The dilemma of agricultural pollination in Brazil: Beekeeping growth and insecticide use

Charles Fernando dos Santos¹*, Alex Otesbelgue¹, Betina Blochtein¹,²*

¹ Departamento de Biodiversidade e Ecologia, Escola de Ciências, Pontifícia Universidade Católica do Rio Grande do Sul, Porto Alegre, Rio Grande do Sul, Brazil, ² Instituto do Meio Ambiente, Pontifícia Universidade Católica do Rio Grande do Sul, Porto Alegre, Rio Grande do Sul, Brazil

* charles.santos@pucrs.br (CFS); betinabl@pucrs.br (BB)

Abstract

Pollination by bees improves agricultural crop yields and improves the financial outlook of beekeepers because it increases honey production and hive rental revenues. However, in Brazil, with a few exceptions, these benefits have been neglected in recent years because beekeepers are more interested in honey production than in agricultural pollination. The excessive and indiscriminate use of insecticides on agricultural fields in Brazil appears to be one of the principal obstacles preventing partnership between farmers and beekeepers. The goal of this study was therefore to evaluate the most recent situation in Brazil in relation to the use of insecticides, agriculture and to honey production in comparison with other countries. Our results show that Brazil is the largest consumer of insecticides in the world and that consumption has increased by > 150% over 15 years. While countries with a high Human Development Index (i.e., a measure that can also be used to question national policy choices) are reducing their levels of insecticide use in agriculture, Brazil is going in the opposite direction. It is highly likely the increase seen in other countries is a result of alternative methods for pest control rather than a result of the amount of area under agricultural cultivation and their capability to shift their economies from agriculture to other sectors. The number of hives (23%) and the volume of honey production (72%) in Brazil have, however, increased over the same period, raising Brazil to the ninth highest honey producer in the world. Although the data on apiculture are promising, the growth in use of insecticides in Brazil is a cause for concern because they leave residuals on bee products, on crops, and in the environment. Civil society and government in Brazil should encourage reductions in insecticide use and better relations between agricultural farmers and beekeepers.

Introduction

Bees contribute to the cross-pollination of many plant species [1]. These insects play an important role in agricultural systems as agents of pollination, thereby contributing to improving the yields of crops [2]. Despite this, it is known that we are currently facing a global pollination crisis [3]. This crisis threatens a deficit of pollinators (e.g., bees) able to meet the demands of agricultural crops [4]. Recent works have demonstrated that biodiversity loss related to functional
The diversity of organisms may have deep consequences for ecosystem resilience because functional groups providing valuable ecological services, such as pest control and pollination, have declined [5,6].

Brazil is a world leader in agricultural production, and many of its agricultural crops depend to a lesser or greater degree on the pollination services provided by bees [7–9]. Studies have estimated that the economic value of crop pollination services provided by bees in Brazil is approximately $12–14 billion [8,10]. Despite the elevated value attributed to bees, with a few exceptions, keepers of honey bees and stingless bees in Brazil invest greater effort in honey production than in renting their hives for agricultural pollination [11–13].

Recent data show that Brazilian honey production came close to 40,000 metric tons, with profits of around $82 million [14]. Thus, while honey production is the main concern of Brazilian beekeepers, the use of bees for agricultural pollination has been relatively neglected [8,10]. Crop pollination may be beneficial to beekeepers, increasing their income [15–17]. Similarly, it would also contribute to increasing the revenues from Brazilian harvests because both the quantity and quality of fruit and seeds are increased when pollination is performed by bees, which increases their market value [17–20].

Considering that both industries could increase their profits through agricultural pollination services provided by bees, it might be expected that there would be a closer partnership between agricultural farmers and beekeepers in Brazil. However, excessive use of insecticides on Brazilian agricultural crops [21–23] could be detrimental for bees. For example, in a recent case study, 90% of interviewed beekeepers reported beehive loss because of agrochemicals being used close to their apiaries [24].

