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Pollinator-dependent crops in Brazil yield nearly half of nutrients for humans and livestock feed

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ABSTRACT

Animal pollination services provide multiple benefits to humanity as they contribute to 35% of global food production and directly account for up to 40% of the dietary nutrient supply to humanity worldwide. Population declines of vertebrate and invertebrate pollination vectors may threaten human nutrition and well-being, particularly where agriculture relies heavily on animal pollinators. We examined the relative differences in nutrient concentrations of 45 leading crops produced throughout Brazil, the world's largest tropical agricultural producer and exporter. We also estimated the overall reductions in nutrient yields under different scenarios of pollinator declines, based on annual agricultural production. Of the 45 top-ranking crops, 29 and 16 were classified as pollinator-dependent and non-dependent, respectively. Pollinator-dependent crops provided 47% of all dietary nutrients supplied in 2017, which had significantly higher concentrations of lipids, vitamin B9, and potassium, while pollinator non-dependent crops provided higher carbohydrate content. Under either a best- or worst-case pollinator declines scenario, we estimate overall nutritional losses of 7.9% and 29.5%, respectively. These losses ranged from 4% to 18% for all macronutrients, 6.8%–26.2% for all minerals, and 2.4%–31.5% for all vitamins. We emphasize the need for land-use strategies that sustain, if not increase pollinator abundance and species diversity to ensure agricultural viability and future food security.

1. Introduction

Pollination is critical for maintaining the populations of almost 90% of all flowering plants, including wild and cultivated species considered useful or essential to human diets and livestock feed, food security, and well-being (Ollerton et al., 2011; Oliveira et al., 2020). Cultivated plants represent almost the entire spectrum of plant reproductive systems and include species with bisexual flowers (hermaphrodite species), unisexual flowers (in the same or separate individuals in monoecious and dioecious species, respectively), or a combination of the two (e.g. Miller and Gross 2011). They also exhibit a variety of pollinator resources (Holzschuh et al., 2016; Saunders, 2018) and pollination systems, including pollination by insects, birds, bats, and wind (IPBES, 2016).

Pollinators are linked to human well-being, directly contributing to food production medicines, biofuels, fibers, construction materials, musical instruments, literature, religion and technology (IPBES, 2016). Animal pollination contributes to 35% of global food production and increases the yield and/or quality of ~75% of globally important crop types, including most fruits, seeds and nuts, and several commercially valuable commodity crops such as orange, coffee and cocoa (Klein et al., 2007, IPBES, 2016). Estimates of the economic value from animal pollination services to agriculture, adjusted for inflation in 2020, ranges from US$195 billion to US$387 billion (Porto et al., 2020). The nutrient contribution from animal-pollinated crops worldwide and its impact on human diets and food security is another key, but poorly understood benefit from animal pollination. It is estimated that pollinators directly account for up to 40% of the dietary nutrient supply to humanity (Eilers et al., 2011). Edible plant parts that depend partially or fully on biotic pollination contain a large portion of dietary lipids, minerals and vitamins (Chaplin-Kramer et al., 2014; Eilers et al., 2011; Ghosh and Jung

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2018). For example, pollinator-dependent crops source more than 70% of all the vitamin A supply from all cultivated food plants (Eilers et al., 2011).

Globally, agricultural diversity of pollinator-dependent crops has increased in recent years, mostly from the expansion of oilseed, nut, and fruit crops, coupled with a far lower expansion rate for crops that do not rely on animal pollinators, such as cereals (Aizen et al., 2019). Even countries that recently experienced rapid agricultural growth over vast areas of one or a few pollinator-dependent crops, such as Brazil, Argentina, and the USA, also rely heavily on animal pollination, mostly due to cropland expansion of the pollinator-dependent soybean (Fearnside, 2001). For example, Brazilian agriculture is highly pollinator-dependent (Giannini et al., 2015) for both high biodiversity of crop types and expansion of pollinator-dependent cultivars (MAPA, 2020). Like other tropical countries, Brazilian food production is also sensitive to multiple environmental stressors. Recent estimates indicate that a pollinator decline in Brazil could reduce food production derived from pollinator-dependent crops by up to 41% (Novais et al., 2016), with negative consequences to global food consumption, since Brazilian agricultural exports over the last 20 years reached over 1.1 billion tons, representing 12.6% of all agricultural exports worldwide (FAO 2021). Therefore, we use agricultural production in Brazil, the world's largest tropical country, to illustrate the consequences of ongoing loss of tropical pollinators on nutrient supply.

We investigate how nutrient concentrations are distributed across pollinator-dependent and non-dependent crops. We hypothesized that pollinator-dependent crops contain higher concentrations of key nutrients compared to those of non-dependent food crops, thereby leading to very different contributions in terms of nutrient supply between these two major functional groups of plant cultivars. We further propose two plausible estimates of reduction in food plant nutrients that are critical to human diets as a consequence of pollinator decline. Potential losses in ecosystem services to agriculture are then discussed in light of food security and the global pollinator crisis.

2. Materials and methods

2.1. Data

We first selected the 45 top-ranking agricultural crops in Brazil in terms of production volume in 2017 (IBGE, 2020). This recent annual harvest (2017) is representative of the country's typical average agricultural production and relative contribution of different crops to overall nutrient supply. These most important 45 crops comprise species that are essential nutritional sources in the human diet. The list includes Brazilian staple foods (such as rice, beans, oranges), crops used in livestock feed that results in other staple foods (e.g. eggs, meat and dairy products), and export commodities of nutritional importance worldwide.

We compiled data on the 20 main nutritional components of raw consumed parts from those 45 crops on the basis of the most widely accepted database on food nutrient composition (TBCA - Tabela Brasileira de Composição de Alimentos - 2020). When data were unavailable in TBCA (2020), we searched for missing data in an analogous database from USDA – United States Department of Agriculture (2020). Crop nutritional concentrations are expressed in percentage mass (g per 100 g) for macronutrients and 10 ppm (mg per 100 g) for minerals and vitamins. To streamline comparisons among all nutrients combined, minerals and vitamins were converted into g/100 g. We also classified crops according to (i) their life cycle (e.g. annual or perennial), (ii) plant parts consumed (fruits and vegetables, legume, roots and tubers, cereals and oilseeds), (iii) their breeding system, and (iv) whether they were either self-compatible or self-incompatible.

