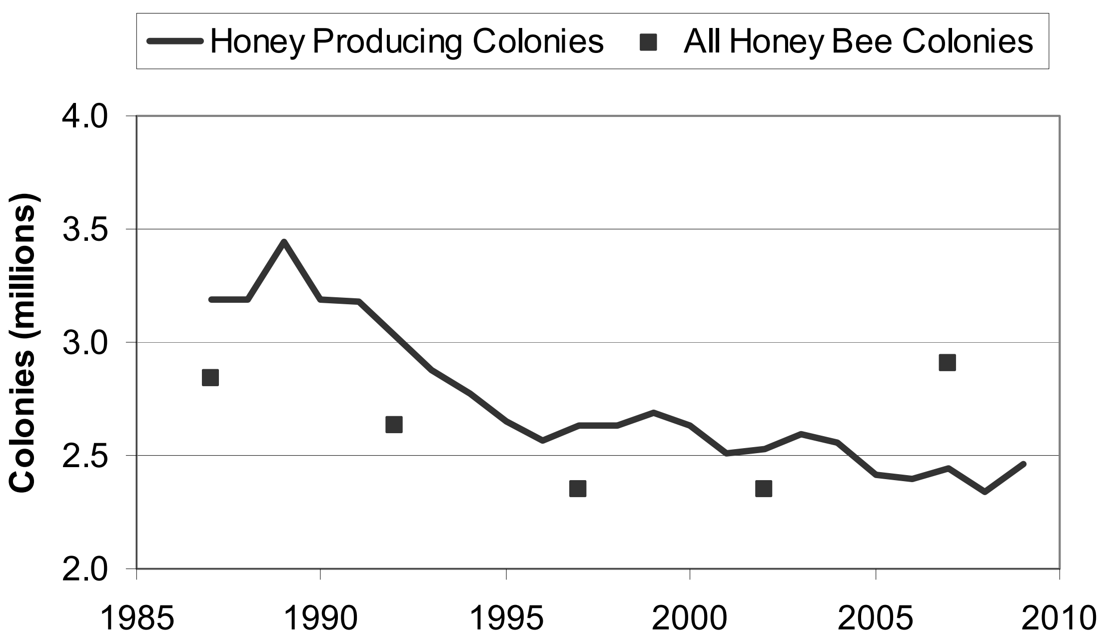

Figure 6. U.S. Honey Bee Colonies (1987- 2009)
Source: USDA (2010a, 2010b).

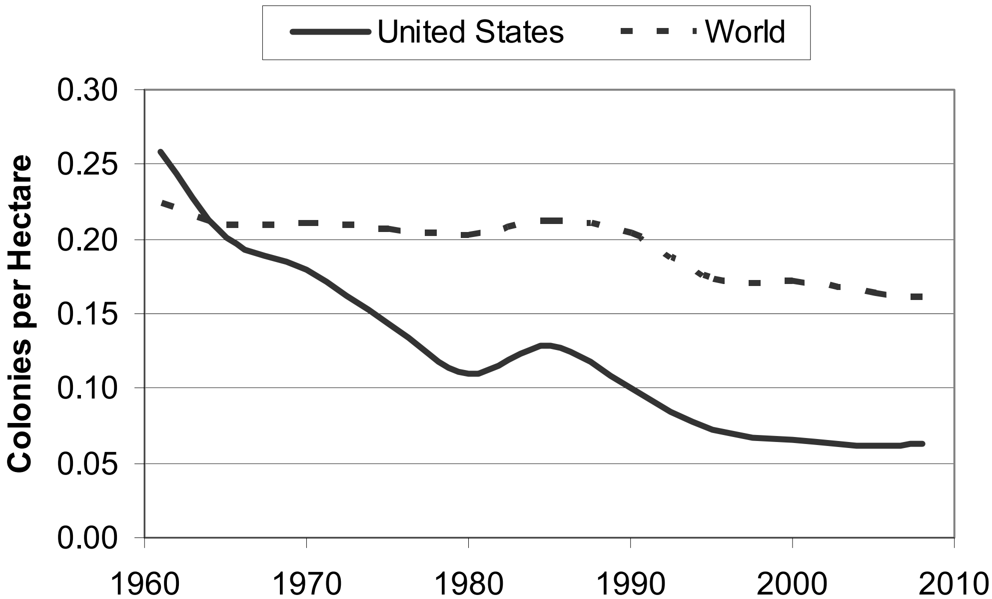

Figure 7. Managed Bee Colonies per Pollinator-Dependent Harvested Acreage (1961–2008)

Source: FAO (2010), Klein et al. (2007).

rival and non-exclusive public good, wild pollination services will be under-provided without some type of government program or policy intervention. This issue is compounded by substantial land use change across the United States and other countries that continues to reduce the availability of pollinator habitat (Brown et al. 2005, Hansen et al. 2005, Alig and Plantinga 2004, Theobold 2001). With continual losses of wild pollinator habitat and corresponding regional declines in wild pollinator populations and diversity, these results would seem to portend future pollinator shortages.