Although bee mortality caused by the lethal effects of agrochemicals garners more visibility by the general public or media due to its dramatic impact [24], the less-detectable sublethal effects of agrochemicals are also seriously detrimental to the long-term survival and viability of hives [25,26]. For example, field studies have detected a plethora of insecticides (e.g., neonicotinoids, fipronil) at residual levels in brood, pollen, honey, and wax, which may compromise the growth, strength, and survival of the bee hives [27,28]. Many experimental studies have shown that insecticides compromise homing, memory abilities, cognition, foraging, and navigation in workers [25–27,29,30], sperm motility in drones [31], and emergence, survival, and reproduction of queens [32–34]. Furthermore, as insecticides act synergistically with other contaminants (e.g., other insecticide classes, fungicides), pathogens (e.g., Nosema ceranae), and nutritional stressors, their negative effects on bee behavior, physiology, and immunity are even more dramatic [27,35–40]. Human health may also be indirectly affected; honey sold at supermarkets worldwide has been found to be contaminated with residual levels of neonicotinoids, demonstrating their long-term presence within colonies [41].

There is no doubt that taking advantage of the benefits offered by bees while at the same time controlling the thousands of agricultural pests using insecticides is a challenge. Brazilian agriculture is faced with approximately 560 species of agricultural pest insects that are controlled mostly with insecticides [21–23]. As such, a proportion of these pesticides have low toxicity to bees and the environment [42] (S1 Fig). This practice can have direct or indirect effects on the 3,000 or so species of wild bees [43] in Brazil and can be harmful to the approximately 1 million hives of honey bees [14] and ~18,000 hives of stingless bees [13] that could be used for agricultural pollination. In other words, all this potential that bees offer is being systematically ignored by Brazilian agriculture for the pollination of its crops.

Pest insects cause large productivity losses and consequently have a major economic impact on Brazilian agriculture [44]. However, it is necessary to find a compromise that is not detrimental to the benefits of pollination by bees through use of sustainable alternatives, since agriculture and apiculture/meliponiculture (stingless beekeeping) are complementary activities...
rather than rivals. Thus, different agricultural activities may be adopted as alternative or complementary practices to agrochemical pest control [45]. For example, methods such as semiochemical control, biological control (predators, parasitoids), entomopathogenic fungi, botanical insecticides, essential oils, crop rotation, recombinant RNA technologies, and even organic cultivation practices can be combined into integrated pest management (IPM) strategies [45–49].

It is known that approximately 60% of Brazilian crops depend primarily on bees for pollination [8]. However, while bee management in fields could both benefit honey production [15–17] and raise crop yields [17–20], increasing insecticide use in Brazil [21–23] could hamper this business [11]. Furthermore, the increase in Brazilian agricultural productivity due to pesticide (e.g., insecticide) use has other costs, such as risks to human health, and poses a great challenge for the preservation of environmental quality [21]. Our objective was to evaluate the Brazilian situation over the last 15 years by analyzing indicators related to use of insecticides, honey production and number of hives and, where possible, to compare Brazil’s position in relation to these issues with other countries. The approach taken was to assess these data in the light of potential conflicts of interest between agricultural farmers and beekeepers in Brazil, with the objective of proposing viable options and reliable solutions.

Materials and methods

We collected data for our analyses from the United Nations Food and Agriculture Organization (http://www.fao.org/faostat/en/#data) [14]: honey production, number of beehives, insecticide use, agricultural area of Brazil and, where needed, other selected nations. Such data can also be freely obtained from national publications, web sites, or trade files as well as from official publications from individual countries [14]. We surveyed for Livestock Primary (item: honey; elements: production quantity), Live Animals (item: beehives; elements: stocks), Pesticide Use (item: insecticides+Total; elements: use) and Land Use (item: agricultural area, organic agricultural area; elements: area).

Our first step was to rank Brazil among other countries in terms of insecticide use, honey production, total agricultural area, and organic agricultural area. To achieve this, we compiled data on the most recent reference year (2015) related to the quantity of active ingredients for insecticides (in metric tons) and ranked the 10 countries (of the 39 for which data were available) that were the greatest consumers of these agricultural supplies (Fig 1). Information for the reference year was missing from many countries, such as the United States, for which the most up-to-date official figures on the use of insecticides are from 2012 (66,770 metric tons of active ingredients). Therefore, we are aware that these missing values could distort the current country rankings (for more details, see S1 Table). We also plotted the insecticide use of these countries divided by agricultural area (ha) to visualize how these nations have effectively managed their croplands concerning insecticide use. Similarly, we performed the same procedure for honey production.