Considering that most food crops rely on biotic pollination to a varying extent, we applied the currently most widely accepted standard of relative dependence on pollinators in world agriculture (Klein et al., 2007; Roubik 2018). Based on the degree to which crop production and quality in fruits and seeds are associated with animal pollination, crop types examined here were assigned to one of five categories of dependence rates (hereafter, DR) adapted from Klein et al., (2007) and Gallai and Vaissière (2009): (1) essential (DR = 0.95); production is reduced by 90% or more when pollination services are discontinued; (2) great (DR = 0.65): reduction of 40%–90%; (3) modest (DR = 0.25): reduction of 10%–40%; (4) little (DR = 0.05): reduction of 0%–10%; (5) no differences in yields (DR = 0) under conditions with and without animal-mediated pollination. We then aggregated the selected crops into two classes of dependence on biotic pollination. In this study, pollinator-dependent crops (hereafter, PD) are represented by species included in above categories 1, 2, 3 and 4, while non-dependent (hereafter, ND) crops that do not depend on biotic pollination represent cultivars included in category 5 (Table 1). Pollinators can also increase seed production of crops that reproduce vegetatively in the field (e.g. onion) and consequently influence the downstream production chain. To err on the conservative side, however, our definition of pollinator dependence in this study is restricted to crops for which pollinators directly affect the production of the consumed plant parts.

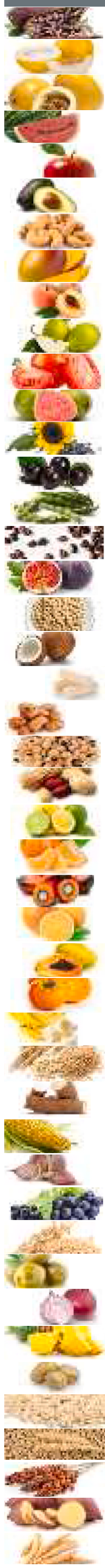
Based on this classification of degree of dependence on biotic pollination (adapted from Klein et al., 2007 and Gallai and Vaissière 2009) and amounts of each nutrient produced from total crop yields throughout Brazil, we predicted losses in nutrient production under both a best-case and worst-case scenarios of lost pollinator-mediated ecosystem services. The nation-wide population status of pollinators could range across these two scenarios depending on, for example, the policy and practice of pesticide use, natural habitat loss trajectories, and physical distance to remnants of native habitat within agricultural landscapes. Therefore, in the worst-case estimate, we project a greater decrease in pollination services and consequently high yield losses for each crop, while in the best-case estimate decreases in pollination services are less severe, leading to moderate yield reductions. In both cases, our predictions are weighted by the degree of dependence on biotic pollination of each crop. For example, "little" dependence refers to a decrease in production from 0% to 10% in the absence of animal pollination, so under the best-case scenario, these crops would be unaffected, whereas we expect a decrease of 0.09 in crop productivity under the worst-case estimate. Nutrient productivity of crops assigned to a "modest" dependence under the best-case estimate is assumed to decline by 0.10–0.39 under the worst-case scenario. Likewise, crops that are "greatly" dependent are assumed to decline by 0.40–0.89 under either the best-case or worst-case scenario, respectively, and those for which animal pollinator are "essential" would decline by 0.9–1.0, under the best-case and worst-case scenarios, respectively. Yields of non-dependent crops are not expected to decline under either scenarios.

2.2. Statistical analysis

We calculated the overall amounts of crop nutrients produced throughout Brazil in the year 2017 for each cultivar type, and these data were subsequently $\log_{10}$-transformed. To test for differences in nutrient concentrations between pollinator-dependent and pollinator-non-dependent crops, we used bootstrapped *t*-tests. We used one-way ANOVAs, followed by a post-hoc Tukey test, to compare nutrient concentrations among crops assigned to all five classes of pollinator dependence (non-dependent, little, modest, great and essential). Statistical differences for bootstrapped *t*-tests and ANOVAs were assessed at $P < 0.05$.

To better understand the dissimilarities between the two crop functional groups, we also used Principal Component Analysis (PCA) to investigate differences in mean nutrient concentrations across all cultivar types, based on the 'FactoMineR' package in R (Lê et al., 2008). All statistical procedures were conducted within the R platform (R Development Core Team, 2014).

Table 1
List of the 45 main crops produced in Brazil, including pollinator-dependent crops (PD) and pollinator non-dependent crops (ND). Numbers in the "pollinator dependence" column indicate the reference used to classify the degree of pollinator dependence for each crop. Sources of information on the degree of pollinator dependence are Klein et al. (2007), many of which were also reiterated in Roubik (2018)[1]; Giannini et al. (2015)[2]; Campbell et al. (2018)[3] and Dorneles et al. (2013)[4].



Crop popular name	Latin name	Dependence degree	Staple Food	Livestock feed	Commodity
Cacao	*Theobroma cacao* (L.)	Essential[1]			
Melon	*Cucumis melo* (L.)	Essential[1]			
Passion fruit	*Passiflora edulis* (Sims)	Essential[1]	x		
Watermelon	*Citrullus lanatus* (Citrullus)	Essential[1]	x		
Apple	*Pyrus malus* (L.)	Great[1]	x	x	
Avocado	*Persea americana* (Mill.)	Great[1]			
Cashew nut	*Anacardium occidentale* (L.)	Great[1]	x		
Mango	*Mangifera indica* (L.)	Great[1]	x		
Peach	*Prunus persica* ((L.) Stokes)	Great[1]			
Pear	*Pyrus communis* (L.)	Great[1]			
Tomato	*Lycopersicon esculentum* (Mill.)	Great[1]	x		x
Guava	*Psidium guajava* (L.)	Great[2]	x		
Sunflower	*Helianthus annuus* (L.)	Great[2]	x		
Assai	*Euterpe oleracea* (Mart.)	Modest[1]	x		
Broad bean	*Vicia faba* (L.)	Modest[1]	x	x	
Coffee	*Coffea arabica* (L.)	Modest[1]	x		x
Fig	*Ficus carica* (L.)	Modest[1]			
Soybean	*Glycine max* ((L.) Merr.)	Modest[1]	x		x
Coconut	*Cocos nucifera* (L.)	Modest[1]	x		
Palm tree	*Euterpe edulis* Mart.	Modest[1]			
Bean	*Phaseolus vulgaris* L.	Modest[3]	x		x
Cow peas	*Vigna unguiculata* ((L.) Walp.)	Modest[4]		x	
Groundnut	*Arachis hypogaea* (L.)	Little[1]	x		
Lemon	*Citrus latifolia* Tanaka	Little[1]	x		
Mandarin	*Citrus reticulata* (Blanco)	Little[1]			
Oil palm	*Elaeis guineensis* (L.)	Little[1]	x		
Orange	*Citrus aurantium* (L.)	Little[1]	x		x
Papaya	*Carica papaya* (L.)	Little[1]	x		
Persimmon	*Diospyros kaki* L.f.	Little[1]			
Banana	*Musa paradisiaca* (L.)	Little[1]	x	x	x
Barley	*Hordeum vulgare* (L.)	Little[1]		x	
Cassava	*Manihot esculenta* (Crantz)	ND [1]	x		x
Corn	*Zea mays* (L.)	ND [1]			x
Garlic	*Allium sativum* (L.)	ND [1]	x		
Grape	*Vitis* spp.	ND [1]	x		
Oat	*Avena sativa* (L.)	ND [1]			
Olive	*Olea europaea* (L.)	ND [1]	x		
Onion	*Allium* spp.	ND [1]	x	x	
Pineapple	*Ananas comosus*((L.) Merr.)	ND [1]	x		
Potato	*Solanum tuberosum* (L.)	ND [1]	x		x
Rice	*Oryza* spp.	ND [1]	x		x
Rye	*Secale cereal* (L.)	ND [1]		x	
Sorghum	*Sorghum bicolor* (L.) Moench	ND [1]		x	
Sweet potato	*Ipomoea batatas* ((L.) Lam.)	ND [1]	x		
Wheat	*Triticum* spp.	ND [1]		x	x