Reading these tea leaves, the principal question that arises is what exactly a sudden decline in the supply of pollination services might mean for global and U.S. crop yields. One way to arrive at an answer is to summarize the quantity of agricultural production at risk on a regional basis, which Figure 1 does. Its aggregation across different crop yields on a mass basis would seem to suggest that the relevant figures are small; however, such a conclusion is belied by the fact that the crops in question differ widely in their characteristics, economic uses, and therefore value. Our preferred summary measure is presented in Table 1, which weights the yields of different crops by their prices, calculating the fractions of the value of three key crop groups that are pollinator-dependent—and therefore at risk. These numbers point to a very different conclusion: while a disappearance in pollination services is unlikely to be catastrophic, in every region of the world it nonetheless constitutes a serious adverse shock to the production of fruits and nuts.

It is then natural to ask how big an economic loss is associated with the decline in yields underlying Table 1. To come to grips with this issue it is necessary to confront the thorny problem of how pollination services should be valued, which is the subject of the next section.

Valuing Pollination Services

Economic valuation of pollination services provides information on the economic consequences of potential pollination shortages and contributes to the decision making process regarding selection of alternative mitigation strategies. Valuation studies focused on pollination services supplied to agriculture have thus far fallen into one of five categories. The first category contains studies that value the pollination services provided by managed, commercially available bee colonies. Because these pollination services are exchanged through markets, the price can be used as a direct

Table 1. Percent Change in Value of Production of Select Crop Sectors Due to Global Pollinator Loss

	Africa	Asia	Europe	North America	South America	Oceania
Fruits	18.54	30.25	15.26	43.07	27.55	29.02
Vegetables	2.07	5.98	3.33	6.81	6.99	4.21
Nuts	21.69	39.72	23.50	13.40	19.23	26.12

per-unit measure of value (Burgett et al. 2010, Caron 2010, Burgett 2009). Although several species of insects are managed for commercial pollination, by far the dominant managed species is the honey bee (NRC 2007). Rental fees for managed honey bees depend on several factors including the price of honey, the price of the pollinated crop, the quality of the honey that gets produced when pollinating a particular crop, the costs of maintaining a colony, and the winter mortality rate, which itself is a function of pests, disease, and weather. Prices for bee colony rentals in 2009 in the Pacific Northwest ranged between \$38 per colony for berries and \$150 per colony for almonds (Burgett 2009).

The second category of pollination valuation uses an approach that calculates the value of total annual crop production that can be directly attributed to animal pollination. The calculation typically entails a simple formula:

$$EVIP = D \times Q \times P, \qquad (1)$$

where $EVIP$ is the economic value due to insect pollination, D is the share of crop yield that depends on pollinators (the "dependency ratio"), Q is annual crop production, and P is crop price. The idea is that if there were a sudden "catastrophic" loss of pollinators, what would be the instantaneous effect on crop production? This approach underlies the construction of Table 1, and has been used to value managed bees (Morse and Calderone 2000, Robinson, Nowogrodzki, and Morse 1989), wild bees (Losey and Vaughan 2006), and both types of pollinators combined (Gallai et al. 2009b). However, it has been criticized for relying on untenable assumptions (Allsopp, de Lange, and Veldtman 2008, Muth and Thurman 1995). The key weaknesses of the approach are its complete omission of the costs of other inputs (e.g., chemicals, labor, and capital) to crop production, its assumption that demand is perfectly elastic and that no price increase will result from the reduction in crop supply, and its lack of recognition of options to substitute for animal pollination, including mechanized and hand pollination or switching to a different, less pollinator-dependent cultivar.

The third category of valuation studies addresses some of these limitations by measuring the economic value of pollination 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 method has been applied to valuing the pollination services provided by managed bees in a developed country context (Southwick and Southwick 1992) and by wild bees in a developing country context (Kasina et al. 2009). In a variant of this approach, Gallai et al. (2009b) estimate the loss in consumer surplus using a constant price elasticity of demand for all crops and then conducting sensitivity analysis over a range of elasticity values. In each case, the result is a partial equilibrium estimate that ignores the indirect effects of changes in crop productivity on the rest of the economy, including changes in other input or output markets. For example, a reduction in the supply of fruit and vegetables will also impact producers of processed foods, as well as raise prices and the cost of food purchases to ultimate consumers.

