Journal of Economic Entomology, XX(XX), 2021, 1–10
doi: 10.1093/jee/toab100
Research

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Temporal Trends in Pollination Deficits and Its Potential Impacts on Chinese Agriculture

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Subject Editor: David Tarpy

Received 22 December 2020; Editorial decision 26 April 2021

Abstract

Worldwide, there is increasing evidence that shows a decline in pollinators, limiting crop pollination and production. However, it is unclear to what extent Chinese agriculture could be impacted by pollinator deficits. Data for 84 major crops in China between 1961 and 2018 were analyzed for the temporal trends in crop area and production, agricultural economic contribution of pollination, crop yield deficits, and honey bee pollination demand. We found a rapid increase in agricultural dependence on insect pollinators: both the cultivated area and total production of pollinator-dependent crops increased faster than those of pollinator-independent crops during 1961–2018. The total economic value of pollination amounted to US$ 106.08 billion in 2010, representing 19.12% of the total production value of Chinese agriculture, approximately twice the 9.5% value estimated for global agriculture. Crops with higher pollinator dependence showed greater mean growth in cultivated area than those with lower dependence, but lower mean growth of crop production and yield. Crop yield growth was also more unstable with increasing pollinator dependence. The minimum pollination demand for honey bee colonies was about three times the stock of honey bee colonies available in 2018. Furthermore, we found a decline in crop yield deficit with the increase in honey bee colony pollination service capacity. We considered that the shortage of pollinators resulted in the yield deficits for pollinator-dependent crops. Future increase in the area of pollinator-dependent crops will increase the need for more pollinators, suggesting the importance of implementing measures to protect pollinators to ensure a better-secured future for agricultural production in China.

Key words: agriculture trends, pollination economic value, honey bee pollination demand, yield deficit

Pollination is an important ecosystem service in agricultural systems provided by managed and wild pollinators. Pollinators play a determinant role in agricultural production because over 70% of the 124 globally most important crops that humans directly use for food depend on or benefit from animal pollination to various extents (Klein et al. 2007). Unfortunately, these pollinators (managed and wild) are increasingly under threat from many factors, such as habitat loss, pesticide use, disease, alien species invasions, and climate change, affecting their abundance and diversity, which ultimately compromises pollination services (Koh et al. 2016; Liu et al. 2016; Potts et al. 2016, 2010; Teichroew et al. 2017; Naeem et al. 2019). The crops that depend on animal-pollinators account for approximately 35% of the global agricultural production volume (Klein et al. 2007). The proportion of total production that may be directly attributed to animal pollinators or that may be lost in the absence of these pollinators ranges from 5% in the developed world to 8% developing worlds (Aizen et al. 2009b).

In addition to global analyses, national-level analyses of pollination value and the size of the impact of pollinator shortage are important because they can facilitate the formulation of specific policies. For instance, 9.5% of the global agricultural production value could have been lost if insect pollinators were absent in 2005 (Gallai et al. 2009). Such absence of pollinators in 2005 could account for a decline in global GDP between 0.5% and 1.1% (Lippert et al. 2021). Effects of a complete loss of pollinators are estimated to be between 1.0% and 1.4% of global GDP in the long term (Lippert et al. 2021). Twelve percent of the total production value would have been lost in East Asia in 2005 (Gallai et al. 2009) and across Europe in 2009 (Leonhardt et al. 2013). Moreover, countries such as Ethiopia (Alebachew 2018) and Brazil (Giannini et al. 2015) could have experienced a decrease in production value of 16% and 30% in 2016 and 2012, respectively; while in the Pará state of eastern Amazon, 33% of the agricultural value could be affected (Borges et al. 2020). In China, US$ 52.2 × 10^9 pollination value of vegetables and fruits could have been lost if pollinators were absent in 2008 (An and Chen 2011). Furthermore, the insect pollination service and value of 22 major crops account for at least 1.3% of the GDP in China, which would also be lost in the absence of insect pollinators (Ouyang et al. 2019).

Over 40% of the global agricultural production volume dependent on animal-pollinators originates from Asia (Bauer and Wing 2010), and China is the largest producer and beneficiary of pollination on this continent (Lautenbach et al. 2012). China alone contributes 30–50% of the global pollination benefits and leads among other great pollination beneficiaries, such as India, the United States, Brazil, Japan, and Turkey (Lautenbach et al. 2012). However, the pollination service in China remains understudied, particularly its level of pollinator dependence under the threat of pollinator decline (Potts et al. 2010, Lautenbach et al. 2012, Teichroew et al. 2017, Aizen et al. 2019).

Moreover, there is an increasing mismatch in agricultural systems due to opposite trends between agricultural pollinator dependence and the abundance and diversity of pollinators. The fraction of agriculture that depends on pollinators is rapidly increasing, and it manifests through the expansion of areas cultivated with insect-pollinated crops (Aizen et al. 2019). The conversion of lands to cultivated areas is commonly used as an immediate strategy to compensate for the loss of crop production or increase in crop consumption. However, in China, almost half of the cultivated area has resulted from vast land-use changes (deforestation) since the 1950s due to economic reforms (Liu et al. 2014, Miao et al. 2016). This area has been increasing more rapidly for pollinator-dependent crops than for pollinator-independent crops (Aizen et al. 2019, 2008). Although pollinator-dependent agriculture is increasing, pollinators (both managed and wild bees) have become more likely to be at high risk of various agents that act individually or synergistically to cause a decline in their populations (Yang 2005, Koh et al. 2016, Liu et al. 2016, Teichroew et al. 2017). On the one hand, the conversion of natural habitats into cultivated areas has fragmented and degraded nesting areas, thus facilitating the decline in the abundance and diversity of pollinators (Koh et al. 2016). On the other hand, the alien western honey bee *Apis mellifera* has reduced >80% of the population and >75% of the distribution of the native honey bee *Apis cerana* since its introduction into China in 1896 (Yang 2005).

Despite these threats, the number of managed honey bee colonies in China has increased significantly (Teichroew et al. 2017), similar to the increasing trend observed globally, with the exception of some countries in Europe and North America that have shown a decline in managed colonies (vanEngelsdorp and Meixner 2010, Koh et al. 2016). However, the global rate of increase in available managed honey bee colonies is outpaced by that in pollinator-dependent agriculture (Aizen et al. 2009b). This has caused a low density of managed colonies per unit area cultivated with pollinator-dependent crops (Teichroew et al. 2017). The current study was performed to determine whether the current pollination ecosystem services are sufficient to satisfy the increasing agricultural pollination demand in China (Teichroew et al. 2017).

The availability of resources, such as naturally available ecosystem services or human inputs supplied agriculturally to supplement natural resources, influences crop yields (Garibaldi et al. 2011). A limitation in the availability of these resources, for example, pollination shortages, hinders crop yield by causing incomplete pollination. Agriculture may currently be at high risk of pollen limitation because of the fast growth in demand for pollination services in relation to supply ability (Aizen and Harder 2009a, Aizen et al. 2019). Indeed, the mismatch between available colonies and demand decreases the probability of flower visitation and the visitation rate, limiting seed and fruit production (Chen and Zhao 2019). Conventional agricultural practices such as fertilizer and pesticide application, irrigation and genetic modification are used to enhance productivity growth or improve yield. However, for pollinator-dependent crops, effective pollination services overtake these conventional practices in improving crop production in terms of both quantity and quality (Klein et al. 2015, Hünicken et al. 2020, Sawe et al. 2020). For instance, the yield of watermelon (*Citrullus lanatus*) improves when honey bee colonies are enhanced compared to when conventional factors such as soil fertility and moisture are improved under the limited availability of honey bees (Sawe et al. 2020). Additionally, the availability of nutrients to apple and pear trees has a weaker effect than honey bee pollination in improving the quantity and quality of fruits (Hünicken et al. 2020). The above information indicates that the impact of pollination on crop production and growth depends on the extent of crop dependence on pollinators. The most vulnerable crops are those that completely rely on pollinators, especially those that depend on a narrow range of pollinator species to set fruit (Klein et al. 2007).