3. Results

The aggregate quantitative production of all 45 crops in 2017 amounted to approximately 309 million tons, approximately half of which depended on natural pollinators to some degree (Fig. 1). Concerning the degree of dependence on biotic pollination, 29 crops were classified as pollinator-dependent (PD), whereas 16 were pollinator non-dependent (ND) crops (Table 1). Among all PD crops, nine depended on pollinators to only a 'little' extent (*sensu* Klein et al., 2007), seven were modestly dependent, nine were greatly dependent and four were entirely dependent (Table 1). Given the range of crop types examined here, pollinator-dependent crops included primarily perennial fruit and vegetable cultivars, oilseeds, nuts, and legumes, whereas non-dependent crops were mostly comprised of vegetatively propagated annual roots and tubers and self- or wind-pollinated cereals [predominantly in the grass (Poaceae) family]. Non-dependent crops also included four perennials: two self-pollinated (olive trees and grapevines) and two fruit crops exhibiting parthenocarpic fruit development (banana and pineapple).

Considering nutrient concentrations per 100 g of edible food parts, all pollinator-dependent crops combined provided 60.8% of all macronutrients, 64.9% of all minerals, and 82% of all vitamins across all 45 crops in the 2017 harvest. In terms of overall amounts (in tons) of nutrients produced throughout Brazil in 2017, pollinator non-dependent crops contributed the most to macronutrient yields (52.6%), while pollinator-dependent crops were more important in their dietary contribution in terms of minerals (67.5%) and vitamins (74.0%).

In terms of concentrations per 100 g, total lipids ($t = -2.094$, $P = 0.004$) and vitamin B9 (folate) ($t = -2.274$, $P = 0.03$), were mostly concentrated in pollinator-dependent rather than pollinator-non-dependent crops, whereas overall carbohydrate production ($t = 2.882$, $P = 0.009$) was dominated by crops that do not rely on animal pollinators (Fig. 2, Table 2). Comparing the concentration of each nutrient examined here among all five levels of pollinator dependence, crops associated with 'great', 'essential' and 'modest' dependence on biotic pollination exhibited higher concentrations of Potassium ($F_{4,40} = 3.405$, $P = 0.01$) and vitamin B9 (folate) ($F_{4,40} = 4.476$, $P = 0.004$), compared to crops that do not depend on biotic pollination (Supplementary Material: Fig. S1, Table S1).

The PCA analysis shows partial compositional dissimilarity in nutrient concentrations between pollinator-dependent and pollinator-non-dependent crops. The first two principal components explained 58.9% (PC_1: 43.7% and PC_2: 15.2%) of the overall variability across all crop types. Pollinator-dependent fruit crops (e.g., melon, apple, watermelon and lemon) were similar in their high concentrations of vitamin C, vitamin A and vitamin E (Supplementary Material, Fig. S2.).

The best-case and worst-case estimates of a complete loss in pollinator services in Brazil would detrimentally impact the overall amount of nutrients produced across all crops. The highest potential decline was predicted for lipids (8.2%–31% for the best-case and worst-case estimates, respectively), calcium (9.6%–37.6%), iron (8%–31%), vitamin C (8.4%–31.5%), vitamin B9 (folate) (8%–31%), and vitamin A (7%–21%) (Fig. 3). In general, production across the entire spectrum of vitamins would be most heavily affected, with expected losses between 7.9% and 29.5%. Overall losses in quantitative production would range from 4% to 18% for all macronutrients and 6.8%–26.2% for all minerals. To put this in perspective, because national-scale food consumption patterns are globalized and heavily trade-dependent, a 31.5% reduction in vitamin C production, would be equivalent to depriving ~405 million adult men and women (nearly two-fold the Brazilian population) of their daily recommended dietary allowance (mean RDA = 82.5 mg) for an entire year (see equivalent estimates for all other nutrients in Supplementary Material, Table S2).

4. Discussion

Our results indicate that pollinator-dependent crops provide a substantial fraction of the essential nutrient contribution to human diets, including lipids, vitamin A, vitamin B9 (folate), vitamin C, vitamin E, potassium and calcium. Also, there was a substantial reduction in nutrient production considering both the best-case and the worst-case estimates of pollinator decline as a consequence of the lower productivity of pollinator-dependent crops, which includes important cash crops (e.g. orange, coffee, palm oil), staple food crops (e.g. beans, coconut), and protein crops used as livestock feed (e.g. soybean).

Our findings reinforce the growing realization that biodiversity and biotic pollination are essential to food security and nutrition from local to global scales (Eilers et al., 2011). For example, pollinator-dependent crops represent over 50% of all cropland products traded at international markets with pollinator-dependent crops produced in Brazil reaching consumers of over 160 countries (Silva et al., 2021). For *essentially* pollinator-dependent crops, such as cocoa, passion fruit, melon and watermelon, the lack of biotic pollination can result in wholesale crop failure, which translates into declines in all plant nutrients produced by those crops. For other crops, reduced nutrient supply in the absence of pollinators may vary according to the mean nutrient concentration of each crop, the degree of pollinator dependence on cultivar reproduction, and total crop yields. Potential quantitative nutrient losses due to pollinator failure would be particularly significant in pollinated crops yielding high volumes. For example, the vitamin C content is high in coffee (moderate dependence) and orange (low dependence), clearly influencing their nutrient supply, but a reduction in soybean (moderate dependence) production would lead to a relatively higher reduction in vitamin C yields due to the vast production volume of Brazilian soybean.

Our results highlight that the importance of pollinator-dependent crops to food security goes far beyond the direct consumption of fruits and vegetables. These crops are also consumed in many other ways that, combined with other crops that do not depend on pollinators, ensure human well-being, and may also impact downstream nutrient supply from animal sources (Bauer and Wing 2016). Soybean, for example, represents 45% of the total annual biomass production across all 45 cultivars examined in this study. Essential nutrients in soybean are important not only in terms of direct consumption (e.g. soybean oil, milk, tofu, soy meat derivatives, soy sauce) but also for livestock feed (FAO 2004), thereby potentially reducing the production of animal protein, such as meat, eggs and dairy, down the supply chain. These would be additional impacts of the pollinator crisis on essential nutrients in the human diet. Yet this study only accounted for gross cropland production, rather than all downstream derivatives in the food chain.

