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Original Article

Pollinator Decline: US Agro-Socio-Economic Impacts and Responses

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Abstract

Pollination is a crucial ecosystem service to crops and is essential for sustainable crop production. Decline in animal pollinator populations can cause parallel decline in production of plants that rely upon them. We present a holistic evaluation of impacts and responses to pollinator decline in the US in an effort to summarize the spatial and temporal state of US pollinators, to review possible pressures and drivers of national pollinator decline, to examine the agro-socio-economic impact of the state of pollinators, and to provide a comprehensive insight into associated problems and solutions. Data on crop yield, pollinator populations, and economic value of pollinators were analyzed for the time period of 1945 through 2010. Results show a significant decline in the number of managed pollinators (specifically honey bees) in most regions of the US; on average, 42,000 colonies of managed pollinators were lost each year from 1945 through 2010. Crop yields increased significantly over the same period; however, crop yield variability increased with increasing pollinator dependence, and both mean relative yield and mean yield growth declined with increasing pollinator dependence. The total economic value of managed pollinators, estimated based on contribution toward agricultural yield of selected major US crops, was approximately $12.8 billion. Analysis indicated US agricultural value in 2010 declined by about $49 million per year compared with 1945 and $75 million per year compared with 1986 due to declining pollinator numbers. Agricultural intensification and increased use of inorganic fertilizer and pesticides, which has increasingly replaced crop rotation for both nutrient and disease management and has led to increasing presence of monoculture-type cropping systems, were likely the primary pressures that led to pollinator decline. Recommendations are to enhance both managed and native pollinator management options at all scales, including improving policy decisions, increasing diversity of cropping systems, and enhancing management of natural habitat.

***Key words**:* Ecosystem, Ecosystem Services, Pollination, Agronomic Impact, Sociologic Impact, Economic Impact

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INTRODUCTION

Pollination is a crucial ecosystem service that enables fertilization and sexual reproduction in angiosperms and is thereby an essential contributor to crop yields. More than 75% of the planet's angiosperms depend on over 200,000 animal pollinator species for fertilization and reproduction (National Research Council 2007). Globally, around 35% of food crop production (in metric tons) is reported as dependent to some extent on animal pollination (Klein et al. 2007). In the US, about 23% of agricultural production comes from pollinator-dependent crops (Johnson 2010). Almonds, apples, avocados, blueberries, cranberries, cherries, kiwi fruit, macadamia nuts, asparagus, broccoli, carrots, cauliflower, celery, cucumbers, onions, legume seeds, pumpkins, squash, alfalfa, and sunflowers are examples of crops that are almost completely dependent (90%–100%) on honey bee pollination (Morse and Calderone 2000). Bees, bumblebees, honey bees, wasps, hoverflies, other flies, beetles, thrips, ants, butterflies, moths, bats, hummingbirds, and other birds are some examples of known animal pollinators. Among these, honey bees (*Apis mellifera*) are the most economically valuable pollinators of agricultural crops worldwide (National Research Council 2007). Often in the United States, managed honey bees are rented and transported far from their home states during pollination season to supplement the services of wild pollinators for pollinator dependent crop producers. The US Department of Agriculture (USDA) estimated the national monetary value of honey bees at approximately $15–$20 billion annually (Johnson 2010).

A decline in national and global pollinator abundance and diversity, both managed and wild, has been reported by many researchers (Abrol 2012; Cane and Tepedino 2001; Garibaldi 2011; Johnson 2010; National Academy of Science 2007). A continued decline in the pollinator population will have a direct impact on provisioning, regulating, cultural, and support services of the ecosystem. Provisioning, or the conditions and processes of natural ecosystems that directly benefit people, includes the provision of food through crop yields (Dailey 1997; Rodriguez et al. 2006). Calderone (2012) stated that diminishing managed or wild pollinators could threaten production of insect pollinated crops and crops grown from insect pollinated seeds. Garibaldi et al. (2011) reported the impact of the declining number of pollinators on global growth and stability of agricultural yield, an issue that has been addressed by many ecological researchers as part of a larger effort to assess biodiversity loss and its associated impact on ecosystem services (Abrol 2012; Hadley and Matthew 2012; MEA 2005; National Research Council 2007); however, little research has been done using a holistic approach for evaluating impacts and providing integrated responses to pollinator decline.

The objectives of this study were to:

(1) summarize the spatial and temporal state of US pollinators;

(2) review the pressures and drivers of national pollinator decline;

(3) provide a holistic examination of the agro-socio-economic impacts of the current pollinator state; and

(4) integrate responses, speculate on future trends, and provide recommendations to overcome the effects of pollinator decline.

Because quantifying the value of pollinator services is difficult, this article valued pollinator services as the value attributed to honey bees, following Morse and Calderone (2000), Southwick and Southwick (1992), and Levin (1983).

MATERIAL AND METHODS

Published data on the distribution and status (state) of pollinators in the US were reviewed. Data on the number and trends of managed honey bees in different regions of the US were analyzed for the years 1945 through 2010 using USDA-NASS (2011a) honey bee colony data from 1945–1976 and 1986–2010. The missing data from 1976–1985 were calculated by interpolation. The time period was chosen to be consistent with the report by the National Research Council (2007) on pollinator status. The status of managed honey bees in the US was analyzed on regional bases, as indicated in Figure 1.

The possible immediate or direct causes (pressures) and fundamental or indirect causes (drivers) of the declining number of pollinators are discussed based on reviews of additional peer-reviewed literature.

To analyze the impact of honey bee pollinator decline on US agriculture, 10 crops were chosen to serve as a representative sample comprising 80% of the US agricultural income in 2010 (USDA Economics, Statistics and Market Information System 2010) and 14% of US land cover (Figure 1, Table 1). The dependence of crop yield on pollination and the proportion of pollinators that are honey bees vary for each of the 10 crops (Table 1). The percentage dependence of a crop on a pollinator is expressed as the amount of yield reduction observed for a crop when a pollinator is excluded (Morse and Calderone 2000). Based on this definition, among the selected crops, alfalfa, apple, almond and sunflower were classified as 100% insect pollinator dependent; cotton was classified as 20% dependent; soybean, tomato and peanut were classified as 10% dependent; and corn and wheat were almost 0% dependent (Morse and Calderone 2000).

Table 1 Honey bee dependency classification (Morse and Calderone 2000).