Data analysis

We performed a linear regression analysis using the \( \text{lm} \) function to test whether there was any relationship between use of insecticides and the size of total agricultural area, as well as the latter variable vs. size of organic agricultural area of all countries \((n = 39)\), with available data on insecticide use in 2015; see Fig 2A–2D. We were also interested in observing the top-10 ranked countries in terms of the human development index (most up-to-date HDI of 188 available countries) and comparing them with Brazil (ranked 79th) to illustrate the amount of insecticide use and expansion/retraction of land used for agriculture over the last 15 years (Fig 3). As part
of these analyses comparing Brazil with other countries, we plotted the 10 (of ~165) largest
honey-producing countries to determine where Brazil ranks according to the most recent data
(2015) (Fig 4).

We then conducted a historical analysis of the three variables for Brazil only, using data
from 2000–2015. In this analysis, the response variables were (1) consumption of active ingre-
dients of insecticides (Fig 5A), (2) number of bee hives (Fig 5B), and (3) honey production
(Fig 5C). The predictive variable was the elapsed period, and the random effect was the years
(longitudinal data).

Thus, we fitted a generalized linear mixed model (GLMM) to evaluate the response vari-
ables above (1 and 2) with a Poisson error distribution (link = log), considering they were
count data. The link function ("log") was chosen as a default, as it directly characterizes how a
linear combination of predictors is related to prediction at the original scale. The first GLMM
was evaluated with a quadratic term, while the second GLMM was evaluated with a cubic
term. Both GLMMs were fitted using the glmer function of the “lme4” package [50]. The third
variable (honey production) was investigated by fitting a linear mixed model (LME) with a
quadratic term using the lme function of aforementioned package [50]. All final GLMMs and
LMEs were selected after running some models with different polynomial regressions. Those
with lower Akaike Information Criteria (AIC) were chosen (data not shown). The parameters
and significance values of these models were extracted using the Anova function from the
“car” package [51]. All analyses were carried out in the R statistical software environment [52].

Results

Brazil’s position in international surveys

Brazil is currently the world’s largest consumer of insecticides, at approximately 71,663 metric
tons of active ingredients (Fig 1A), and has been among the greatest consumers over the last
According to currently available data, Brazil uses more insecticides than the second- through ninth-leading consumers combined (Fig 1A). However, when agricultural area is proportionally considered, we can see that insecticide use by Brazil is relatively low compared to other countries (Fig 1B).

However, when considering insecticide use vs. total size of agricultural area, we found a strong positive relationship ($F_{(1,36)} = 953.08, p < 0.001, R^2_{adj} = 0.962$; Fig 2A). Similarly, if these data are reanalyzed without Brazil (since it is apparently an outlier), a positive relationship remains, but the percentage of variance explained is reduced ($F_{(1,35)} = 24.83, p < 0.001, adj.R^2 = 0.39$, Fig 2B). When the total size of the agricultural area of these same countries is considered against its allocation to organic farming (i.e., non-traditional insecticide use), we did not find any relationship between these variables ($F_{(1,32)} = 1.88, p > 0.05, R^2_{adj} = 0.02$, Fig 2C). However, when Brazil was removed from the sample due to its outlier status, we again found a positive relationship between total size of agricultural area vs. organic agricultural area ($F_{(1,31)} = 11.31, p < 0.002, R^2_{adj} = 0.24$, Fig 2D).