Decreases in PD crops due to the pollinator crisis potentially lead to marked swings in the supply chain and demand for pollinator independent crops, with macroeconomic impacts at regional to global scales (Bauer and Wing 2016). In addition, pollination shortages will intensify the demand for further agricultural cropland. The cropland area of crops that are independent to little-dependent on pollination services is already expanding faster than highly pollinator-dependent crops (Aizen et al., 2009). Furthermore, the growing global demand for food and higher market value of the PD crops and products compared to ND crops (Lautenbach et al., 2012) would exert great pressure on the supply of agricultural lands, contributing significantly to further natural habitat loss and global environmental change.

In addition, to ensuring or increasing sexual reproduction of pollinator-dependent crops in terms of the number, size, or weight of fruits and seeds, and therefore the total nutrient output of these crops, pollinators also influence the quality of nutritional content of these reproductive plant parts (Ellis et al., 2015). For example, bee pollination enhances the amount of vitamin E in sunflower seeds by 45% (Silva et al., 2018), while supplementary hand-pollination in Braeburn apples (*Malus domestica* Borkh) at the onset of the flowering period increases calcium concentrations (Volz et al., 1996). Conversely, biotic pollination reduces the sugar-acid-ratio of Strawberry fruit (Klatt et al., 2014). Pollination can also have unexpected effects on the quality of almond by influencing nutrient content ratios (e.g. lipids and vitamin E), in addition to reducing costly irrigation and fertilizer input (Brittain et al., 2014). However, crop phytochemistry in terms of how nutrient concentrations in fruits and seeds respond to the effectiveness and diversity of pollinator agents remains poorly investigated. Non-dependent crops examined here are dominated by the Poaceae (grass) family, while the families Arecaceae, Fabaceae, and Rutaceae are widely represented in the pollinator-dependent group. We emphasize that phylogenetic relationship among domesticated grass species may be related to the clustered pattern observed in this study. Indeed, closely related species tend to exhibit similar physiological and stoichiometric strategies related to nutrient production and composition (e.g. Jordano 1995). Plant phylogeny may therefore determine similar nutrient responses in edible crops belonging to either one of these two groups.

Nevertheless, the evolutionary role of mutualisms in the domestication of cultivated plants also helps us understand the diversity and nutritional distinctions between these functional groups of crops. In fruit dispersal coevolution, endozoochoric plants, such as tomatoes, mangos, and apples, invest heavily in large fleshy fruits, high pulp-to-seed ratios, pericarp tissue, and high sugar concentrations, which made the wild precursors of these species nutritionally attractive to humans (Spengler 2020). Conversely, seeds of desiccated or sclerocarpic fruits that are often emancipated from animal vectors (e.g. via ballistic seed dispersal), such as wheat, barley, rice, and millet, have invested in toughening of the rachises, indehiscent pods, loss of seed dormancy, and thinning of the seed coat (Spengler 2020). Considering embryo fertilization, selective domestication pressure strongly acts upon crop populations leading to marked morphological and genetic divergences from their wild progenitors (Miller and Gross 2011). Furthermore, some species have entirely bypassed pollinator dependence and shifted their reproductive systems from unisexual to bisexual flowers, by becoming self-compatible (e.g. grapevines), and through a selective transition from sexual to parthenocarpic reproduction from the wild ancestors to their modern cultivars (e.g. banana) (Miller and Gross, 2011).

Causes of ongoing pollinator declines worldwide include the intensification of agriculture accompanied by loss of natural habitats and foraging and nesting resources, large-scale use of agrochemicals, invasive species, and spread of pathogens (IPBES, 2016). Additionally, drastic environmental drift and disruption of co-occurrence between crops and their pollinators are expected to occur due to climate change over the next 50 years (Giannini et al., 2017). These pressures will further reduce the richness and abundance of service-providing organisms, with negative consequences for crop yields (Dainese et al., 2019; IPBES, 2016). Moreover, the expansion of pollinator-dependent croplands and a modest increase in global agricultural diversity (Aizen et al., 2019) are expected to vastly amplify global demand for pollination services. As a consequence, agricultural economies, food security and public health may be compromised, especially in low-income countries where farming pollinator-dependent crops is prevalent (Chaplin-Kramer et al., 2014; Ellis et al., 2015; Smith et al., 2015).

The detrimental human health consequences of pollinator declines will be most severe in developing countries where the rural poor are often reliant on insect-pollinated crops (Eilers et al., 2011). Nutrient intake is already insufficient in many low-income countries, but local nutrient shortages would be further aggravated in a pollination crisis (Ellis et al., 2015), depriving millions of people of the recommended daily dietary allowance. For example, 2%–56% and up to 23% of all children in low-income countries would be at risk of vitamin A and folate deficiencies, respectively (Ellis et al., 2015). Public health adaptation in wealthy developed countries may be more resilient, but the impact of pollinator losses can still potentially erode human dietary