Crops	Contribution to US agricultural income in 2010 (%)	US land cover (%)	D_I[a] (%)	$P_{I:HB}$[b] (%)	D_{HB}[c] (%)
Almond	1.46	0.05	100	100	100
Apples	1.16	0.01	100	90	90
Sunflower	0.33	0.08	100	90	90
Alfalfa hay	11.72	2.24	100	60	60
Cotton	3.85	0.64	20	80	16
Soybean	19.67	4.03	10	50	5
Tomato	0.49	0.01	10	50	5
Peanut	0.49	0.07	10	20	2
Corn	33.86	4.55	0	0	0
Wheat	6.72	2.59	0	0	0
Total	79.75	14.27			

[a]D_I: Dependence of crop yield on insect pollination
[b]$P_{I:HB}$: Proportion of insect pollination dependence that is due to honey bees
[c]D_{HB}: Dependence of crop yield on honey bee pollination ($= D_I \times P_{I:HB}$)

Beyond insect-pollinator dependence, the product of the insect pollinator dependency ratio (D_I) with the proportion of insect pollination dependence due to honey bee pollinators ($P_{I:HB}$) equates to the honey bee dependency ratio (D_{HB}). In Table 1, the calculated honey bee dependency ratios show the 10 crops fall into five categories of crop production dependence on honey bees: essential (91–100% dependent), great (41–90% dependent), modest (11–40% dependent), little (1–10% dependent), and not dependent (0% dependent) (after Klein et al. 2007).

Crop data (yield per unit area, received price/production ($) and harvested area) for tomato and apple were obtained from USDA Economics, Statistics and Market Information System (2010a,b); for other crops, these data were obtained from USDA National Agricultural Statistic Services (2011b).

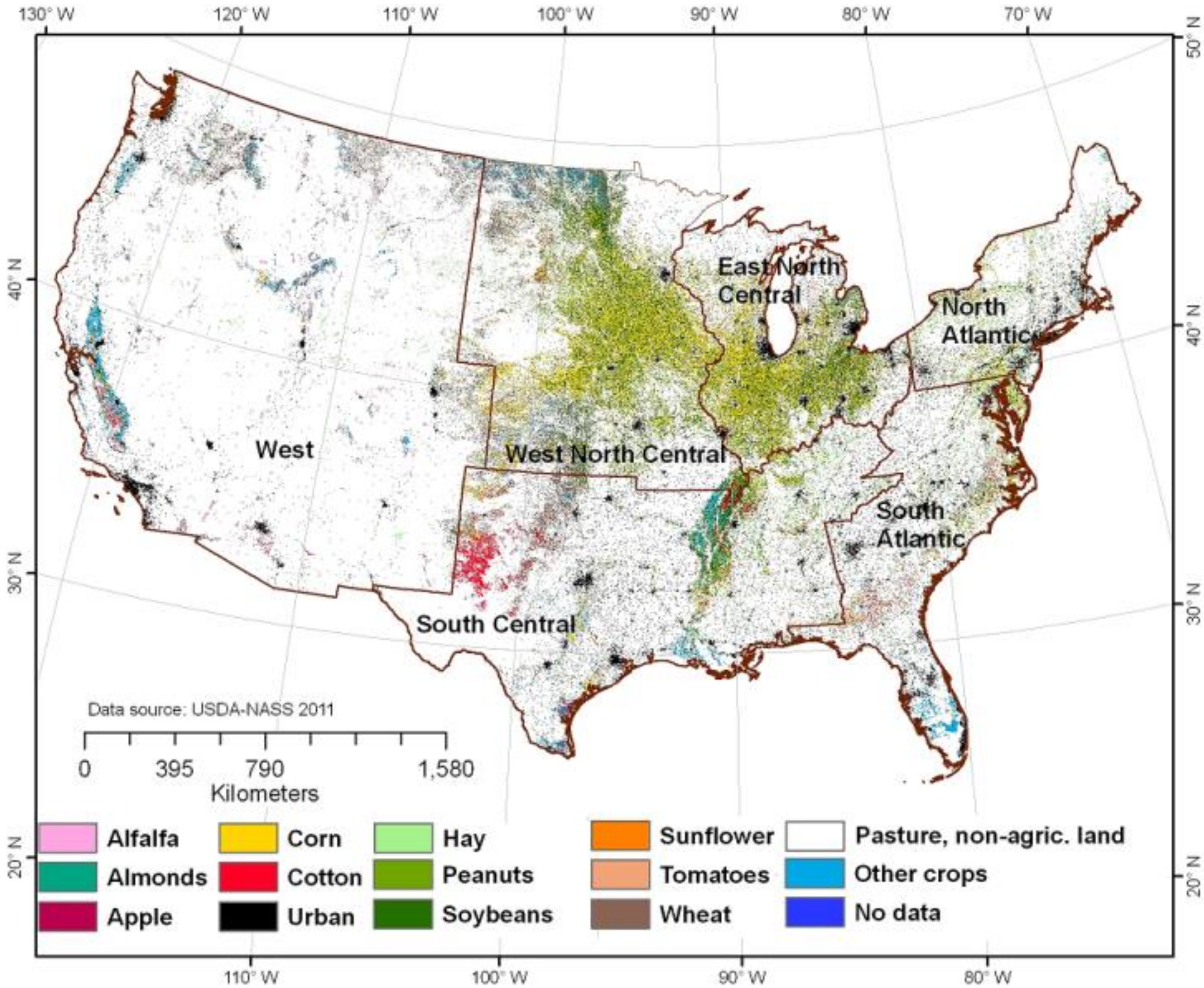


Figure 1. Distribution of 10 crops within 6 regional divisions (USDA-NASS 2011a) used in honey bee colony trend analysis in this study.

In order to help visualize the dominant crops or cropping systems in US agriculture, a line graph that depicted the area allocated for the 10 crops for the time period from 1945 through 2010 was constructed. The average decadal yields for each of the 10 selected crops were determined for six complete decades (1945 through 2004) and the most recent partial decade (2005 through 2010) and compared using Duncan's multiple range test in SAS (Duncan 1955; SAS Institute Inc., Cary, NC).