The fourth type of analysis uses a replacement cost approach, whereby non-animal pollination alternatives are considered viable substitutes. The idea is to estimate the costs of other market-based pollination alternatives involving labor (hand pollination) or capital (mechanized pollen dusting) that would be needed to maintain the level of crop production at that specific level provided by animal pollinators (Allsopp, de Lange, and Veldtman 2008). However, caution must be used when applying replacement costs as they do not reflect individual preferences or actual behavior and, thus, are not true welfare measures (NRC 2005). Farmers might not be willing to pay the full amount for equivalent pollination services, particularly if the lost ecosystem services were "free" non-marketed public goods.

In the final category of pollination valuation, a landscape-based approach is used to value wild pollinator habitat. The objective of these studies is to relate the characteristics of habitat fragments (e.g., size, shape, distance to crop land, density and diversity of pollinator species) to crop yields (Morandin and Winston 2006, Olschewski et al. 2006, Ricketts et al. 2004). The strengths of this approach include its ability to rank a set of alternative landscape configurations based on net benefits—benefits of increased crop yields less costs associated with modifying or restoring the landscape—(Morandin and Winston 2006) and to simulate the effects of future land use change scenarios (Priess et al. 2007). Analyses of this kind have thus far concentrated on the production of coffee (*Coffea arabica*), a high-valued crop which grows mainly in tropical countries where managed pollinators are not widespread (Veddeler et al. 2008, Priess et al 2007, Olschewski et al. 2006, Ricketts et al. 2004). Although coffee is a self-fertilizing plant species, it benefits substantially from animal pollination in both quality and quantity of production (Klein, Steffan-Dewenter, and Tshcarntke 2003).

Economic Consequences of Declining Pollination Services: General Equilibrium Analysis

In an effort to address some of the limitations of existing methods for assessing the economic implications of pollinator loss, we developed a multi-region, multi-sector CGE model of agricultural production and trade which incorporates the pollinator dependency of primary agricultural crops. For two decades, CGE models have been widely used to perform numerical assessments of the economy-wide consequences of agricultural policies and programs (Fraser and Waschik 2005, Roe et al. 2005, Hertel and Tsigas 1988) and the mitigation of large-scale environmental externalities such as climate change (Sue Wing 2009, Bohringer and Loschel 2006). By comparison, the use of CGE models to investigate the potential impacts of environmental change—including climate impacts and changes in the supply of ecosystem services—on prices and welfare is still in its infancy (Carbone and Smith 2008, 2010, Carbone, Helm, and Rutherford 2009, Espinosa and Smith 1995). The crucial improvement of the general equilibrium modeling approach over the valuation methods described above lies in its ability to track changes in prices across multiple interrelated markets in a consistent fashion, summarize the macroeconomic effects of shocks by utilizing theoretically derived measures of welfare change, and test the consequences of different possibilities to substitute for pollination inputs. Apart from highly stylized theoretical work on the topic (Gallai et al. 2009a), to the best of our knowledge we are the first to pursue this kind of analysis.

Our model is a static simulation of the global economy which divides the world into 18 regions, each containing 13 producing sectors, chosen to resolve the details of interrelated agricultural markets. The model is numerically calibrated on the Global Trade Analysis Project (GTAP) benchmark input-output dataset for the year 2004 (Narayanan and Walmsley 2008), augmented with ancillary data from FAOSTAT on crop prices and production (FAO 2010). The model incorporates Klein et al.'s (2007) pollinator dependency ratios as exogenous neutral shocks to four broad crop sectors, in which production was represented using nested constant elasticity of substitution (CES) functions that combined inputs of labor, capital, land, and intermediate commodities to create the output good.

Pollinator loss scenarios were envisaged to be catastrophic shocks to each regional economy, with the services of pollinators (globally or regionally) being completely lost and the productivity of pollinator-dependent crops declining by the mean fraction of the corresponding dependency category (Klein et al. 2007). The model computes the changes in the prices of commodities and factors and in sectors' activity levels and households' income levels necessary to re-establish equilibrium in commodity, factor, and international trade markets in every world region. In the process, it generates estimates of welfare loss (expressed as percent equivalent variation) and revised prices, domestic production, imports, and household expenditures. The simulated values of output losses were compared to the results of a partial-equilibrium "value of pollinator-dependent production" calculation based on the same crop data and the same catastrophic pollinator loss.