Chinese agriculture might be vulnerable to a loss of pollinators due to the presence of a high number of pollinator-dependent crops. A shortage of agricultural pollination in China may have important consequences for food security and livelihoods at the national and global scale (Lautenbach et al. 2012, Teichroew et al. 2017). Therefore, in this study, we quantified how dependent Chinese agriculture is on pollinators. To do so, we assessed temporal trends in 1) crop area and production according to pollinator dependence, 2) the agricultural economic contribution of pollination, and 3) crop yield deficits and honey bee pollination demand. Such analysis will facilitate the formulation of pollinator conservation strategies to secure a better future for Chinese agriculture.

Materials and Methods

Data Collection

Data concerning crop cultivated area, production, yield, and honey bee colony stock were collected annually from 1961 to 2018 from FAOSTAT (FAOSTAT 2020). Price data were collected annually only from 1991 to 2010 (because price data were not available after 2010 for most crops). Our study focused on 84 major crops planted in China that had full records between 1961 and 2018 from FAOSTAT. The 84 crops were categorized following Klein et al. (2007) and Gallai et al. (2009) into five pollinator-dependence classes: no increase (insect pollination does not affect production, pollinator dependence [D] = 0, 41 crops), little (in the absence of insect pollination, production reduction >0 but <10%, D = 5%, 15 crops), modest (production reduction ≥10% but <40%, D = 25%, 12 crops), great (production reduction ≥40% but <90%, D = 65%, 12 crops), and essential (production reduction ≥90%, D = 95%, 4 crops) (Supp Material 1: Table S1 [online only] and Supp Fig. S1 [online only]). The crops that pollination increases breeding were considered as pollinator-independent crops.

The recommended honey bee colony pollination densities for crops cultivated in China were extensively searched and recorded from the literature in both English and Chinese sources including Web of Science, Google Scholar, PubMed, and CNKI (Breeze et al. 2011, 2014, Rollin and Garibaldi 2019; see Supp Material 2 [online only]). The minimum, maximum, and median values of the recommended colony density (RCD) of honey bee were recorded (Supp Table S2 [online only]). Crops for which honey bee RCDs were not found in the literature and that require buzz pollination such as tomatoes, eggplants, chillies, and peppers (i.e., pollinated by other pollinators, e.g., *Bombus* sp.) were excluded, with a total of 34 crops analyzed for pollination demand in this study.

Trends in Crop Area and Production From 1961 to 2018

The changes in cultivated area and the total production of pollinator-dependent and pollinator-independent crops have been calculated annually since 1961 (Aizen et al. 2019). The change in each dependent variable, X, from 1961 until year *t* was represented as a percentage of the value of X in 1961, i.e., $100\ (X_t - X_{1961})/X_{1961}$. The annual growth in the cultivated area and total production was calculated as the ratio of each dependent variable in consecutive years (X_t/X_{t-1}) (Garibaldi et al. 2011).

Economic Value of Insect Pollination

A bioeconomic approach (Gallai and Vaissière 2009, Gallai et al. 2009) was adopted to estimate the economic value of pollinator loss between 1991 and 2010. The economic value (EV) is the product of the quantity (Q_i) and price (P_i) of crop *i*, while the insect pollination economic value (IPEV) is the product of the quantity (Q_i), price (P_i), and the dependency ratio on insect pollinators (D_i) of crop *i*. We estimated China's agricultural economic vulnerability (RV) to pollinator loss as the ratio of the IPEV of insect-pollinated crops to the EV of all 84 crops.

$$\mathrm{EV} = \sum\nolimits_{i=1}^{84} (\mathrm{P}i \times \mathrm{Q}i)$$

$$\mathrm{IPEV} = \sum\nolimits_{i=1}^{84} (\mathrm{P}i \times \mathrm{Q}i \times \mathrm{D}i)$$

$$\mathrm{RV} = \frac{\mathrm{IPEV}}{\mathrm{EV}} \times 100\%$$

Crop Yield Deficits and Honey Bee Pollination Demand

The annual growth in yield was calculated as the ratio of the mean yield in consecutive years (Y_t/Y_{t-1}), and the mean relative yield was estimated as the ratio of the mean annual yield to the maximum yield during the analyzed period ($Y_t\ /Y_{max}$). The yield deficit was estimated as the difference between the maximum yield observed during the analyzed period and the mean annual yield in year *t* ($Y_{max} - Y_t$) (Garibaldi et al. 2011). Honey bee pollination demand (the total number of colonies required to provide adequate pollination service) was calculated as the product of the area of honey bee pollinated crops and the RCD of these crops (Breeze et al. 2011, 2014). Our focus was on managed honey bee colonies because the abundance and distribution of wild honey bees has been insufficiently studied, their nesting behavior is complex and their nests difficult to find, and their pollination impact cannot be estimated at present (Breeze et al. 2011, Utaipanon et al. 2019). We assumed that within a year, a colony could be moved (*d*) at least once; thus, the pollination demand was divided by 2 to represent the capacity that hives can be moved once within year *t* for pollination purposes (Breeze et al. 2014).

$$\mathrm{TD}t = \frac{\sum_{it}(\mathrm{A}i \times \mathrm{RCD}id)}{2}$$

Where TD*t* is the total honey bee pollination demand, A*i* is the area of crop *i*, and RCD*id* is the honey bee RCD for crop *i*. The pollination service capacity (PSC) was calculated by dividing the honey bee stock by the total honey bee pollination demand in the year *t* (Breeze et al. 2014).

$$\mathrm{PSC}t = \mathrm{HC}t/\mathrm{TD}t$$

Where PSC*t* is the pollination service capacity of honey bee stock to provide adequate pollination service to crops and HC*t* is the honey bee colony stock.

Results

Trends in Crop Area and Production

From 1961 to 2018, different trends were observed in China's cultivated area and production of pollinator-dependent and pollinator-independent crops (Fig. 1). The total agricultural area of the 84 crops increased by 22% from 1961 to 2018, representing an increase of 3×10^7 hectares. The area cultivated with pollinator-dependent crops expanded by 49.7%, whereas the area cultivated with pollinator-independent crops increased by only 14.3% (Fig. 1A). The percentage of the agricultural area in China occupied by pollinator-dependent crops was 21.8% in 1961, but in 2018, this percentage increased to 26.7%. The total production of the 84 crops increased by 454.3% from 2.8×10^8 tons in 1961 to 1.6×10^9 tons in 2018, during which the percentage of pollinator-dependent crop production in terms of total agriculture increased from 16.7% in 1961 to 30.5% in 2018. From 1961 to 2018, the production of pollinator-dependent crops increased by 913.8%, whereas the production of pollinator-independent crops increased by only 362.5% (Fig. 1B). Both crop area and production grew significantly in consecutive years for all five pollinator-dependence classes (Fig. 2, i.e., >1). However, the growth in area increased with pollinator dependence for all crops except for those with little pollinator dependence ($F = 23.722$, $P = 0.039$, Fig. 2A), whereas the growth in mean production decreased with pollinator dependence ($F = 24.688$, $P = 0.016$, Fig. 2B).