Mean relative yield was calculated for each crop by detrending (subtracting crop yield from one year by yield from the previous year), dividing this value by the maximum detrended yield over the 1945 to 2010 period, and taking the average of these annual values. Mean yield growth was calculated for each crop by another detrending method (dividing crop yield from one year by yield from the previous year), and taking the average of the annual detrended yield ratios. The mean relative yield and mean yield growth were plotted against honey bee dependence for each crop to compare yield growth trends among the ten crops. The coefficient of variation for yield, i.e., the standard deviation of annual yields of each crop divided by mean yield of the crop over the period of analysis, was also calculated to compare variability in yield growth among these crops.

The economic value of honey bees (EV_{HB}) and the impact of honey bee decline on the economy were analyzed for six US regions. The total EV_{HB} was calculated using equation 1. This approach was previously used by Morse and Calderone (2000) and Robinson et al. (1989).

$$EV_{HB} = \sum\left[(Q \times D_{HB}) \times P\right] \quad (1)$$

EV_{HB}: Economic value attributed to honey bees ($)
Q: Annual crop production (Mg)
D_{HB}: Honey bee dependency (%)
P: Crop price ($/Mg)

Annual crop yield (Q) data and crop price (P) reported by USDA Economics, Statistics and Market Information System (2010a,b) and USDA-NASS (2011b) for each state were aggregated to identify a total yield for each of the 10 crops in each of the six regions for each year (1945–2010). To remove the effects of price changes over time, price (P) for each crop in each region for each year (1945–2010) was expressed in terms of corresponding 2010 price, following the procedure of Morse and Calderone (2000). Honey bee dependency values (D_{HB}) were obtained from Morse and Calderone (2000) (Table 1).

To evaluate the impact of honey bee population decline on agro-economic value, two baseline years were selected: 1945 and 1986. Baseline year 1986 was selected to exclude the interpolated pollinator data (1976–1985). The amount of economic loss (expressed in 2010 dollars) due to honey bee population decline relative to each baseline year was determined by multiplying the percentage change in honey bee colonies by EV_{HB}.

Based on the declining number of pollinators and their estimated impact on crop yield and economics, possible social impacts are discussed. Through a discussion of the related peer-reviewed literature, social impacts are considered and suggestions (responses) were made to improve the pollinator situation.

RESULTS AND DISCUSSION

State of Pollinators in the US

The US has both managed and wild pollinators. Assessing the status of wild pollinators is difficult due to inadequate taxonomical and ecological characterization. Additionally, no records or long-term data are available on wild pollinators; however, adequate evidence exists to show a population decline in wild bee species (notably bumblebees) and some butterflies, bats, and hummingbirds (National Research Council 2007). Figure 2a shows the current distribution of important wild pollinator species in the US.

Honey bees are commercially managed for pollination in North America. Population of managed honey bee colonies is greatest in California, North and South Dakota, and Florida (Figure 2b), with 157,000 to 510,000 colonies. These bees contribute to the production of fruits, vegetables, nuts, forage crops, some field crops, and other specialty crops (Johnson 2010) in these regions.

The number of managed honey bee colonies in the US has declined from around five million in the 1950s to around two and a half million in 2010 (Figure 3). Honey bee colonies show an increasing trend from 2005, after they were imported for the first time since 1920 (National Research Council 2007). Long-term population data (1940–2010) showed a declining trend in colonies in five of the six regions (Figure 4). The declining trend was higher for the North Atlantic (NA), East North Central (ENC), South Atlantic (SA), and South Central (SC) regions, whereas the West North Central (WNC) region had a slightly increasing trend. This WNC region includes North and South Dakota, which account for 27% of the national honey bee population.

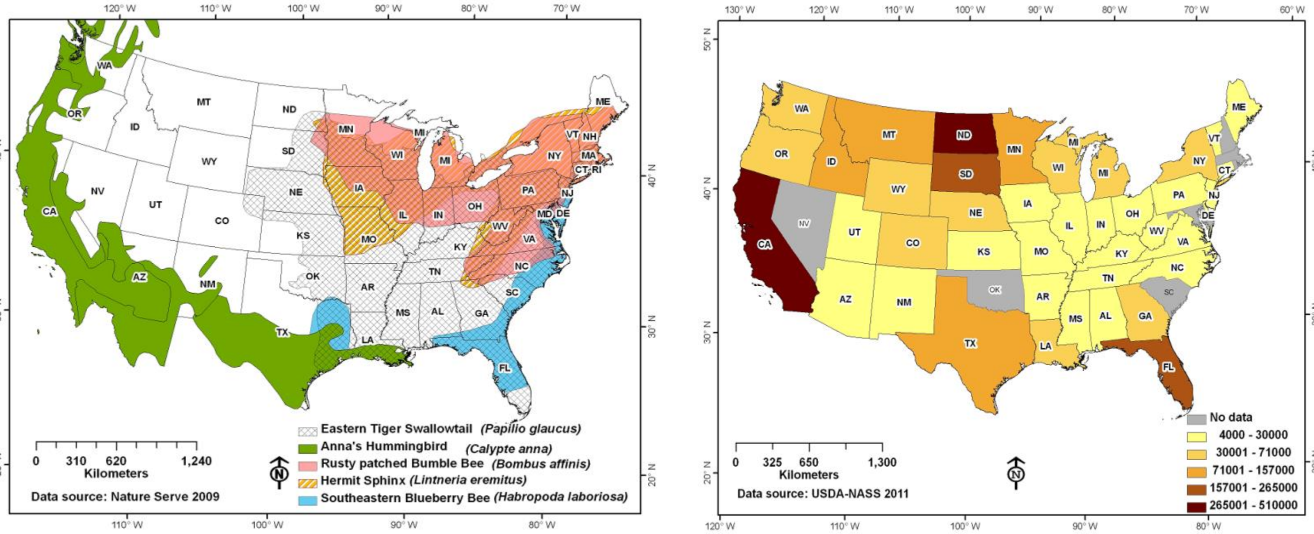


Figure 2. Spatial distributions of (a) important wild pollinator species in the US (left) and (b) managed honey bee colonies in the US in 2010 (right)