The estimated annual value of the reduction in global production due to lost pollination services is listed in Table 2. By definition, the partial equilibrium analysis includes only those losses in the agricultural crop sector. In comparison, the general equilibrium analysis includes both direct crop sector effects and indirect non-crop sector effects. The partial equilibrium analysis estimates the economic risk due to pollinator loss at $138.3 billion, while the general equilibrium analysis estimates the crop sector losses to be $10.5 billion, an order of magnitude less, but total economy-wide losses to be $334.1 billion, more than twice as much. Thus, the partial equilibrium approach dramatically overestimates the direct impact to farmers while underestimating the total impact on the economy by not accounting for price effects on downstream sectors and households.

Although the precise values of losses presented here are intended to be illustrative, three important insights emerge from them. The first, mentioned above, is that the general equilibrium model captures both direct and indirect effects of pollinator loss. While the indirect effects are substantially larger than the direct effects in absolute dollar value (Table 2), when viewed as percent changes from their baseline values, the direct effects (Figure 8) outweigh both the indirect and the total effects (Figures 9 and 10). Second, the interregional distribution of the burden of pollinator 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 (Figure 11), our general equilibrium analysis helps put these shocks in context. Thus, western Africa appears to be particularly vulnerable (Figures 8 and 10) because pollinator-dependent crops make up a relatively large share of that region's agricultural output, and agriculture sectors account for a substantial proportion of aggregate income. 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 (Figure 9).

These examples highlight the enormous potential of our general equilibrium approach, which we note is also capable of simulating the consequences of pollinator declines for employment, welfare, and the terms of trade. Elaboration of these impacts is the subject of ongoing research.

Conclusions and Future Work

In this paper, we argue that there is compelling evidence for impending local or regional shortages of pollination services that could have dramatic economic implications. We initially characterized the effects of a global pollinator loss by estimating the value of crop production that would be lost due to an instantaneous shock to the system with no allowance for substitution or mitigation. 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.

However, 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, mechanized or hand pollination can substitute for pollination by animals, or other inputs such as agro-chemicals can substitute for pollination altogether. 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

Table 2. Reduction in Value of Global Production Due to Global Pollinator Loss ($ billions)

Partial Equilibrium	General Equilibrium		
Value of Production	Crop Sectors	Non-Crop Sectors	Total
138.3	10.5	323.6	334.1