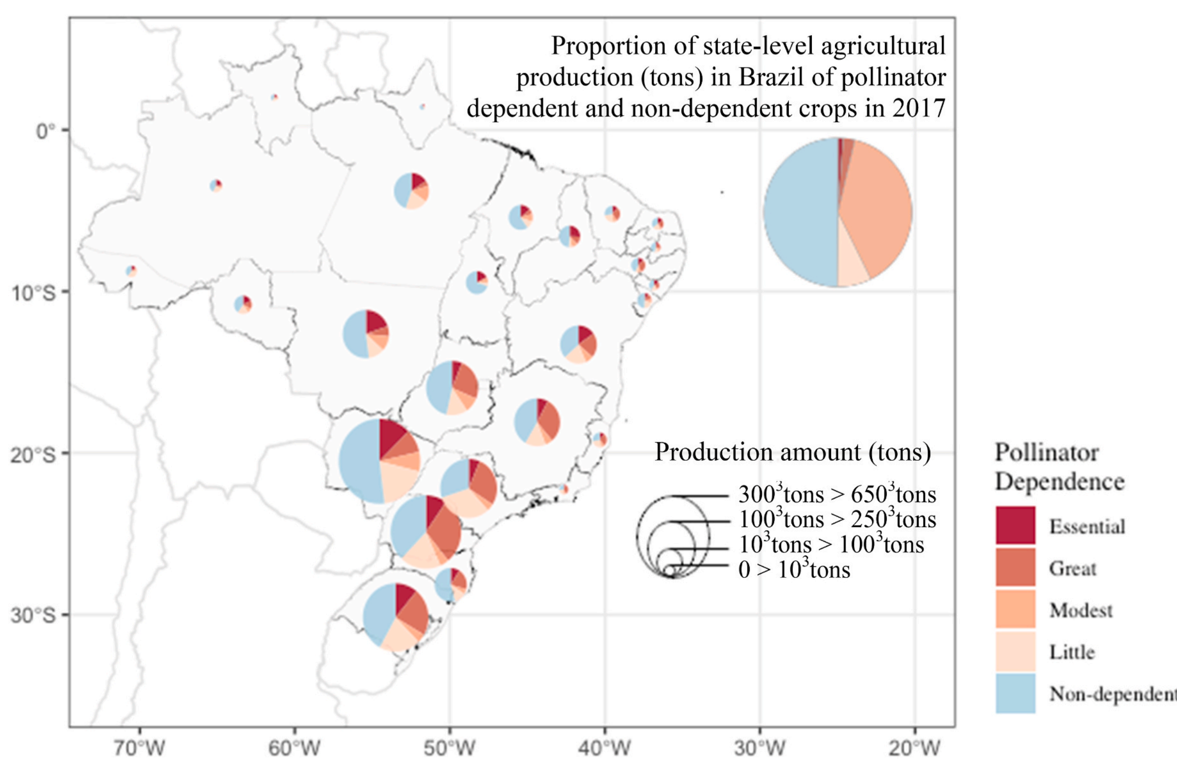


Fig. 1. The state-level proportion of total production amounts (top-right) and production yields (tons per hectare) of 45 leading crops throughout Brazil in 2017. Crops were categorized by pollinator dependence. Pie sizes represent production amounts (in tons) of the 45 crops; slice sizes represent average yields broken-down by the degree of pollinator dependence. The pie chart on top-right represents the proportion of pollinator dependence on the total production amount in 2017. Pie charts are color-coded according to the degree of pollinator dependence. Source: IBGE, 2020. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

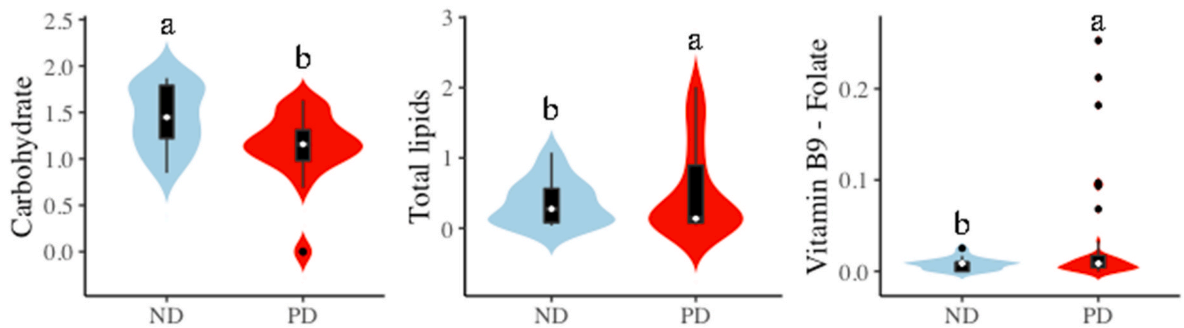


Fig. 2. Box and violin plots showing average nutrient concentrations in 45 crops classified as either pollinator non-dependent (ND, blue) or pollinator-dependent (PD, red). Median values are represented by white dots and outliers are black dots. Nutrients showing statistical differences between the two groups: carbohydrates ($P = 0.009$), lipids ($P = 0.004$) and vitamin B9 - folate ($P = 0.03$). Crops were grouped and color-coded following their category of pollinator dependence (*sensu* Klein et al., 2007). Distinct letters in each violin plot indicate statistically significant differences at $P < 0.05$. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Comparisons of nutrient components between pollinator-dependent (PD) and pollinator non-dependent (ND) crops. Nutritional components, means, standard deviation and bootstrap *t*-test results of nutrient values (expressed as 100 g of consumed plant parts). Statistical significance at $P < 0.05$ for all comparisons is indicated in bold.

Nutritional component	Relative concentration (amount of nutrient/100 g of crop)					
	Total		Mean ± SD		Statistical test	
	ND	PD	ND	PD	*t*	*P*
Macronutrients						
Protein	90.3	161.2	5.65 ± 5.45	5.56 ± 8.61	0.04	0.963
Carbohydrate	560.3	475.9	35.02 ± 24.33[a]	16.41 ± 11.64[b]	**2.882**	**0.009**
Fiber	79.59	177.2	4.97 ± 4.73	6.11 ± 7.86	−0.606	0.549
Total lipids	34.36	372.9	2.15 ± 2.97 [b]	12.86 ± 27.25[a]	**−2.094**	**0.004**
Minerals						
Calcium	584.4	1044.1	36.53 ± 46.1	36 ± 46.93	0.036	0.948
Iron	29.54	48.55	1.85 ± 1.83	1.67 ± 2.48	0.265	0.789
Magnesium	1035	1474.2	64.67 ± 59.19	50.84 ± 74.46	0.683	0.505
Phosphorus	2700	3122.3	168.73 ± 177.24	107.67 ± 163.46	1.136	0.239
Potassium	4933	12838	308.31 ± 146.41	442.68 ± 502.61	−1.340	0.133
Sodium	805.5	208.15	50.34 ± 182.64	7.18 ± 8.22	0.944	0.156
Zinc	20.44	28.03	1.28 ± 1.43	0.967 ± 1.51	0.682	0.473
Vitamins						
Vitamin C	151.7	807.05	9.48 ± 13.52	27.83 ± 52.02	−1.792	0.082
Vitamin B1, Thiamin	3.42	3.47	0.21 ± 0.21	0.12 ± 0.18	1.526	0.101
Vitamin B2, Riboflavin	1.34	1.62	0.08 ± 0.08	0.056 ± 0.06	1.184	0.175
Vitamin B3, Niacin	30.44	42.55	1.9 ± 2.34	1.47 ± 3.06	0.533	0.633
Vitamin B6	4.4	4.24	0.28 ± 0.3	0.15 ± 0.2	1.543	0.068
Vitamin B9, Folate	0.3	3.03	0.02 ± 0.02[b]	0.1 ± 0.2[a]	**−2.274**	**0.030**
Vitamin A	0.27	5.94	0.02 ± 0.05	0.2 ± 0.94	−1.078	0.145
Vitamin E	3.71	79.73	0.23 ± 0.42	2.75 ± 8.34	−1.621	0.116
Vitamin K	0.32	0.2	0.02 ± 0.07	0.007 ± 0.01	0.694	0.401

quality and increase reliance on synthetic vitamin supplements and other micronutrients (Vanbergen et al., 2014).