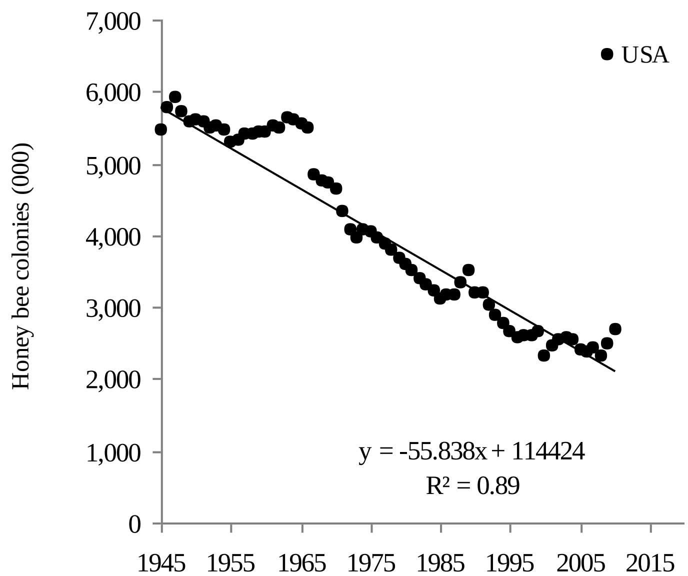


Figure 3. Trend in managed honey bee colonies in the US. Note: Honey bee data from 1976–1985 were unavailable and thus estimated by interpolation.

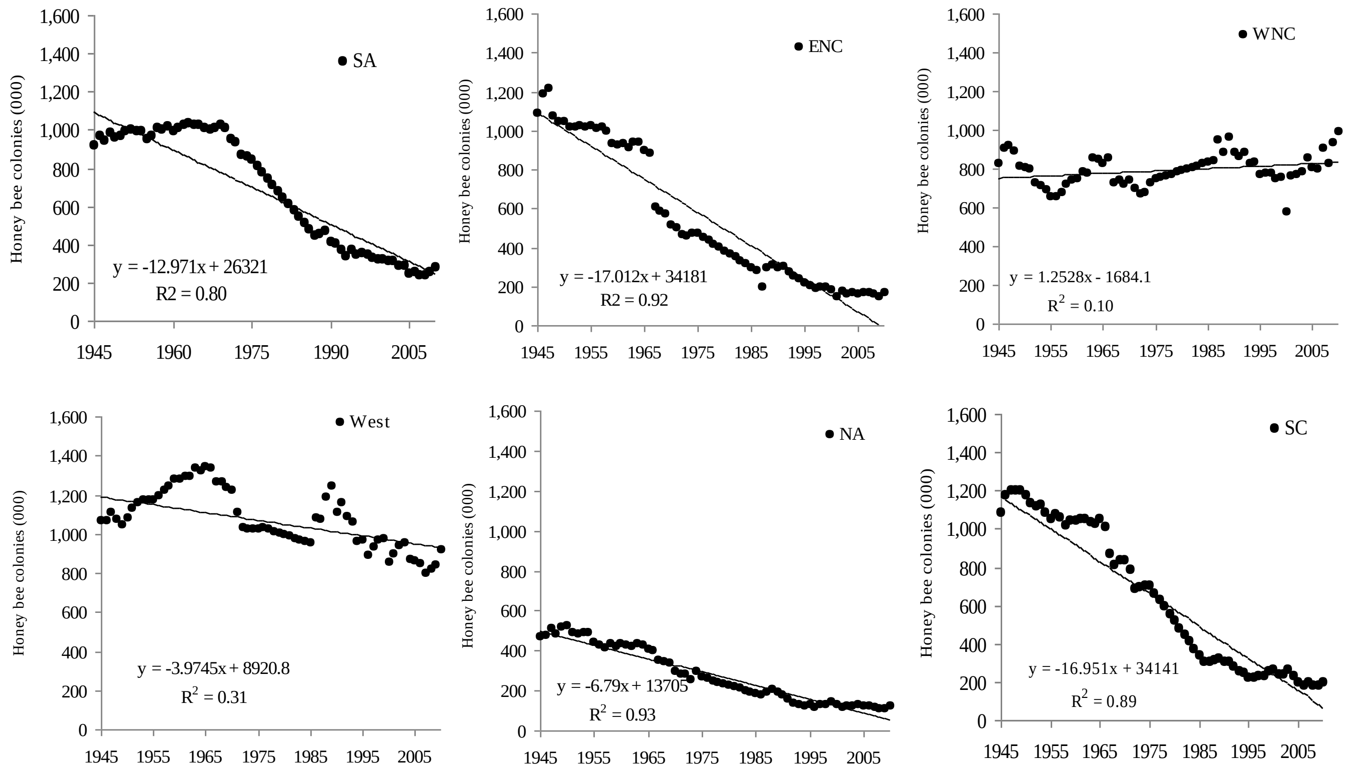


Figure 4. Trend in managed honey bee colonies among six US regional divisions (USDA NASS 2011a). Note: Honey bee data from 1976–1985 were unavailable and thus estimated by interpolation.

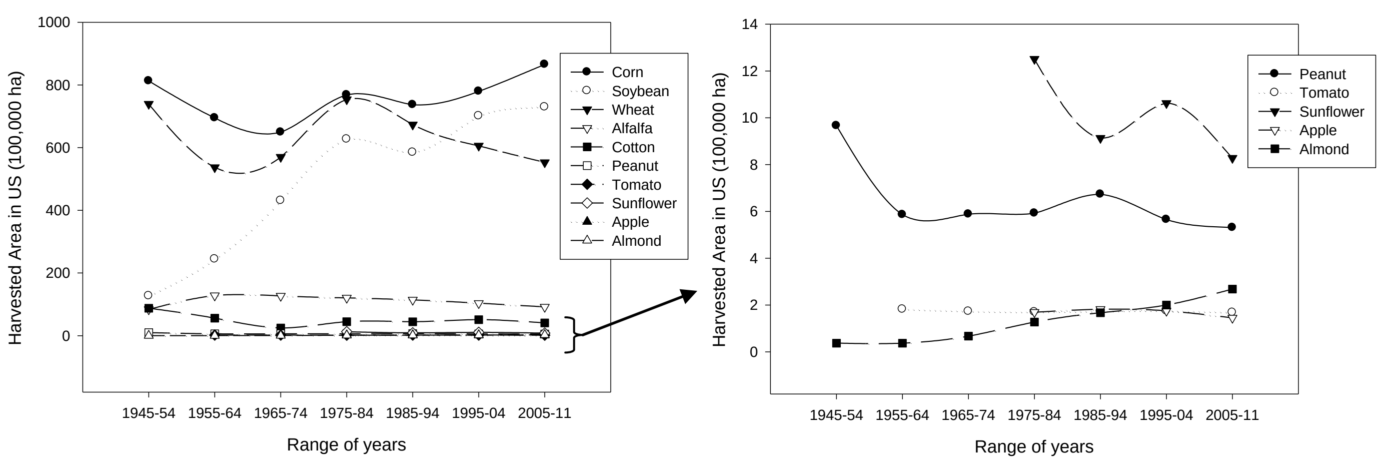


Figure 5. The average total harvested area of (a) all 10 crops used in this study and (b) 5 crops with lowest harvested area (expanded y-axis scale) in the US at different time intervals for the past six decades (1945–2011).