Economic Value of Insect Pollination

There has been a strong increasing trend in the contribution of insect pollination to the economic value of China's agricultural production (Fig. 3). The vulnerability ratio of China's agricultural production to pollinator loss was only 7.6% in 1991, but it increased to 19.12% in 2010. In 2010, the economic value of the 84 evaluated crops used directly for human food was US\$ 554.92×10^9, and the value of the 43 pollinator-dependent crops was US\$ 250.7×10^9, equivalent to 45.18% of the total economic value. The economic value of insect pollination was US\$

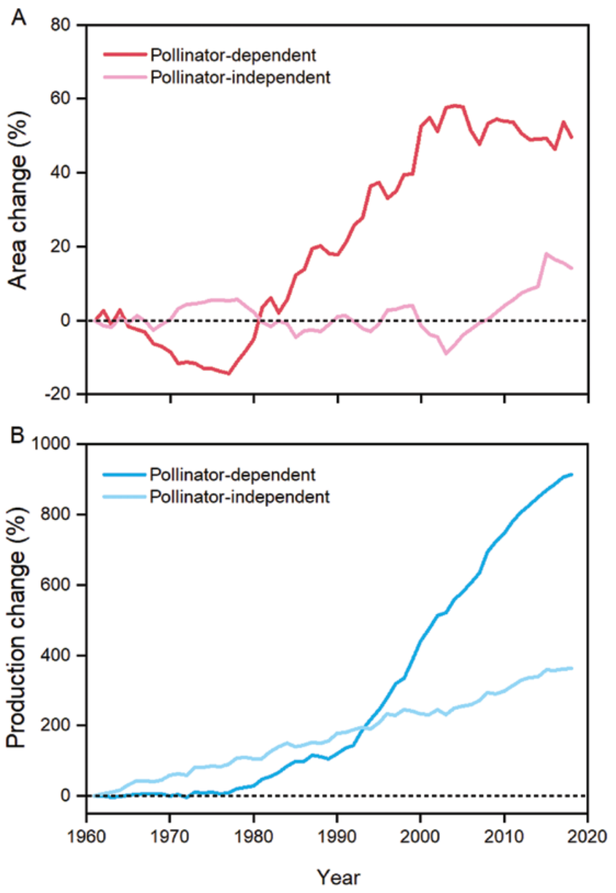

Fig. 1. Changes in the cultivated area and total production of pollinator-dependent and pollinator-independent crops from 1961 to 2018 in China. For each dependent variable, *X*, the change from 1961 until year *t* is represented as a percentage of the value of *X* in 1961, that is, $100(X_t - X_{1961})/X_{1961}$.

106.08×10^9. Vulnerability per crop category was determined as the ratio of insect pollination value to the total production value in a category in order to compare the susceptibility to pollinator decline between the categories. Based on the data from 2010, fruits were the most vulnerable category, followed by vegetables, oil crops, pulses, tree nuts, spices, and stimulant crops (Table 1). However, the average vulnerability ratio of each crop category from 1991 to 2010 showed that oil crops are more vulnerable than vegetables and that pulses are less vulnerable compared to tree nuts (Supp Fig. S2A [online only]). The trends in the vulnerability ratios between 1991 and 2010 differed among the categories, while those of oil crops, pulses, spices, and stimulant crops were relatively stable. The vulnerability ratio of tree nuts showed an obvious decline from 2009, while that of vegetables increased rapidly from 2007 (Supp Fig. S2B [online only]). The vulnerability ratio's value is, of course, determined by the relative prices of crops, especially pollinator-dependent versus pollinator-independent crops. The increase in vulnerability ratio of vegetables was associated with increase in the price of pollinator-dependent crops such as melons while the relative increase in the prices of pollinator-independent crops such as walnuts was associated with the decline in vulnerability ratio of treenuts category in 2010. The top 10 crops showing high economic value of insect pollination in China in order from high to low were watermelon, apple, seed cotton, mango, pear, eggplant, muskmelon, peach, soybean, and pumpkin (Fig. 4).

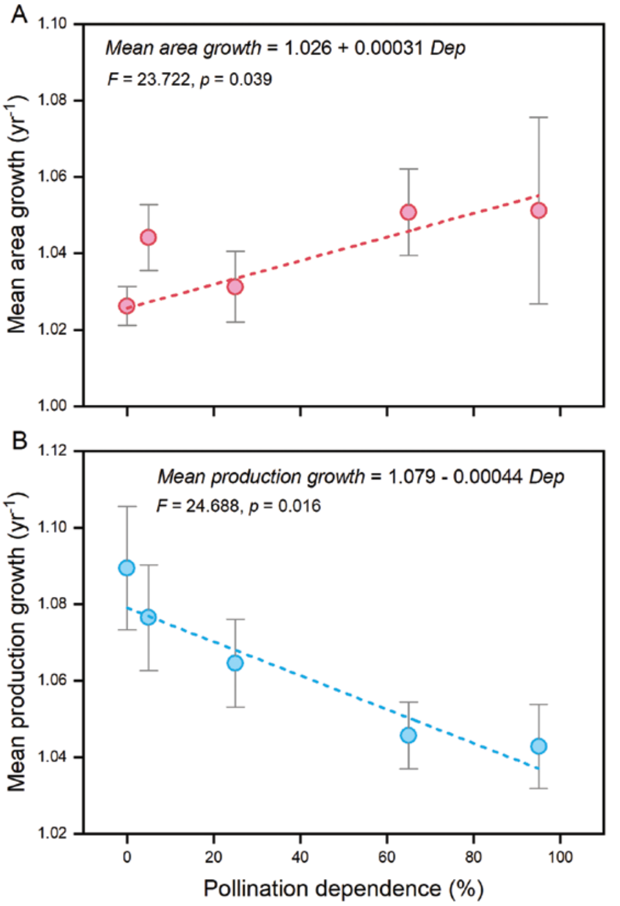

Fig. 2. Trends in the mean (±SE) annual growth of cultivated area and total production between 1961 and 2018 for the 84 Chinese crops categorized according to pollinator dependence. Dashed lines represent linear regressions based on individual crops. For each dependent variable, X, the annual growth in year *t* is represented as the ratio for consecutive years, that is, X_t/X_{t-1}.

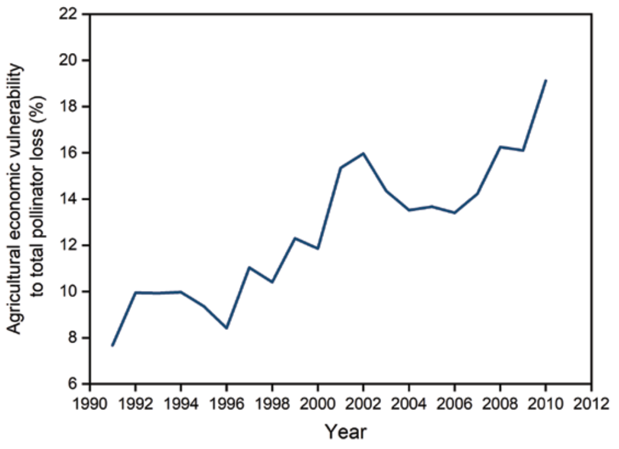

Fig. 3. Trend of the contribution of insect pollination to the agricultural production economic value in China between 1991 and 2010. The agricultural economic vulnerability (*RV*) is represented as the percentage ratio of insect pollination economic value to the total production economic value, that is, (*IPEV* / *EV*) × 100%.