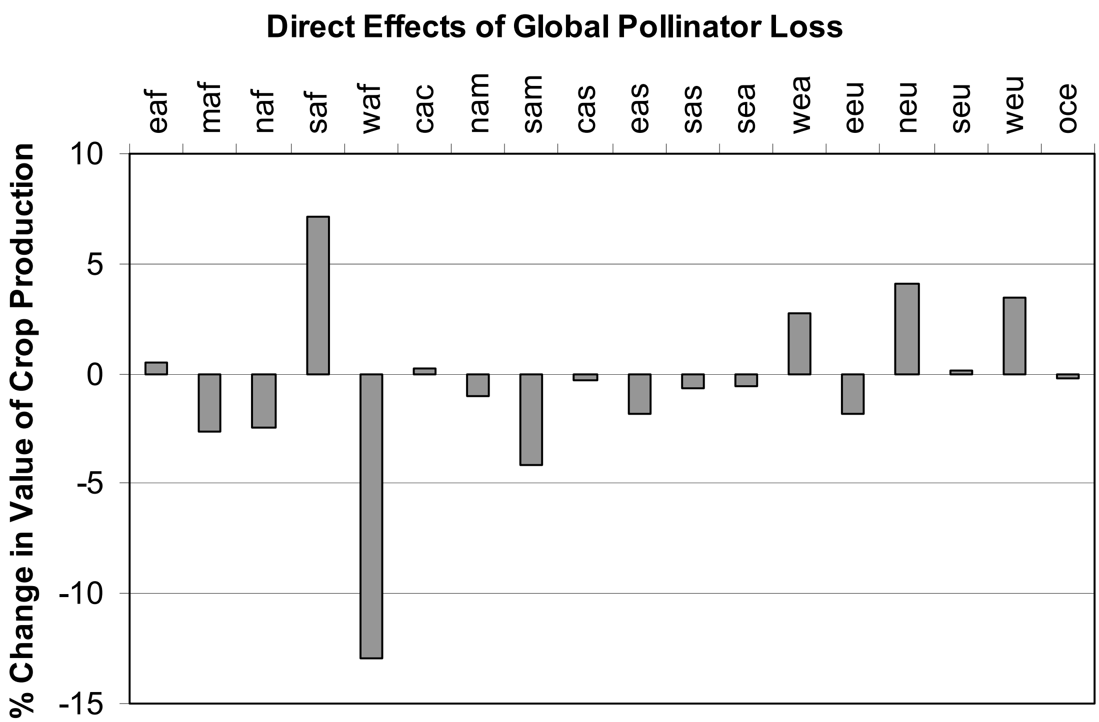

Figure 8. Economic Risk of Global Pollinator Loss to Crop Sectors—General Equilibrium Analysis

Note: See box below for world region abbreviations.

World Region Abbreviations

eaf	Eastern Africa	nam	Northern America	wea	Western Asia
maf	Middle Africa	sam	South America	eeu	Eastern Europe
naf	Northern Africa	cas	Central Asia	neu	Northern Europe
saf	Southern Africa	eas	Eastern Asia	seu	Southern Europe
waf	Western Africa	sas	Southern Asia	weu	Western Europe
cac	Central America and the Caribbean	sea	Southeastern Asia	oce	Oceania

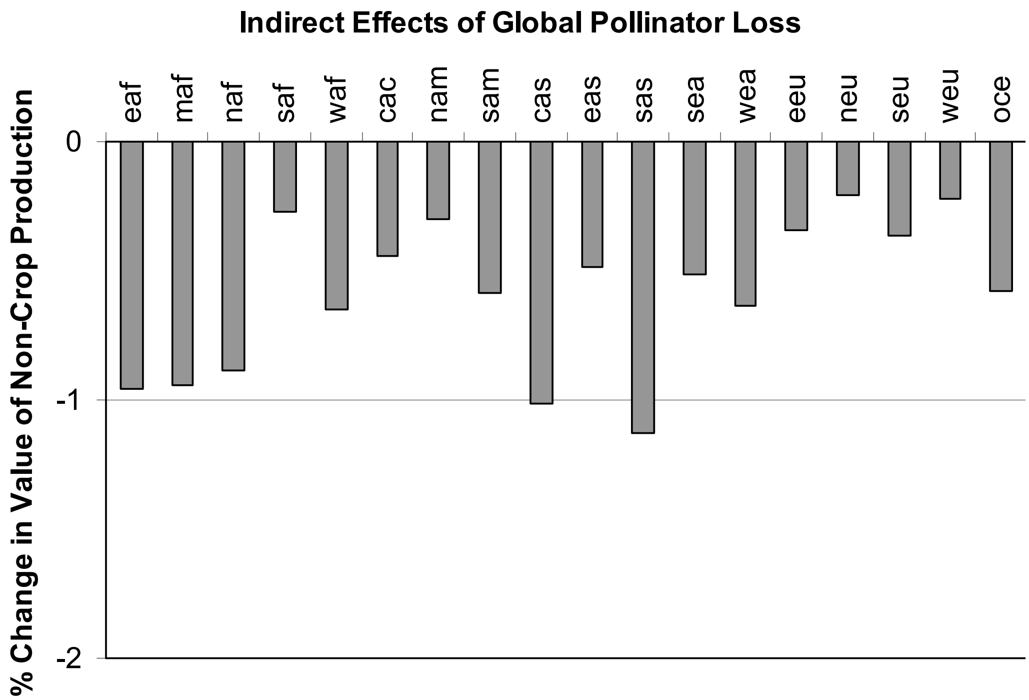

Figure 9. Economic Risk of Global Pollinator Loss to Non-Crop Sectors—General Equilibrium Analysis

Note: See box on page 379 for world region abbreviations.