Causes of Pollinator Decline

Many direct and indirect causes of the declining number of honey bee pollinators have been reported: intensive cropping systems; increased agrochemical usages and consequent susceptibility to pest and diseases; global climate change, which alters plant phenology and changes pollinator phenology due to local changes in temperature and climate; and other stresses, including the competition between managed and wild pollinators for floral resources.

Intensive Cropping Systems

Agricultural development and urbanization are the most prevalent land-use changes in the US (Cane and Tepedino 2001). Increased use of inorganic fertilizers and pesticides associated with agricultural development, which will be discussed in subsequent sections, reduces the necessity of crop rotation for disease and nutrient management and has contributed to the trend toward a monoculture production system (Altieri 2000; Huang and Uri 1994; Valavanidis and Vlachogianni 2010). This simplification of land use generally causes biodiversity loss (Foley et al. 2005; MEA 2005). The sum of areas allocated to corn, wheat, soybean, peanut, sunflower, and alfalfa in 2010 accounted for about 60% of total cropland (165 million ha) in the US (Figure 5; US Census 2012). The area allocated to corn and wheat was greater than the area allocated to any other crops for all decades, except in the last decade in which the area allocated to soybeans exceeded wheat (Table 1).

As much of US agriculture continues to be dominated by only a few crops, this trend towards monoculture is impacting pollinators through habitat destruction and reduced habitat diversity. Corn encompasses up to 20% of cultivated area in midwestern states (Cane and Tepedino 2001), and about 7.1% of continental US land area (Table 1, Figure 1) is used to grow corn and wheat, which are essentially non-pollinator-dependent crops. With the rise of these non-pollinator-dependent crops, further damage is inflicted upon pollinator habitat, which is exacerbating the decrease in the pollinator population. A geographic divide induced by the predominant non-pollinator-dependent crop monoculture in the Midwest is making pollinator survival more difficult.

The extensive use of agrochemical applications have been stated as a significant factor in North American pollinator decline (Mullin et al. 2010; Pettis et al. 2011). Insecticides and pesticides are applied not only on agricultural fields, but also on golf courses, in residential areas, across rangelands, etc. These pesticides and insecticides generally do not kill pollinators outright, but instead impair their development and behavior (Johnson 2010); for example, agrochemicals cause impaired odor discrimination and abnormal communication dances, which can cause mistakes in estimating distances and direction to food sources (Kearns and Inouye 1997; Thompson 2003). Gill et al. (2012) reported reduced worker foraging performance, especially pollen collecting efficiency, with chronic exposure of neonicotinoid and pyrethroid pesticide in bumblebees. Also they showed field-level exposure of these pesticides caused reduction in brood development and colony success. When agrochemical use is associated with reduced use of crop rotations, crop diversity and availability of other pollen sources are also lessened, which compounds the negative impacts on pollinators.

Parasite Attacks and Disease Outbreaks

Parasitic mites, especially *Varroa* species, were reported as the major cause for honey bee population decline in 1995 after it was introduced to US in 1987 (Huang 2012). Effects of parasites on bees include altered behavior and reduction in healthy sperm production. These influences eventually result in reduction in number of worker bees and viable replacement broods. Additionally, parasites also are reported as one of the major reasons for colony collapse disorder (CCD), along with other factors such as pathogens, management, and environmental stresses (Johnson 2010). Colony collapse disorder was reported as the major reason for significant declines in colonies along the US east coast starting in late 2006 (Johnson 2010; VanEngelsdorp et al. 2012) and was identified as similar to the disappearing disease found in the 1970s. Parasites and pests can also lead to behavioral changes and overall mortality of bee populations (Schmid-Hempel and Durrer 1991).

Climate Change

Global climate change predictions show shifts in temperature and precipitation, increases in carbon dioxide (CO_2) concentrations, depletion in ozone layer, and increases in ultraviolet (UV) light levels across the US. Regional and global climate change effects on ecosystems have been projected in many studies (IPCC 2007; Parmesan 2006; Walther et al. 2002), but the effect of climate change on pollinators has not yet been supported by empirical evidence (Kremen et al. 2007). Nonetheless, many researchers have speculated on the disruptions of plant-pollinator interactions due to climate change (Harrington et al. 1999; Parmesan 2006); for example, Parmesan and Yohe (2003) predicted a species range shift of 6.1 km per decade toward the poles due to spring occurring 2.3 days earlier per decade.

Kuldna et al. (2009) reported that changes in temperature and precipitation may lead to changes in habitat and plant species composition. The shifts in phenology induced by climate warming may disrupt the temporal overlap between pollinators and their floral resources. Although parallel phenological responses may occur in plants and pollinators, considerable mismatch in responses should be expected (Hegland et al. 2009); however, this effect depends on how interactions among species are influenced and where the interactions occur. The general strength and direction of large-scale phenological responses to global warming remain largely unknown (Hegland et al. 2009).

Studies show an increased reproductive effort to in response to experimental warming in the arctic and alpine (Arft et al. 1999). Mass flowering may positively affect pollinator activity and population density. Little evidence exists on temperature-mediated flower abundance of pollinators. Because some pollinators prefer colder and wetter areas (e.g., flies) and others prefer a drier habitat (e.g., honey bees), changes in pollinator composition are expected (Hegland et al. 2009).

Hegland et al. (2009) also reported an expectation for spatial distribution changes of pollinators with the historical spatial distribution changes of crops, including advance in flowering time, change in pollinator phenology, and spatial mismatch due to global temperature and precipitation change-disruption of coordinated interaction.