Crop Yield Deficits and Honey Bee Pollination Demand

There was a decrease in the consistency of yield growth with the increase in pollinator dependence, in which the yield of

Table 1. Economic impact of insect pollination for the 84 crops used directly for human food in China in 2010

Crop category	Number of pollinator-dependent crops	Number of pollinator-independent crops	Total cultivated area	Total crop production	Total production economic value (EV)	Insect pollination economic value (IPEV)	Ratio of vulnerability (RV)
			10^6 ha	10^6 tons	10^9 \$	10^9 \$	%
Fruits	17	4	11.61	120.37	97.22	43.19	44.43
Vegetables	9	12	23.90	377.74	166.34	50.58	30.41
Oil crops	9	1	27.12	65.95	54.23	11.27	20.77
Pulses	2	3	2.76	3.78	3.19	0.32	10.10
Tree nuts	3	3	0.77	3.05	8.43	0.67	7.90
Spices	2	3	0.16	0.70	0.73	0.014	1.92
Stimulant crops	1	1	1.47	1.52	6.14	0.04	0.65
Cereals	0	8	89.19	497.04	142.14	0.0	0.0
Roots and tubers	0	4	8.41	148.68	44.88	0.0	0.0
Sugar crops	0	2	1.91	120.80	31.61	0.0	0.0
Total	43	41	167.30	1,339.62	554.92	106.08	19.12

The total production economic value (*EV*) is represented as the sum of the product of price and quantity, that is, *Pi* × *Qi*; insect pollination economic value (*IPEV*) as the sum of the product of price, quantity and pollinator dependence ratio, that is, *Pi* × *Qi* × *Di*; and the ratio of vulnerability (*RV*) as the percentage ratio of insect pollination economic value to the total production economic value, that is, (*IPEV/EV*) × 100% (values are not adjusted for inflation).

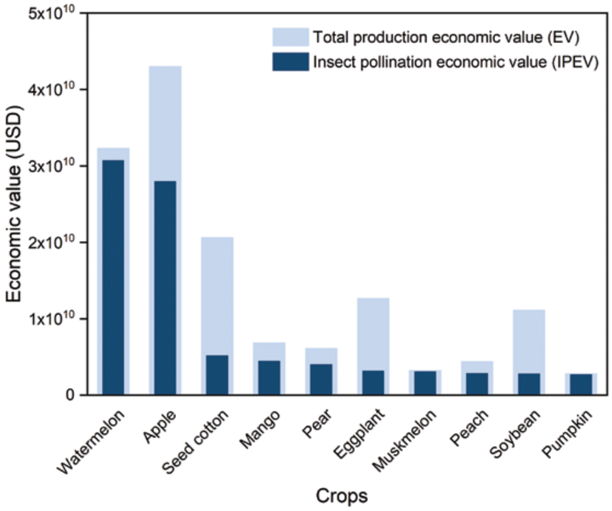

Fig. 4. The top 10 crops in order from high to low of insect pollination economic value in China in 2010. The total production economic value (*EV*) is represented as the sum of the product of price and quantity of production, that is, P*i* × Q*i*, and insect pollination economic value (*EV*) as the sum of the product of price, quantity and dependence ratio, that is, P*i* × Q*i* × D*i* (values are not adjusted for inflation).

pollinator-independent crops increased at a steady rate, while more fluctuations were found in the yield growth of pollinator-dependent crops (Fig. 5). The yield of crops in all categories increased from 1961; however, the rate of yield improvement decreased with increasing pollinator dependence (Fig. 6A). Moreover, crops with high pollinator dependence had a lower relative yield than less dependent crops, except for the four crops in the 'essential' category (Fig. 6B). The available honey bee stock in China is far below the demand, causing it to be unable to provide adequate pollination services, and the shortage of honey bee colonies might have caused a yield deficit for pollinator-dependent crops. Although the stock of honey bee colonies in China rose to 9.17 × 10^6 in 2018, which was 73.4% higher than that in 1961, the pollination demand for honey bee colonies increased three times at the minimum RCD (Fig. 7). Moreover, we found a decline in the crop yield deficit with an increase in the pollination service capacity for the 34 crops pollinated by honey bees (Fig. 8).

Discussion

Trends in Crop Area and Production

The options to satisfy the increasing demand from a growing and more affluent population involve the increase of cultivation area, crop yield, or both (Edgerton 2009). Although approximately 12% of the Earth's terrestrial surface (ice-free) is already under crop cultivation, more land continues to be converted to expand the cultivation areas (Schmitz et al. 2014). This has resulted in an increase in the global cultivated area of over 40% from 1961 to 2016 (Aizen et al. 2019), and in countries such as China, the area under crop cultivation increased by 22% from 1961 to 2018. More pasture and forest areas (Bahar et al. 2020) are under threat of being converted to cultivated areas in response to changes in climate and food demands (Molotoks et al. 2020).

The area cultivated with crops that depend on pollinators to set seeds and fruits increases faster than the area cultivated with pollinator-independent crops (Fig. 1A). Pollinator-dependent crops occupied 26.7% of the total cultivated area in China in 2018, having expanded by approximately 50% since 1961. Such an increase in the proportional area devoted to pollinator-dependent crops and a decrease in that occupied by pollinator-independent crops indicates an increase in the dependence of Chinese agriculture on pollinators (Aizen et al. 2008). Indeed, global agriculture is rapidly increasing in pollinator dependence. For instance, animal-pollinated crops occupied 32.8% of the global total cultivated area in 2016, equivalent to an increase of 70% from 1961 (Aizen et al. 2019). The increase in the rate of agricultural dependence on insect pollinators shows growing demand for pollination services (Aizen et al. 2019).

The increase in production showed different temporal trends between pollinator-dependent and pollinator-independent crops, in line with the cultivated area (Fig. 1B) (Aizen et al. 2009b). Our results