Micronutrient deficiency, especially vitamins, can increase the incidence of a variety of chronic and infectious diseases (Ellis et al., 2015). A recent estimate suggests that a 50% loss of pollination services would add 700,000 deaths each year and subtract 13.2 million disability-adjusted-life-years, while the complete defaunation of pollinators could increase mortality by 1.42 million and reduce 27 million disability-adjusted-life-years worldwide (Smith et al., 2015). Nutrient deficiencies and hunger-prevention are even more alarming emergencies in the post-COVID-19 period (HLPE 2020). Although the full-scale, long-term impact of the coronavirus pandemic on food security is yet to be properly assessed, evidence shows that in countries already hit by intermediate to acute hunger, people are increasingly struggling to access food supplies as incomes fall and instability in the food chain increases (FAO 2020).

Because pollinator declines are complex and have multiple interacting cause-effect pathways, they cannot be solved by tackling a single isolated driver (Van der Sluijs and Vaage, 2016). Thus, the IPBES (2016) suggests an integrated approach to promote more sustainable agriculture, such as ecological intensification, strengthening diverse farming systems and investments in ecological infrastructure. For example, an integrated farming system through multiple crops that are intercropped by several plant species that combine forest crop systems and livestock, can promote higher revenues, minimize the risk of monoculture failure, and make the best of local resources as efficiently as possible to ensure a more sustainable environmentally-friendly farming system (Ansar and Fathurrahman 2018). Several other measures can be applied to ensure the viability and sustainable intensification cropland production. Pollinator-friendly practices that include the introduction of beehives, especially of native bees; reduction in pesticide use; introduction of hedges and flower strips; and the retention or restoration of natural set-asides adjacent to crop fields (Hipólito et al., 2016, Garrat el at. 2017). Those key mitigation strategies can counteract pollinator declines, establishing a balance that ensures food security and ecosystem integrity for the future (IPBES, 2016). In addition to benefiting pollinator-dependent crops, these measures can also increase non-pollinator crop yields through, among other co-benefits, the introduction of natural enemies (Pywell et al., 2015).

5. Conclusions

Our analysis provides a resounding confirmation of the large-scale effects of pollination services on nutrient supplies sourced from tropical croplands. Non-dependent crops are mainly wind-pollinated annuals, grow by vegetative propagation and yield much higher production volumes, while pollinator-dependent crops are mostly

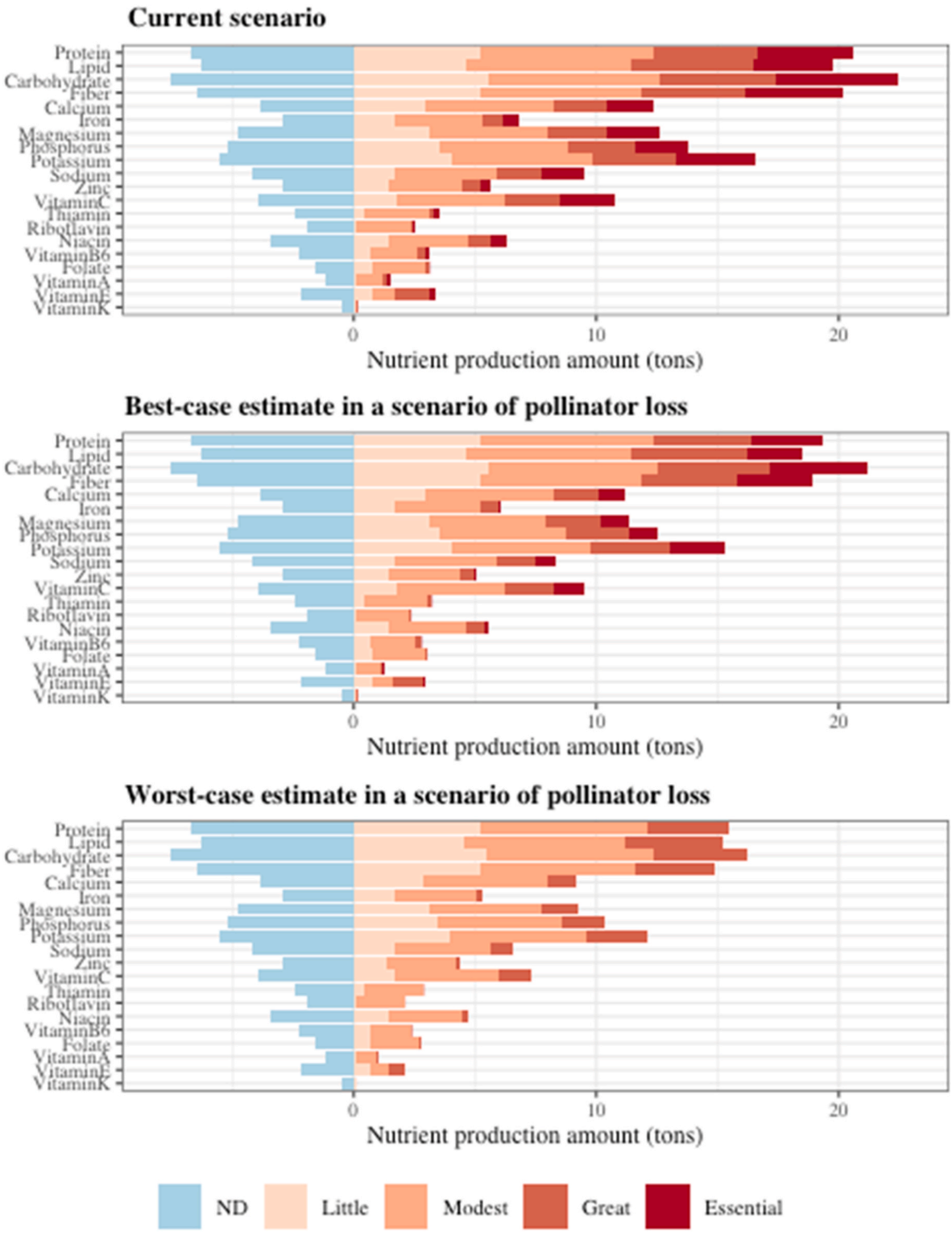


Fig. 3. Worst-case and best-case estimates based on a scenario of pollinator loss in terms of nutrient production based on 45 leading crops cultivated in Brazil in 2017 (current scenario). The degree of pollinator dependence is represented as essential, great, modest, little, and non-dependent (ND) (*sensu* Klein et al., 2007 and Gallai and Vaissière 2009). Production of pollinator non-dependent crops and pollinator-dependent crops is shown as horizontal bars on the left and right, respectively. Current status of cropland production in Brazil (top panel). Best-case estimate (middle panel) indicates moderate impacts on nutrient production. Worst-case estimate (bottom panel) indicates further declines in nutrient production and a complete collapse in the productivity of 'essential' pollinator-dependent crops. Source: IBGE, 2020.

perennial, bear abundant fleshy fruits and on average yield a lower production volume. Widespread pollinator declines could lead to losses in nutrient supply because crops that benefit from pollinators contribute with a large fraction of plant macro and micronutrients, and on average yield higher relative concentrations and overall amounts of lipids, vitamins A, folate, vitamin C, vitamin E, calcium, and potassium. The full impact of pollinator declines could be even harsher depending on how much and which crops are grown locally or regionally. For instance, the reduction of vitamin C and calcium, under the hypothetical scenarios of pollinator loss, is more severe than other nutrients due to the vast cropland area and productivity of soybean, which contains a high concentration of these nutrients. Therefore, potential collapses in nutrient supplies from pollinator-dependent crops emphasize the need for management strategies that maximize agricultural diversification through the implementation of more pollinator-friendly landscape design and practices that maintain and increase pollinator diversity and richness to ensure future agricultural viability and food security.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2021.100587.