Rusterholz and Erhardt (1998) investigated the effects of elevated CO_2 on flowering phenology and nectar production in *Trifolium pratense*, *Lotus corniculatus*, *Scabiosa columbaria*, *Centaurea jacea*, and *Betonica offcinalis*, which are all important nectar plants for butterflies. Juvenile plants were exposed to ambient (350 ppm) and elevated (660 ppm) CO_2 concentrations for 60–80 days in a glasshouse. The researchers reported that buds in *C. jacea* and *B. officinalis* flowered earlier, and *L. corniculatus* produced more flowers under elevated CO_2, but the amount of nectar per flower was not affected by elevated CO_2.

In contrast, Lake and Hughes (1999) tested two levels of CO_2 (380 ppm and 750 ppm) for *Tropaeolum majus* (nasturtiums) and reported an increased nectar secretion rate. They also reported that the elevated CO_2 did not affect time to flowering, total number of flowers produced, pollen-to-ovule ratio, or the total or individual concentrations of nectar amino acids. Kirkham (2011) reported that elevated CO_2 advanced flowering in long-day species and delayed flowering in short-day species.

These results demonstrate that determining the effect of elevated CO_2 on pollinators is difficult and uncertain. The response to elevated CO_2 clearly differs from species to species and with level of CO_2. More studies are needed to determine the effect of CO_2 on phenology (Kirkham 2011), nectar production, and pollinator interactions.

Elevated intensities of UV-B radiation result from atmospheric ozone degradation and can delay flowering and reduce flower production in some plants (National Research Council 2007). This will also adversely affect the pollinator populations.

Competition and other Stresses

Invasive or non-native pollinators cause local pollinator species to decline through competition and transmission of parasites and pathogens (Goulson 2003).

Other stresses on pollinators include poor nutrition due to overcrowding, pollination of crops with low nutritional value (Johnson 2010), limited or contaminated water supply, and migratory stresses (e.g., mobile transmissions and power radiation; Kumar et al. 2011).

Agricultural, Economic, and Sociologic Impacts of the Decline in Pollinators

A continued decline in pollinators could threaten natural processes as well as societal-dependent practices. These threats have agricultural, economic, and sociologic impacts, including possible impacts on crop yield and agricultural stability, monetary loss within the agricultural sector, and a loss of ecosystem services.

Crop Yield and Yield Stability Impacts

Average decadal yields of 10 crops for six complete decades (1945 through 2005) and the most recent partial decade (2005 through 2010 or 2011, depending upon data availability) are presented in Table 2. The results indicate that the yield in the most recent decade is the highest in all considered crops except for apple. For the crops that are less dependent on honey bee pollination (corn, wheat, peanut, soybean, tomato), yield has increased in almost every decade from 1945 through 2010. For crops highly dependent on pollinators, yield increase was inconsistent through the decades.

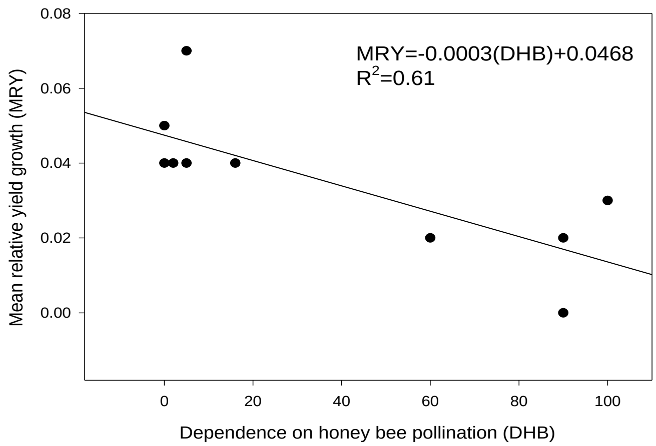
The mean relative yield and mean yield growth for crops is given in Figure 6. The mean yield growth for almond (1.11 yr^{-1}) was excluded because it was extremely high and biased the trend line substantially. The mean relative yield and mean yield growth were greater for crops that depended less on pollinators than those that were highly dependent on pollinators. From these data, we can conclude that even if an increase in crop yield occurred in both highly pollinator-dependent and non-pollinator-dependent crops, yield growth by those crops that are less dependent on pollinators was greater than the highly pollinator-dependent crops. This could have substantial influence on the negative impact that is contributing to the decline in number of pollinators.

The coefficient of variation (CV) for yield of the 10 crops is plotted in Figure 7. Again, the CV for apple (120) was excluded because it was extremely high and exhibited undue bias on the trendline. The CV of the remaining nine crops, plotted in Figure 7, indicated that the CV increased with pollinator dependency of the crop. Therefore, we can conclude that yield of pollinator-dependent crops is more variable than those that are less pollinator-dependent.

Table 2 Decadal average crop yields among the ten crops analyzed.

Crop	Yield data set used	Average yield (Mg ha^{-1}) (except for alfalfa, Gg ha^{-1})						
		1945–54	1955–64	1965–74	1975–84	1985–94	1995–04	2005–10/11†
Corn	1945–2011	2.4g‡	3.5f	5.1e	6.1d	7.3c	8.4b	9.6a
Wheat	1945–2011	1.2g	1.6f	2.0e	2.3d	2.5c	2.7b	2.9a
Peanut	1945–2011	0.9f	1.3e	2.2d	2.8cb	2.7c	3.0b	3.6a
Soybean	1945–2011	1.3g	1.6f	1.8e	1.9d	2.3c	2.5b	2.8a
Tomato	1960–2010	-	17.4e	19.0e	22.3d	28.4c	34.2b	40.3a
Cotton	1945–2010	1.8f	2.6d	2.1e	2.6d	3.1c	3.4b	4.3a
Alfalfa	1945–2011	2.8f	3.0e	3.7d	4.1c	4.5b	4.8a	4.7ba
Sunflower	1975–2011	-	-	-	1.3b	1.4b	1.4b	1.6a
Apple	1980–2010	-	-	-	17.2a	15.8a	14.2b	16.0a
Almond	1945–2010	0.6e	0.8de	0.9dc	1.1c	1.5b	1.7b	2.3a

†Most recent data covers a partial decade, either 2005–2010 (6 years) or 2005–2011 (7 years), depending upon data availability.
‡Numbers in a row followed by same letter are not significantly different (α = 0.05) by Duncan's multiple range test.