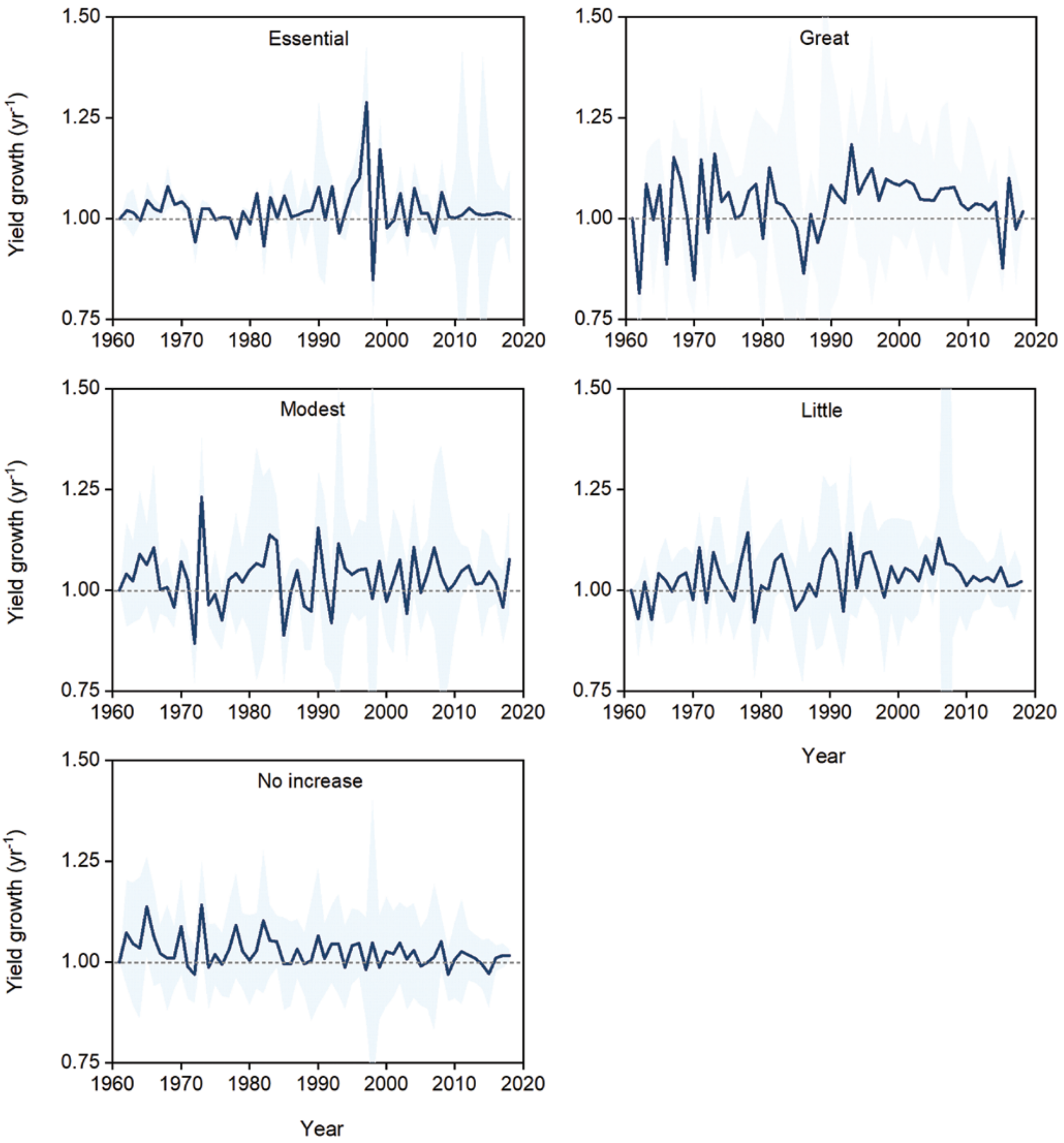

Fig. 5. Temporal trends in mean yield growth between 1961 and 2018 for the 84 crops categorized by pollinator dependence in China. Data are presented as the mean ± SD.

show that the percentage of the production of the 84 crops that can be directly attributed to insect pollination was above 30% in 2018. This is the aggregate result of the production of crops in the little, modest, great, and essential pollinator-dependence categories. The changes over time in the production of both pollinator-dependent and pollinator-independent crops are strongly associated with the change in the land area cultivated with these crops (Fig. 1) (Aizen et al. 2008). For all five pollinator-dependence classes, both crop area and production grew significantly in consecutive years (Fig. 2, i.e., >1). A study conducted at the global scale revealed that growth in both area and production increased with pollinator dependence for all pollinator-dependent crops (Garibaldi et al. 2011). However, in China, we found a similar trend of area growth, showing an increase with pollinator dependence (Fig. 2A), but a contrasting trend of mean production growth that decreased with the increase in pollination dependence (Fig. 2B). This may be an indication of pollination limitations because the available density of pollinators in China is becoming insufficient to supply adequate pollination services and meet the increasing pollination demand of Chinese agriculture.

Economic Value of Insect Pollination

Pollination services significantly contribute to agricultural economic production in China. Insect-pollinated crops contributed US$ 250.7 × 10^9, equivalent to 45.18% of the total crop production value in 2010, and higher than the economic contribution of insect-pollinated crops in other countries that greatly benefit from pollination service such as Brazil, with a value of US$ 42 × 10^9, in 2013. The agricultural pollination service in China was valued at US$ 106.08 × 10^9, almost half of the estimated global insect-pollination economic value (€153 × 10^9 ≈ US$ 200 × 10^9) in 2005 (Gallai et al. 2009). However, the global pollination values have been re-estimated and revealed that loss of pollinators in 2005 could cause loss of total

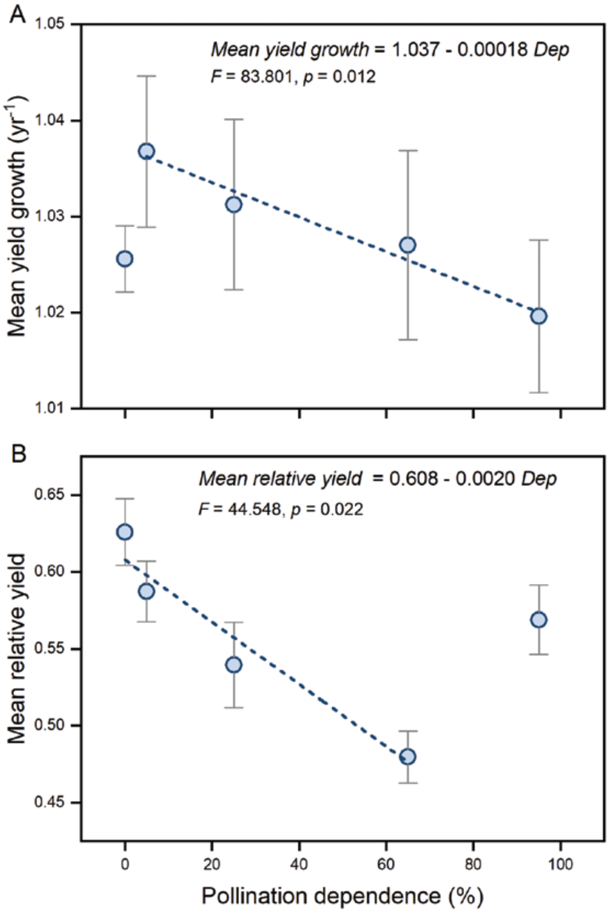

Fig. 6. Trends in the mean (±SE) yield growth and relative yield between 1961 and 2018 for 84 Chinese crops categorized by pollinator dependence. Dashed lines represent linear regressions based on individual crops (in A, the pollinator-independent crops were excluded from the regression; in B, the four crops in the 'essential' category were excluded from the regression analysis). Yield growth in year *t* is represented as the ratio for consecutive years, that is, Y_t/Y_{t-1}. The relative yield in year *t* is represented as the annual yield to the maximum yield during the analysis period, that is, Y_t/Y_{max}.