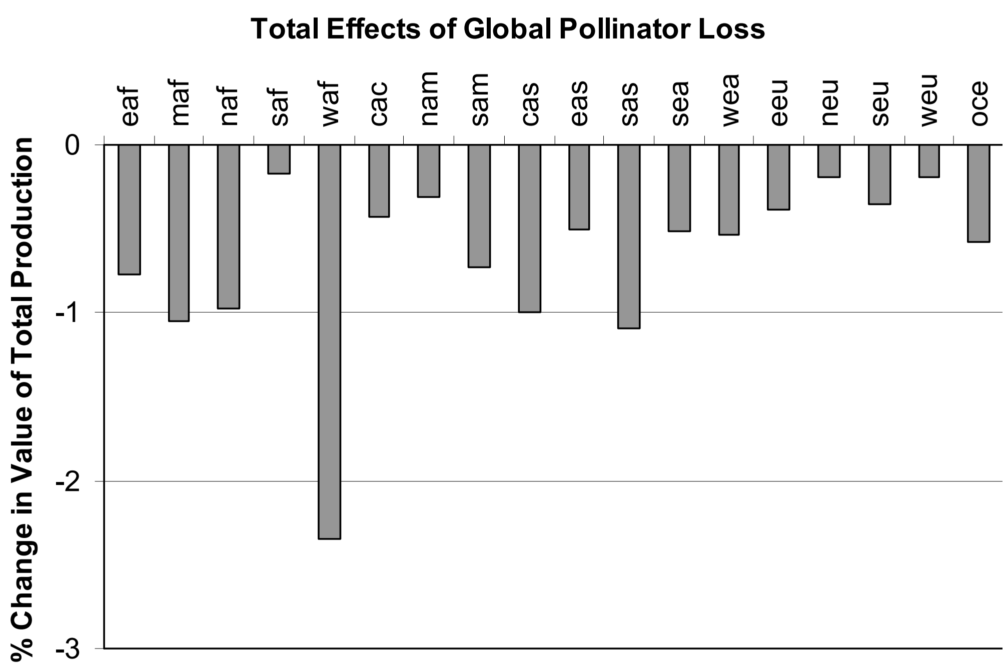

Figure 10. Economic Risk of Global Pollinator Loss to All Sectors—General Equilibrium Analysis

Note: See box on page 379 for world region abbreviations.

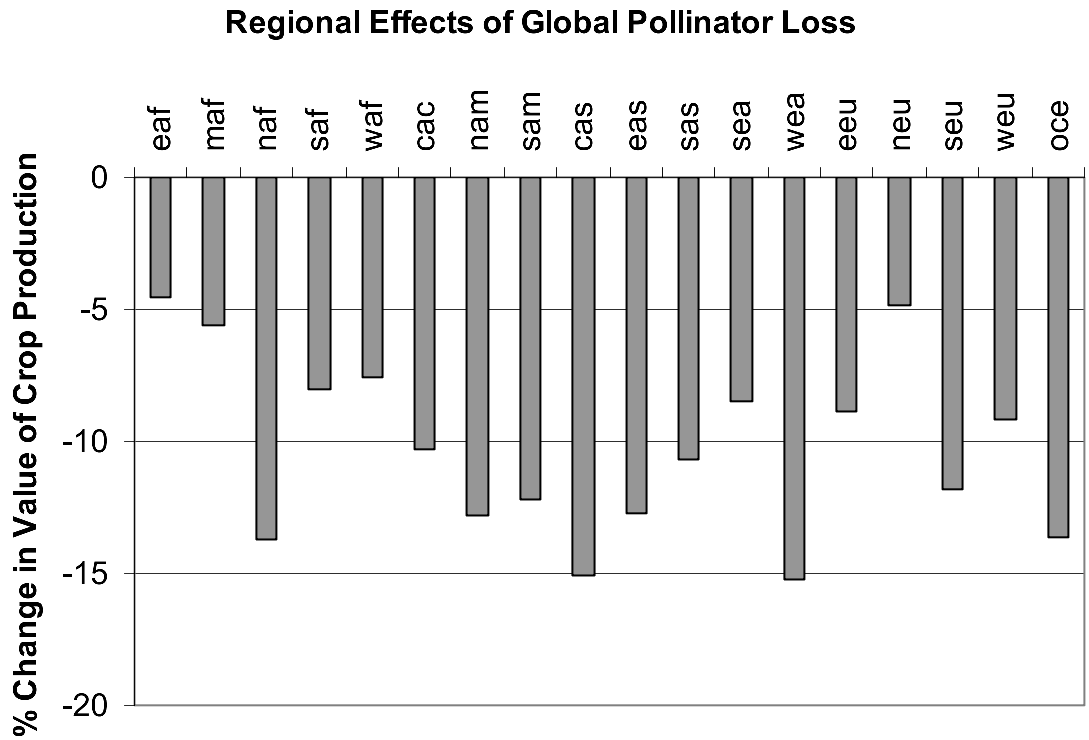

Figure 11. Economic Risk of Global Pollinator Loss—Partial Equilibrium Analysis

Note: See box on page 379 for world region abbreviations.

production that resolve pollination services as a separate input.

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. 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.

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