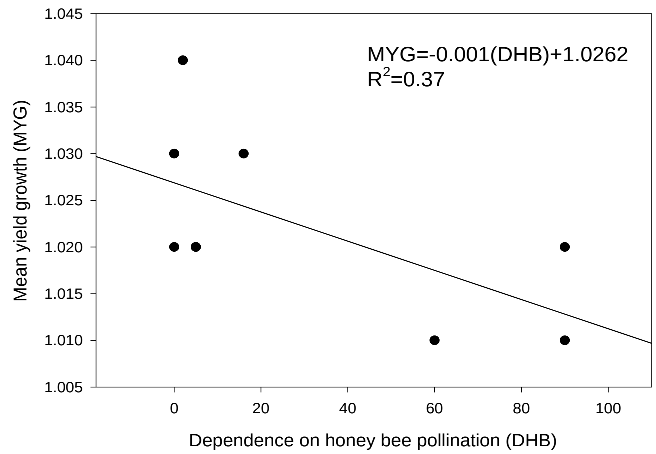


Figure 6. Relationship of honey bee pollinator dependence (%) to mean relative yield (dimensionless) and mean yield growth (yr^{-1}) for 10 crops

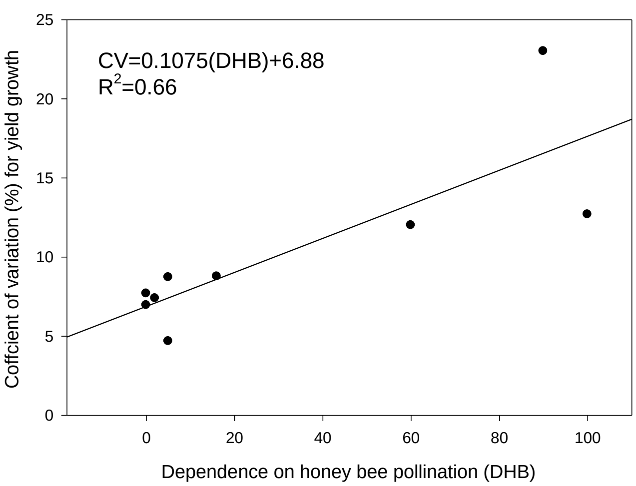


Figure 7. Trends in mean temporal stability measured by the coefficient of annual variation (CV) of detrended data from 1945 through 2010 for 10 crops with a range of honey bee pollinator dependence (D_{HB}).

Economic Impact

The total monetary value of honey bee pollinators expressed in 2010$, based on their contribution to the yields of the 10 crops for years 1945 and 2010, was about $3 billion for 1945 production and about $13 billion for 2010 production (Figure 8, Table 3). The 2010 value was similar to that calculated by Morse and Calderone (2000), who estimated the monetary value of honey bees as $15 billion, including all other field crops, vegetables, and fruits in their calculations.

Table 3 shows the monetary value loss in 2010 compared with 1945 and 1986. The year 1986 was selected here because it included all 10 crop data. Nearly 143% honey bee loss corresponded to around $1.8 billion economic loss ($75 million per year average). These losses increased to around $3 billion compared with a 1945 baseline year ($49 million per year average) (Table 3).

The process of interpolation used to estimate missing data for managed honey bee populations from 1976–1985 did not appear to cause unrealistic magnitudes or trends in ΔHB and ΔEV_{HB} in most cases (Table 3). In all regions (except West), reductions (or, in the case of WNC, increases) in ΔHB and ΔEV_{HB} were lower in magnitude for the 1986 to 2010 period relative to the 1945 to 2010 period. Cyclical variation in honey bee population in the West region (Figure 4), however, was not well simulated by the interpolation method. Thus, the interpolated estimation method might have contributed to the greater reduction in ΔHB (-14.9%) and ΔEV_{HB} (-$975m) for the 1986 to 2010 period relative to the 1945 to 2010 period (-13.9% and -$907m) (Table 3).

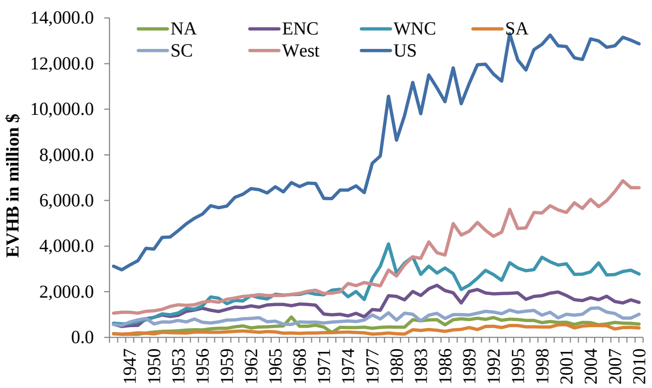


Figure 8. Change in EV_{HB} among six US regional divisions and entire US.

Table 3 Changes in honey bee populations (ΔHB) and associated economic value (ΔEV_{HB}) from 1945 or 1986 through 2010.

	2010	2010–1945		2010–1986	
Region	EV_{HB} (million $)	ΔHB (%)	ΔEV_{HB} (million $)	ΔHB (%)	ΔEV_{HB} (million $)
SA	410	-69.8	-286	-41.7	-171
ENC	1,532	-84.5	-1,294	-39.9	-611
WNC	2,774	20.2	562	17.5	486
West	6,528	-13.9	-907	-14.9	-975
NA	580	-73.2	-425	-30.0	-174
SC	1,014	-81.6	-828	-34.3	-348
Sum	**12,839**	**-302.8**	**-3,179**	**-143.3**	**-1,792**

Highest EV_{HB} was observed in 1994. The early period (1945–1969) in these calculations does not include apples. The west region has the higher contribution, followed by WNC (Figure 9, Tables 3 and 4).

The largest portion (76.6% in 1945–1969 and 57.3% in 1990–2010) of the estimated EV_{HB} was alfalfa and hay (Table 5). The second largest contributor was apple, followed by almond, cotton, and soybeans. EV_{HB} attributed to almonds increased from 1.9% in 1945–1969 to 15.6% in 1990–2010. Sunflower, apple, and soybean also had increasing contributions.