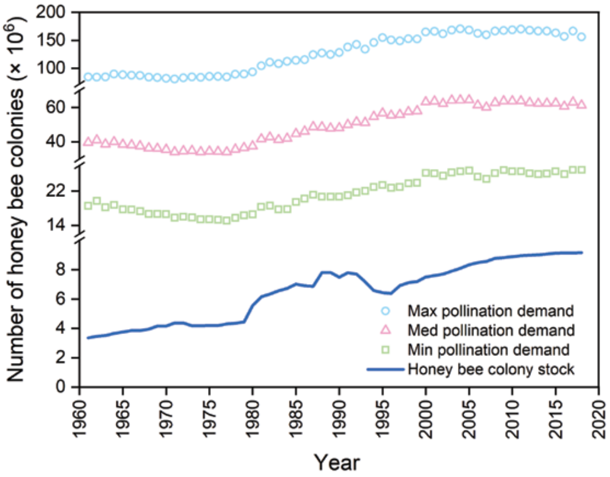

Fig. 7. Trends of the demand for agricultural pollination by honey bees and the honey bee colony stock in China between 1961 and 2018.

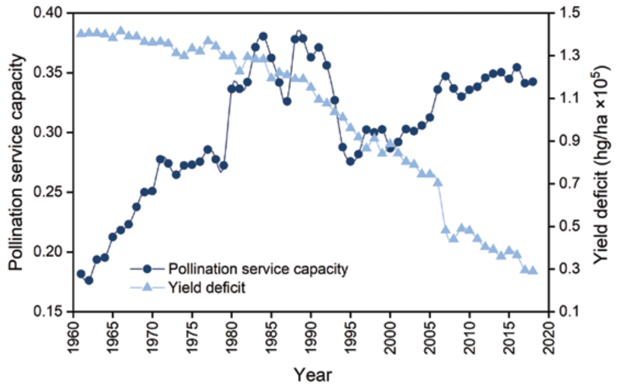

Fig. 8. Trends of the pollination service capacity and yield deficit for the 34 honey bee pollinated crops in China between 1961 and 2018. The yield deficit is represented as the difference between the maximum yield during the analysis period and the annual yield in year *t* ($Y_{max} - Y_t$). The pollination service capacity is represented as the honey bee stock divided by the honey bee pollination demand.

welfare between €191 ×10⁹ and €422 ×10⁹ (≈ US$ 226 ×10⁹ and US$ 498 × 10⁹) (Lippert et al. 2021). Lippert and colleagues estimate that the plausible long-term losses of total welfare lie between US$ 805 × 10⁹ and US$ 1176 × 10⁹ in the absence of pollinators (Lippert et al. 2021). Furthermore, the value of insect pollination in China is about six times higher than the annual economic contribution of insect pollination (€14.6 × 10⁹ ≈ US$ 17 × 10⁹) across Europe (Leonhardt et al. 2013). Moreover, the contribution of pollination to China's agricultural economy is much higher than the value in the United States (US$ 14.2–23.8 × 10⁹) (Chopra et al. 2015). This corresponds with the finding that China is the leading pollination beneficiary country globally (Lautenbach et al. 2012).

Insect-pollination economic value differs spatially among the crop categories. The categories of vegetables, fruits, and oil crops, were in order, the highest contributors to pollination value in China, similar to global-scale contributions (Gallai et al. 2009). However, this pattern is reversed in the United States where oilseed accounts for the highest pollination economic value, followed by fruits and vegetables (Chopra et al. 2015). In European agriculture, the fruits category has the highest pollination value, followed, in order, by spices, vegetables, oil crops, and nuts (Gallai et al. 2010). And the most important insect-pollinated crop is apple, which accounts for 16% of the total insect pollination economic value in Europe (Leonhardt et al. 2013). The top 10 individual crops with high insect-pollination economic value in China are, in order, watermelon, apple, seed cotton, mango, pear, eggplant, muskmelon, peach, soybean, and pumpkin (Fig. 4). Besides, the pollination function and service value for the major crops in China differ among the provinces. The top five provinces with high pollination function are Shandong, Henan, Hebei, Shaanxi, and Xinjiang (Ouyang et al. 2019).

Despite the fact that agricultural production has increasingly become more economically vulnerable to the loss of pollinators, a high spatial-temporal variation exists on this vulnerability. The economic vulnerability of China increased to 19.12% in 2010 (Fig. 3), being approximately two times higher than that of European and global agriculture (9.5%) in 2005 (Gallai et al. 2010, 2009). A spatial and temporal trends analysis in global pollination benefits also found that China was more economically vulnerable (15.3%) to a decline in pollinators than Turkey (12%), the United States (11%), Brazil

(10%), Russia (6.6%), and India (4.5%) in 2009 (Lautenbach et al. 2012). Moreover, Northern European countries are less economically vulnerable to pollinator declines (6.2%) than the countries of the south (12.6%) (Gallai et al. 2010, Leonhardt et al. 2013); however, the interannual variability in the economic vulnerability to pollinator declines is high in the Northern than in Southern Europe (Leonhardt et al. 2013). This is due to differences in economic activities (e.g., industrialization), the biodiversity of wild pollinators, the number of pollinator-dependent crops grown, and climatic conditions that limit the growth of many pollinator-dependent crops, particularly in colder (northern) European countries (Gallai et al. 2010, Leonhardt et al. 2013). Nuts and fruits are the most vulnerable crops in Europe, while edible oil crops, vegetables, pulses, and spices are less vulnerable (Gallai et al. 2010).

Moreover, estimation of pollination value by bioeconomic approach assumes a reference crop production level under complete pollination services and uses the pollinator dependence ratios to assess the real impact of pollinator disappearance (Gallai et al. 2009). In reality, complete pollination in ecosystems is unlikely attained, especially in the current context of increasing pollinator decline (Goulson et al. 2015, Soroye et al. 2020). Most crop production is realized under partial pollination services. In this regard, the pollination values estimated can be underestimating the potential impact of total collapse in pollination services. Nevertheless, this approach and the assumptions it makes provide a practical tool for prioritizing pollinator conservation for the sustainability of agricultural production.

Crop Yield Deficits and Honey Bee Pollination Demand

Yield growth of crops in Chinese agriculture was more unstable with the increase in pollinator's dependence (Fig. 5). Similarly, a global analysis revealed that the yields of pollinator-dependent crops fluctuated more than those of pollinator-independent crops and that the consistency of yield growth decreased with an increase in pollinator dependence (Garibaldi et al. 2011). Likely, except for the crops in the 'essential category' (four crops in China), the mean relative yield was lower in higher pollinator-dependent crops than in less pollinator-dependent crops (Fig. 6B). This decline in yield growth of the pollinator-dependent crops (Fig. 6A) may be attributed to the shortage of pollinators, which was offset by higher growth in the cultivated area (Fig. 2A; Aizen et al. 2008, Garibaldi et al. 2011).

Globally, there is higher growth in yield and lower growth in the cultivated area for the essential crop category than for the other dependence categories (i.e., 0–65% dependence) (Garibaldi et al. 2011, 2009). The high yield growth of the crops in the 'essential' category indicates that the pollination management practices applied for these crops decrease the limitations that could be imposed by pollinators on yield due to environmental degradation (Garibaldi et al. 2011, 2009). For instance, the production of essential crops in Japan is more stable than other pollinator-dependent crop categories due to intensive management including pollination, which is motivated by economic gains from these crops (Oguro et al. 2019). Four essentially pollinator-dependent crops are cultivated in China: watermelon, melon, pumpkin, and vanilla (Fig. 1 and Supp Table S1 [online only]). Honey bees are used to pollinate watermelon, melon, and pumpkin on a large scale, or hand pollination can be used on a small scale, while vanilla is grown under hand pollination techniques (Garibaldi et al. 2009, Sawe et al. 2020). This shows a significant interaction between pollinator dependence and the management practices of farmers (Garibaldi et al. 2009, Oguro et al. 2019).