References

Aizen, M.A., Garibaldi, L.A., Cunningham, S.A., Klein, A.M., 2009. How much does agriculture depend on pollinators ? Lessons from long-term trends in crop production. Ann. Bot. 103, 1579–1588. https://doi.org/10.1093/aob/mcp076.

Aizen, M.A., Aguiar, S., Biesmeijer, J.C., Garibaldi, L.A., Inouye, D.W., Jung, C., Martins, D.J., Medel, R., Morales, C.L., Ngo, H., Pauw, A., Paxton, R.J., Sáez, A., Seymour, C.L., 2019. Global agricultural productivity is threatened by increasing pollinator dependence without a parallel increase in crop diversification. Global Change Biol. 25, 3516–3527. https://doi.org/10.1111/gcb.14736.

Ansar, M., Fathurrahman, 2018. Sustainable integrated farming system: a solution for national food security and sovereignty. IOP Conf. Ser. Earth Environ. Sci. 157 https://doi.org/10.1088/1755-1315/157/1/012061.

Bauer, D.M., Wing, I.S., 2016. The macroeconomic cost of catastrophic pollinator declines. Ecol. Econ. 126, 1–13. https://doi.org/10.1016/j.ecolecon.2016.01.011.

Brittain, C., Kremen, C., Garber, A., Klein, A., 2014. Pollination and plant resources change the nutritional quality of almonds for human health. PLoS One 9. https://doi.org/10.1371/journal.pone.0090082.

Campbell, A.J., Carvalheiro, L.G., Maués, M.M., Jaffé, R., Giannini, T.C., Freitas, M.A.B., Coelho, B.W.T., Menezes, C., 2018. Anthropogenic disturbance of tropical forests threatens pollination services to açaí palm in the Amazon river delta. J. Appl. Ecol. 55 (4), 1725–1736. https://doi.org/10.1111/1365-2664.13086.

Chaplin-Kramer, R., Dombeck, E., Gerber, J., Knuth, K.A., Mueller, N.D., Mueller, M., Ziv, G., Klein, A.-M., 2014. Global malnutrition overlaps with pollinator-dependent micronutrient production. Proc. R. Soc. B-Biol. Sci. 281 https://doi.org/10.1098/rspb.2014.1799.

Dainese, M., Martin, E.A., Aizen, M.A., Albrecht, M., Bartomeus, I., Bommarco, R., Carvalheiro, L.G., Chaplin-Kramer, R., Gagic, V., Garibaldi, L.A., Ghazoul, J., Grab, H., Jonsson, M., Karp, D.S., Letourneau, D.K., Marini, L., Poveda, K., Rader, R., Smith, H.G., Takada, M.B., Taki, H., Tamburini, G., Tschumi, M., 2019. A Global Synthesis Reveals Biodiversity-Mediated Benefits for Crop Production 1–14.

Dorneles, L.L., Zillikens, A., Steiner, J., Padilha, M.T.S., 2013. Biologia da polinização de Euterpe edulis Martius (Arecaceae) e associação com abelhas sociais (Apidae: Apini) em sistema agroflorestal na Ilha de Santa Catarina. Iheringia, Série Botânica 68, 47–57. https://isb.emnuvens.com.br/iheringia/article/view/38.

Eilers, E.J., Kremen, C., Greenleaf, S.S., Garber, A.K., Klein, A.-M., 2011. Contribution of pollinator-mediated crops to nutrients in the human food supply. PLoS One 6. https://doi.org/10.1371/journal.pone.0021363.

Ellis, A.M., Myers, S.S., Ricketts, T.H., 2015. Do pollinators contribute to nutritional health? PLoS One. https://doi.org/10.1371/journal.pone.0114805.

FAO, 2004. FAO Commodities and Trade Division, Basic Foodstuffs Service. The Role of Soybean in Fighting World Hunger. http://www.fao.org/3/a-bs958e.pdf.

FAO, 2020. COVID-19 and the Risk to Food Supply Chains: How to Respond. COVID-19 Risk to Food Supply Chain. How to Respond 1–7. https://doi.org/10.4060/ca8388en.

FAO, 2021. Food and Agriculture Organization of the United Nations FAOSTAT - Data (FAO). http://www.fao.org/faostat/en/#data.

Fearnside, P.M., 2001. Soybean cultivation as a threat to the environment in Brazil. Environ. Conserv. 28 (1), 23–38. https://doi.org/10.1017/S0376892901000030.

Gallai, N., Vaissière, B.E., 2009. Guidelines for the Economic Valuation of Pollination Services. FAO. https://doi.org/10.1086/204094.

Garratt, M.P.D., Senapathi, D., Coston, D.J., Mortimer, S.R., Potts, S.G., 2017. The benefits of hedgerows for pollinators and natural enemies depends on hedge quality and landscape context. Agric. Ecosyst. Environ. 247, 363–370. https://doi.org/10.1016/j.agee.2017.06.048.

Ghosh, S., Jung, C., 2018. Contribution of insect pollination to nutritional security of minerals and vitamins in Korea. J. Asia Pac. Entomol. https://doi.org/10.1016/j.aspen.2018.03.014.

Giannini, T.C., Cordeiro, G.D., Freitas, B.M., Saraiva, A.M., Imperatriz-Fonseca, V.L., 2015. The dependence of crops for pollinators and the economic value of pollination in Brazil. J. Econ. Entomol. 108 (3), 849–857. https://doi.org/10.1093/jee/tov093.

Giannini, T.C., Costa, W.F., Cordeiro, G.D., Imperatriz-Fonseca, V.L., Saraiva, A.M., Biesmeijer, J., Garibaldi, L.A., 2017. Projected climate change threatens pollinators and crop production in Brazil. PLoS One 12, 1–13. https://doi.org/10.1371/journal.pone.0182274.

Hipolito, J., Viana, B.F., Garibaldi, L.A., 2016. The value of pollinator-friendly practices: synergies between natural and anthropogenic assets. Basic Appl. Ecol. 17, 659–667. https://doi.org/10.1016/j.baae.2016.09.003.

HLPE, 2020. Impacts of COVID-19 on Food Security and Nutrition: Developing Effective Policy Responses to Address the Hunger and Malnutrition Pandemic. https://doi.org/10.4060/cb1000en. Rome.