Sociological Impact

The decline in pollinators is likely to have a strong social impact due to the potential for a decrease in provisioning, regulating, cultural, and supporting ecosystem services that are provided by pollinators. Bees directly contribute to the provisioning of food (honey and crops) and indirectly influence regulation of the environment by pollinating plants that help to synchronize the climate of natural habitat (MEA 2005). Bees also make cultural contributions through recreation and education services (Rodriguez et al. 2006).

Table 4 Economic value of honey bees (EV_{HB}) averaged over several time periods.

	EV_{HB} (million $)		
Region	1945–1969	1970–1989	1990–2010
NA	362	552	685
ENC	1,107	1,536	1,784
WNC	1,358	2,583	2,949
SA	206	243	464
SC	693	850	1,061
West	1,532	3,048	5,590
US	5,259	8,812	12,533

Table 5 EV_{HB} attributed to specific crops averaged over several time periods. The values in parentheses show the percentage contribution for the given period.

	EV_{HB} attributed to specific crops (million $)		
Crop	1945–1969	1970–1989	1990–2010
Almond	104 (1.9%)	539 (5.7%)	1,470 (15.6%)
Sunflower	10 (0.2%)	603 (6.4%)	685 (7.3%)
Apple	--	1,271 (13.5%)	2,156 (22.9%)
Alfalfa, Hay	4,145 (76.6%)	5,142 (54.5%)	5,397 (57.3%)
Cotton	597 (11.0%)	578 (6.1%)	922 (9.8%)
Soybean	302 (5.6%)	963 (10.2%)	1,500 (15.9%)
Tomato	244 (4.5%)	314 (3.3%)	395 (4.2%)
Peanut	8 (0.2%)	16 (0.2%)	18 (0.2%)
Corn	0 (0.0%)	0 (0.0%)	0 (0.0%)
Wheat	0 (0.0%)	0 (0.0%)	0 (0.0%)

Alterations to natural processes that affect ecosystem services aid in the creation of the sociological impact of the decline in pollinators, because the number of available pollinators directly influences the stability of natural systems. This sociological impact can be seen through the effects of pollinators on human welfare, through provisioning for food production and consumption, as well as regulating, supporting, and maintaining the composition of the natural landscape and aesthetics of the surrounding environment. Even a small projected change to agricultural yield from a decline in pollinators could have extensive effects on human life (Aizen et al. 2009; MEA 2005).

Four main societal impacts are projected as a result of continued pollinator loss. First, a loss of pollinators will cause a decrease in diversity of plants, alter the spatial and temporal structure of plant growth events, and potentially change the landscape of all pollinator-influenced ecosystems (Ashworth et al. 2009; Dailey 1997), causing shifts in human-directed environmental management and planning. Second, compensation for pollinator shortage would require a significant increase in total cultivated area, and as a result, create a disproportionate increase in the demand for agricultural space. This disproportionate increase has the potential to escalate pressure on the global food supply, causing the decline in pollinators to become a heightened driver of global environmental change (Aizen et al. 2009). Third, the current increase in diversification of the human diet, paired with the globalized food trade, has increased demand for pollinator-dependent crops and restrained the replacement of pollinator-dependent crops with non-pollinator-dependent crops, which could trigger unstable economic markets and cause societal alarm regarding food availability and security at all levels of scale. Fourth, although research suggests that the world food supply could maintain production of what is needed for consumption, a large portion of world population could suffer from nutrient deficiencies even if their overall caloric intake is considered sufficient (Power 2010).

The sociologic concerns discussed here are serious. The scale on which these effects would be felt is unevenly distributed across all regions, making some areas more vulnerable than others (Ashworth et al. 2009; Power 2010). This disproportionality emphasizes that no singular concrete solution is applicable on a global scale to solve the sociological implications of pollinator decline, thus highlighting the need for more research.

Measures (Responses) to Counteract and Restore Declined Pollinator Population

A number of possible responses to the current decline in pollinators are applicable at the local and regional level. Because monoculture is an important driver of the declining pollinator population, a restoration of habitat heterogeneity by targeting intensively used and homogeneous landscapes could be one of the solutions. This can be achieved by incorporating compatible hedgerows and buffer plants that flower at different times and will provide an alternative pollen source to pollinators and decrease flying distance. Providing appropriate natural habitat for bees and other pollinators would be one of the easiest ways to support them. Leaving buffer strips between agricultural fields to encourage nesting grounds for bees and preservation of forest habitat at certain intervals is also recommended (Kearns and Inouye 1997).

As Garibaldi et al. (2011) suggested, yield growth and agricultural stability will benefit more from active management of wild bees and other pollinator species and an increase in the use of honey bees for crop pollination rather than honey production in places of increased land cultivation. Adaptation and disease were also reasons for declining pollinator populations in the US, so increasing honey bee culture with diverse honey bee communities or re-introducing native pollinators in areas of need is also recommended (Kearns and Inouye 1997).

Because the economic contribution of honey bee pollinators is immense, action is warranted. Improved agricultural policy provisions and protection to farmers who work to keep diverse cropping systems are recommended. Subsidizing economic losses or otherwise supporting farmers who adopt best management practices that encourage better ecosystem function is likely the best policy. Such best management practices include minimum usage of chemical fertilizers and pesticides, keeping beehives, and adding crop rotations that include legumes, among others.

Proper management of agricultural lands influences the possible negative impact on the natural ecosystem (loss of habitat, pesticide poisoning, etc.) while maintaining many positive ecosystem services (Power 2010). Therefore, options that reward best management systems as well as options that discourage improper agricultural management systems should be investigated. Such actions will most efficiently support a reduction in potential sociological impacts of pollinator decline.

CONCLUSIONS

Our analysis of honey bee pollination confirms a significant decline in pollinator population across the US. As might be expected, the decline in pollinator population has also caused a slower and more unstable yield increase for crops that are dependent on pollinators. Analysis of the yield reduction of selected crops that resulted from pollinator decline demonstrated a substantial economic loss. If we consider all crops with different levels of dependency, however, what we are losing in terms of provision of honey, environmental regulation services, and cultural and educational values, the decline in pollinators will have bigger impact than indicated in the present paper.

The agricultural, economic, and social impacts of pollinator decline might not have been fully felt in the past due to increased crop yields because of technological advancements; however, if nothing changes in terms of protecting ecosystems important to pollinators, we will start to feel these effects in coming years. Improved agricultural practices and policies that encourage diverse cropping system should be devised and implemented.

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