Since agriculture has become more pollinator-dependent, the demand for pollination services has increased beyond the availability of the honey bee stock. The gap between the density of available pollinators and the demand of agriculture for pollination is unprecedentedly high. Globally, the honey bee stock increased by 45%, but the pollination demand increased by 300% (Aizen and Harder 2009a). Across Europe, the amount of honey bee colonies required to provide adequate crop pollination increased 4.9 times as fast as the available honey bee stock (Breeze et al. 2014). The number of stocked honey bee colonies in China was 9.17×10^6 in 2018, but to provide adequate pollination services for Chinese agriculture, the demand was approximately $26.8–152 \times 10^6$ colonies, at least three times the number of available stocked honey bee colonies at a minimum RCD and 17 times that at a maximum RCD (Fig. 7). This shows the existence of a rapidly growing gap in pollination for honey bee pollinated crops in China (Teichroew et al. 2017).

Despite the richness and abundance of insect pollinators (e.g., bees, both managed and wild), the increase in threat factors (habitat degradation, parasites and disease-causing pathogens, pesticides, and climate change) causes a decline in pollinators that affects pollination services in agricultural and natural landscape systems (Teichroew et al. 2017). Due to the increase in the area of pollinator-dependent crops, the pollination service capacity of the available honey bee stock has decreased, since only a small percentage of the area cultivated with pollinator-dependent crops can be adequately supplied with honey bee colonies (Breeze et al. 2014). For the 34 honey bee pollinated crops in China, we found a declining trend of yield deficit with the increase in pollination service capacity (Fig. 8). The crop yield deficit could decrease through time both because of the increasing honey bee colony stock and other factors such as the improving techniques of breeding and chemical nutrient managements (Marini et al. 2015, Tamburini et al. 2017). The shortage of honey bee colonies is associated with pollen limitations such as incomplete and variable pollen delivery to pollinator-dependent crops (Chen and Zuo 2018a, Chen et al. 2018b, Chen and Zhao 2019). Such pollen limitation hinders the yield growth of pollinator-dependent crops and the temporal stability of agricultural production, thus promoting further compensatory land conversion to agriculture (Garibaldi et al. 2011).

Conclusion

This study assessed the temporal trends in Chinese agriculture and pollination demand. Our analysis showed that there has been a rapid increase in agricultural dependence on pollinators, vulnerability to pollinator loss, and agricultural pollination demand, which far exceeds the available stock of honey bee colonies in China. This calls for effective strategies to conserve wild pollinators, and to promote beekeeping for pollination to ensure productive and sustainable agriculture in China.

Supplementary Data

Supplementary data are available at *Journal of Economic Entomology* online.

Acknowledgments

We are very grateful to Yanhui Lu for comments on the manuscript. This work was supported by the Special Program for Basic Resources of Science and Technology (2018FY100404) and the Agricultural Science and Technology Innovation Program (CAAS-ASTIP-2015-IAR).

References Cited

Aizen, M. A., L. A. Garibaldi, S. A. Cunningham, and A. M. Klein. 2008. Long-term global trends in crop yield and production reveal no current pollination shortage but increasing pollinator dependency. Curr. Biol. 18: 1572–1575.

Aizen, M. A., and L. D. Harder. 2009a. The global stock of domesticated honey bees is growing slower than agricultural demand for pollination. Curr. Biol. 19: 915–918.

Aizen, M. A., L. A. Garibaldi, S. A. Cunningham, and A. M. Klein. 2009b. How much does agriculture depend on pollinators? Lessons from long-term trends in crop production. Ann. Bot. 103: 1579–1588.

Aizen, M. A., S. Aguiar, J. C. Biesmeijer, L. A. Garibaldi, D. W. Inouye, C. Jung, D. J. Martins, R. Medel, C. L. Morales, H. Ngo, *et al*. 2019. Global agricultural productivity is threatened by increasing pollinator dependence without a parallel increase in crop diversification. Glob. Chang. Biol. 25: 3516–3527.

Alebachew, W. G. 2018. Economic value of pollination service of agricultural crops in Ethiopia: biological pollinators. J. Apic. Sci. 62: 265–273.

An, J., and W. Chen. 2011. Economic value of insect pollination for fruits and vegetables in China. Acta Entomol. Sin. 54: 443–450.

Bahar, N. H. A., M. Lo, M. Sanjaya, J. Van Vianen, P. Alexander, A. Ickowitz, and T. Sunderland. 2020. Meeting the food security challenge for nine billion people in 2050: what impact on forests? Glob. Environ. Chang. 62: 102056.

Bauer, D. M., and I. S. Wing. 2010. Economic consequences of pollinator declines: a synthesis. Agric. Resour. Econ. Rev. 39: 368–383.

Borges, R. C., R. M. Brito, V. L. Imperatriz-Fonseca, and T. C. Giannini. 2020. The value of crop production and pollination services in the Eastern Amazon. Neotrop. Entomol. 49: 545–556.

Breeze, T. D., A. P. Bailey, K. G. Balcombe, and S. G. Potts. 2011. Pollination services in the UK: how important are honeybees? Agric. Ecosyst. Environ. 142: 137–143.

Breeze, T. D., B. E. Vaissière, R. Bommarco, T. Petanidou, N. Seraphides, L. Kozák, J. Scheper, J. C. Biesmeijer, D. Kleijn, S. Gyldenkærne, *et al*. 2014. Agricultural policies exacerbate honeybee pollination service supply-demand mismatches across Europe. PLoS One. 9: e82996.

Chen, M., and X. Y. Zhao. 2019. Impact of floral characters, pollen limitation, and pollinator visitation on pollination success in different populations of *Caragana korshinskii Kom*. Sci. Rep. 9: 9741.

Chen, M., and X. A. Zuo. 2018a. Pollen limitation and resource limitation affect the reproductive success of *Medicago sativa* L. BMC Ecol. 18: 28.

Chen, M., X. Y. Zhao, and X. A. Zuo. 2018b. Pollinator activity and pollination success of *Medicago sativa* L. in a natural and a managed population. Ecol. Evol. 8: 9007–9016.

Chopra, S. S., B. R. Bakshi, and V. Khanna. 2015. Economic dependence of U.S. industrial sectors on animal-mediated pollination service. Environ. Sci. Technol. 49: 14441–14451.

Edgerton, M. D. 2009. Increasing crop productivity to meet global needs for feed, food, and fuel. Plant Physiol. 149: 7–13.

FAOSTAT. 2020. Food and agriculture organization corporate statistical database. Available from http://www.fao.org/faostat/en/#home.

Gallai, N., and B. E. Vaissière. 2009. Guidelines for the economic valuation of pollination services at a national scale. Food and Agriculture Organization, Rome.

Gallai, N., J. M. Salles, J. Settele, and B. E. Vaissière. 2009. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. Ecol. Econ. 68: 810–821.

Gallai, N., J. M. Salles, G. Carré, N. Morison, and B. E. Vaissiérek. 2010. Monetary valuation of the pollination service provided by insects to European agriculture, pp. 190–193. *In* J. Settele, L. Penev, T. Georgiev, R. Grabaum, V. Grobelnik, V. Hammen, S. Klotz, M. Kotarac and I. Kühn (eds.), Atlas of biodiversity risk. Pensoft Publishers, Sofia-Moscow.