Holzschuh, A., Dainese, M., González-Varo, J.P., Mudri-Stojnić, S., Riedinger, V., Rundlöf, M., Scheper, J., Wickens, J.B., Wickens, V.J., Bommarco, R., Kleijn, D., Potts, S.G., Roberts, S.P.M., Smith, H.G., Vilà, M., Vujić, A., Steffan-Dewenter, I., 2016. Mass-flowering crops dilute pollinator abundance in agricultural landscapes across Europe. Ecol. Lett. 19, 1228–1236. https://doi.org/10.1111/ele.12657.

IBGE, 2020. Departamento de Agropecuária. Produção agrícola municipal, culturas temporárias e permanentes. IBGE. https://biblioteca.ibge.gov.br/index.php/biblioteca-catalogo?view=detalhes&id=766.

IPBES, 2016. The assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production. In: Potts, S.G., Imperatriz-Fonseca, V.L., Ngo, H.T. (Eds.), Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany, 552 pages. https://doi.org/10.5281/zenodo.3402856.

Jordano, P., 1995. Angiosperm fleshy fruits and seed dispersers: a comparative analysis of adaptation and constraints in plant-animal interactions. Am. Nat. 145, 163–191.

Klatt, B.K., Holzschuh, A., Westphal, C., Clough, Y., Smit, I., Pawelzik, E., Tscharntke, T., 2014. Bee pollination improves crop quality, shelf life and commercial value. Proc. Biol. Sci. 281, 20132440. https://doi.org/10.1098/rspb.2013.2440.

Klein, A.M., Vaissière, B.E., Cane, J.H., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C., Tscharntke, T., 2007. Importance of pollinators in changing landscapes for world crops. Proc. Biol. Sci. 274, 303–313. https://doi.org/10.1098/rspb.2006.3721.

Lautenbach, S., Seppelt, R., Liebscher, J., Dormann, C.F., 2012. Spatial and Temporal Trends of Global Pollination Benefit 7. https://doi.org/10.1371/journal.pone.0035954.

Lê, S., Josse, J., Husson, F., 2008. FactoMineR: an R package for multivariate analysis. J. Stat. Software 25, 1–18. https://doi.org/10.18637/jss.v025.i01.

MAPA, 2020. Ministério da Agricultura, Pecuária e Abastecimento. Projeções do Agronegócio. MAPA. https://www.gov.br/agricultura/pt-br/assuntos/noticias/ao-completar-160-anos-ministerio-da-agricultura-preve-crescimento-de-27-na-producao-de-graos-do-pais-na-proxima-decada/ProjecoesdoAgronegocio2019_20202029_2030.pdf. (Accessed 5 January 2021).

Miller, A.J., Gross, B.L., 2011. From forest to field: perennial fruit crop domestication. Am. J. Bot. 98, 1389–1414. https://doi.org/10.3732/ajb.1000522.

Novais, S.M.A., Nunes, C.A., Santos, N.B., D'Amico, A.R., Fernandes, G.W., Quesada, M., Braga, R.F., Neves, A.C.O., 2016. Effects of a possible pollinator crisis on food crop production in Brazil. PLoS One 13, e0197396. https://doi.org/10.1371/journal.pone.0167292.

Oliveira, W., Silva, J.L.S., Porto, R.G., Cruz-Neto, O., Tabarelli, M., Viana, B.F., Peres, C. A., Lopes, A.V., Signatories 62, 2020. Plant and pollination blindness: risky business for human food security. Bioscience 70, 109–110. https://doi.org/10.1093/biosci/biz139.

Ollerton, J., Winfree, R., Tarrant, S., 2011. How many flowering plants are pollinated by animals? Oikos 120, 321–326.

Porto, R.G., Almeida, R.F., Cruz-Neto, O., Tabarelli, M., Viana, B.F., Peres, C.A., Lopes, A. V., 2020. Pollination ecosystem services: a comprehensive review of economic values, research funding and policy actions. Food Secur. https://doi.org/10.1007/s12571-020-01043-w.
Pywell, R.F., Heard, M.S., Woodcock, B.A., Hinsley, S., Ridding, L., Nowakowski, M., Bullock, J.M., 2015. Wildlife-friendly farming increases crop yield: evidence for ecological intensification. Proc. R. Soc. B Biol. Sci. https://doi.org/10.1098/rspb.2015.1740.
R Development Core Team, 2014. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/.
Roubik, D., 2018. Food and Agriculture Organization. The Pollination of Cultivated Plants: A Compendium for Practitioners. FAO.
Saunders, M.E., 2018. Insect pollinators collect pollen from wind-pollinated plants: implications for pollination ecology and sustainable agriculture. Insect Conserv. Divers. https://doi.org/10.1111/icad.12243.
Silva, C.A.S., Godoy, W.A.C., Jacob, C.R.O., Thomas, G., Câmara, G.M.S., Alves, D.A., 2018. Bee pollination highly improves oil quality in sunflower. Sociobiology 65, 583–590. https://doi.org/10.13102/sociobiology.v65i4.3367.
Silva, F.D.S., Carvalheiro, L.G., Aguirre-Gutiérrez, J., Lucotte, M., Guidoni-Martins, K., Mertens, F., 2021. Virtual pollination trade uncovers global dependence on biodiversity of developing countries. Sci. Adv. 7, 1–11. https://doi.org/10.1126/sciadv.abe6636.
Smith, M.R., Singh, G.M., Mozaffarian, D., Myers, S.S., 2015. Effects of decreases of animal pollinators on human nutrition and global health: a modelling analysis. Lancet. https://doi.org/10.1016/S0140-6736(15)61085-6.
Spengler, R.N., 2020. Anthropogenic seed dispersal: rethinking the origins of plant domestication. Trends Plant Sci. 25, 340–348. https://doi.org/10.1016/j.tplants.2020.01.005.
TBCA, 2020. Tabela Brasileira de Composição de Alimentos. USP. Available: http://www.tbca.net.br. (Accessed 10 December 2020).
USDA, 2020. Food Data Central. USDA. Available: https://fdc.nal.usda.gov. (Accessed 10 December 2020).
Van der Sluijs, J.P., Vaage, N.S., 2016. Pollinators and global food security: the need for holistic global stewardship. Food Ethics 1, 75–91. https://doi.org/10.1007/s41055-016-0003-z.
Vanbergen, A.J., Heard, M.S., Breeze, T., Potts, S.G., Hanley, N., 2014. Status and Value of Pollinators and Pollination Services. A Report to the Department for Environment. Food and Rural Affairs (DEFRA), ID PH0514. 1–54.
Volz, R.K., Tusk, D.S., Ferguson, I.B., 1996. Pollination effects on fruit mineral composition, seeds and cropping characteristics of 'Braebum' apple trees, 66, pp. 169–180.