Garibaldi, L. A., M. A. Aizen, S. A. Cunningham, and A. M. Klein. 2009. Pollinator dependency effects on global crop yield: looking at the whole spectrum of pollinator dependency. Commun. Integr. Biol. 2: 37–39.

Garibaldi, L. A., M. A. Aizen, A. M. Klein, S. A. Cunningham, and L. D. Harder. 2011. Global growth and stability of agricultural yield decrease with pollinator dependence. Proc. Natl. Acad. Sci. USA. 108: 5909–5914.

Giannini, T. C., G. D. Cordeiro, B. M. Freitas, A. M. Saraiva, and V. L. Imperatriz-Fonseca. 2015. The dependence of crops for pollinators and the economic value of pollination in Brazil. J. Econ. Entomol. 108: 849–857.

Goulson, D., E. Nicholls, C. Botías, and E. L. Rotheray. 2015. Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. Science. 347: 1255957.

Hünicken, P. L., C. L. Morales, N. García, and L. A. Garibaldi. 2020. Insect pollination, more than plant nutrition, determines yield quantity and quality in apple and pear. Neotrop. Entomol. 49: 525–532.

Klein, A. M., B. E. Vaissière, J. H. Cane, I. Steffan-Dewenter, S. A. Cunningham, C. Kremen, and T. Tscharntke. 2007. Importance of pollinators in changing landscapes for world crops. Proc. Biol. Sci. 274: 303–313.

Klein, A. M., S. D. Hendrix, Y. Clough, A. Scofield, and C. Kremen. 2015. Interacting effects of pollination, water and nutrients on fruit tree performance. Plant Biol. (Stuttg). 17: 201–208.

Koh, I., E. V. Lonsdorf, N. M. Williams, C. Brittain, R. Isaacs, J. Gibbs, and T. H. Ricketts. 2016. Modeling the status, trends, and impacts of wild bee abundance in the United States. Proc. Natl. Acad. Sci. USA. 113: 140–145.

Lautenbach, S., R. Seppelt, J. Liebscher, and C. F. Dormann. 2012. Spatial and temporal trends of global pollination benefit. PLoS One. 7: e35954.

Leonhardt, S. D., N. Gallai, L. A. Garibaldi, M. Kuhlmann, and A. M. Klein. 2013. Economic gain, stability of pollination and bee diversity decrease from southern to northern Europe. Basic Appl. Ecol. 14: 461–471.

Lippert, C., A. Feuerbacher, and M. Narjes. 2021. Revisiting the economic valuation of agricultural losses due to large-scale changes in pollinator populations. Ecol. Econ. 180: 106860.

Liu, J., W. Kuang, Z. Zhang, X. Xu, Y. Qin, J. Ning, W. Zhou, S. Zhang, R. Li, C. Yan, *et al*. 2014. Spatiotemporal characteristics, patterns and causes of land use changes in China since the late 1980s. J. Geogr. Sci. 24: 195–210.

Liu, Z., C. Chen, Q. Niu, W. Qi, C. Yuan, S. Su, S. Liu, Y. Zhang, X. Zhang, T. Ji, *et al*. 2016. Survey results of honey bee (*Apis mellifera*) colony losses in China (2010–2013). J. Apic. Res. 55: 29–37.

Marini, L., G. Tamburini, E. Petrucco-Toffolo, S. A. M. Lindström, F. Zanetti, G. Mosca, and R. Bommarco. 2015. Crop management modifies the benefits of insect pollination in oilseed rape. Agric. Ecosyst. Environ. 207: 61–66.

Miao, L., F. Zhu, Z. Sun, J. C. Moore, and X. Cui. 2016. China's land-use changes during the past 300 years: a historical perspective. Int. J. Environ. Res. Public Health. 13: 847.

Molotoks, A., R. Henry, E. Stehfest, J. Doelman, P. Havlik, T. Krisztin, P. Alexander, T. P. Dawson, and P. Smith. 2020. Comparing the impact of future cropland expansion on global biodiversity and carbon storage across models and scenarios. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 375: 20190189.

Naeem, M., M. Liu, J. Huang, G. Ding, G. Potapov, C. Jung, and J. An. 2019. Vulnerability of east Asian bumblebee species to future climate and land cover changes. Agric. Ecosyst. Environ. 277: 11–20.

Oguro, M., H. Taki, A. Konuma, M. Uno, and T. Nakashizuka. 2019. Importance of national or regional specificity in the relationship between pollinator dependence and production stability. Sustain. Sci. 14: 139–146.

Ouyang, F., L. Wang, Z. Yan, X. Men, and F. Ge. 2019. Evaluation of insect pollination and service value in China's agricultural ecosystems. Acta Ecol. Sin. 39: 131–145.

Potts, S. G., J. C. Biesmeijer, C. Kremen, P. Neumann, O. Schweiger, and W. E. Kunin. 2010. Global pollinator declines: trends, impacts and drivers. Trends Ecol. Evol. 25: 345–353.

Potts, S. G., V. Imperatriz-Fonseca, H. T. Ngo, M. A. Aizen, J. C. Biesmeijer, T. D. Breeze, L. V. Dicks, L. A. Garibaldi, R. Hill, J. Settele, *et al*. 2016. Safeguarding pollinators and their values to human well-being. Nature. 540: 220–229.

Rollin, O., and L. A. Garibaldi. 2019. Impacts of honeybee density on crop yield: a meta-analysis. J. Appl. Ecol. 56: 1152–1163.

Sawe, T., K. Eldegard, Ø. Totland, S. Macrice, and A. Nielsen. 2020. Enhancing pollination is more effective than increased conventional agriculture inputs for improving watermelon yields. Ecol. Evol. 10: 5343–5353.

Schmitz, C., H. van Meijl, P. Kyle, G. C. Nelson, S. Fujimori, A. Gurgel, P. Havlik, E. Heyhoe, D. M. D'Croz, A. Popp, ***et al.*** **2014**. Land-use change trajectories up to 2050: insights from a global agro-economic model comparison. Agric. Econ. 45: 69–84.

Soroye, P., T. Newbold, and J. Kerr. 2020. Climate change contributes to widespread declines among bumble bees across continents. Science. 367: 685–688.

Tamburini, G., F. Lami, and L. Marini. 2017. Pollination benefits are maximized at intermediate nutrient levels. Proc. R. Soc. 284: 20170729.

Teichroew, J. L., J. Xu, A. Ahrends, Z. Y. Huang, K. Tan, and Z. Xie. 2017. Is China's unparalleled and understudied bee diversity at risk? Biol. Conserv. 210: 19–28.

Utaipanon, P., T. M. Schaerf, and B. P. Oldroyd. 2019. Assessing the density of honey bee colonies at ecosystem scales. Ecol. Entomol. 44: 291–304.

vanEngelsdorp, D., and M. D. Meixner. 2010. A historical review of managed honey bee populations in Europe and the United States and the factors that may affect them. J. Invertebr. Pathol. 103 Suppl 1: S80–S95.

Yang, G. 2005. Harm of introducing the western honeybee *Apis mellifera* L. to the Chinese honeybee *Apis cerana* F. and its ecological impact. Acta Entomol. Sin. 48: 401–406.