On the other hand, Brazil (ranked 79th in HDI worldwide) appears to be heading in the opposite direction when compared to the top-10 countries with the highest HDIs over the last 15 years (S2 Table).
Fig 3. Insecticide use and expansion/retraction of land use for agriculture over the last 15 years among the top-10 ranked countries (decreasing order) in terms of human development index (HDI) and Brazil (ranked 79th). Here, HDI was used as a summary measure of average quality of the nations. This measure emphasizes that people and their capabilities should be the ultimate criteria for assessing the development of a country, not economic growth alone. The HDI can also be used to question national policy choices. For more details, see [http://hdr.undp.org/en/data](http://hdr.undp.org/en/data) or [http://hdr.undp.org/en/content/human-development-index-hdi](http://hdr.undp.org/en/content/human-development-index-hdi). Data adapted from the United Nations Food and Agriculture Organization [12].

https://doi.org/10.1371/journal.pone.0200286.g003

Fig 4. Honey production. A–World’s 10 leading honey producers, reference year 2015. B–Honey production divided by total of agricultural area. Data adapted from the United Nations Food and Agriculture Organization [12]. FAOSTAT search query: Livestock Primary (items: honey; elements: production quantity).

https://doi.org/10.1371/journal.pone.0200286.g004
been reducing their demand for agrochemical supplies (insecticides) in their agricultural fields over recent years, Brazil has substantially increased its rate of consumption (Fig 3). In just the last 15 years, there was a 152% increase in use of insecticides in Brazil, with only a slight increase in the land area used for agriculture (approximately 8.1%).

Brazil (agricultural area: $282,589 \times 10^3$ ha; beehives: 1,020,000) is also among the world’s leading honey producers, ranked 9th out of all countries (approximately 40,000 metric tons), although its production is 12 times less than that of the world leader, China (473,600 metric tons, agricultural area: $528,634 \times 10^3$ ha; beehives: 9,131,487) (Fig 4A). However, Brazil has great potential for increasing its honey production once its agricultural area expands and especially because forage sources for honeybees remains underused (Fig 4B).

**Trends in Brazil’s use of insecticides, honey production and number of hives**

The data show that over the last 15 years, Brazil has increased its use of insecticides in agriculture (Figs 3 and 5A), the number of hives in its apiaries (Fig 5B) and the volume of its honey production (Fig 5C). However, of these three variables, the greatest increase was in the use of insecticides on Brazilian crops. Consumption of the active ingredients of insecticides in Brazil more than doubled (152%) from 28,382 to the current level of 71,663 metric tons (quadratic, Poisson GLMM, degrees of freedom = 2, $\chi^2 = 215.13, p < 0.0001$, Fig 5A). Meanwhile, the number of bee hives increased by 23%, to approximately 1,020,000 hives (cubic, Poisson GLMM, degrees of freedom = 3, $\chi^2 = 76.12, p < 0.0001$; Fig 5B). Finally, honey production increased by 72%, to 380,000 metric tons (quadratic LME, F = 92.80, degrees of freedom = 2, $p < 0.0001$; Fig 5C).
Discussion

The data indicate that, over the last 15 years, the world consumed more than five million metric tons of the active ingredients of insecticide and that Brazil has taken a leading role in this consumption among all the world’s countries (S1 Table). In recent years, Brazil has remained among the five highest insecticide consumers worldwide. Despite some asymmetry over country-reported information regarding insecticide use (in 2010, approximately 100 countries reported such information, versus only 40 countries in 2015; more details in S1 Table), Brazil has increased this consumption substantially. Thus, even though this nation has proportionally used less insecticide than other countries with smaller agricultural areas, the agrochemical consumption remains elevated, showing a bias for this pest control method despite alternatives that organic farmers use. The effectiveness of chemical products for controlling insect pests in agriculture is not a subject investigated in this study. We do not ignore that agrochemicals are useful [44]. However, their lethal and sublethal effects on non-target organisms can compromise the survival and viability of populations such as pollinators and parasitoid insects that are actually beneficial to agriculture [25,26,53].

Although the size of Brazil’s agricultural area is considerable, this only partly explains the need to use such large quantities of insecticides in the country’s agriculture over recent years. In contrast, alternative methods of pest control, such as integrated pest management (IPM), recombinant RNA technologies or even organic cultivation practices [45–47], are underused practices [21,47,54–56]. Farmers usually prioritize agrochemicals as a method of pest control, and many express reservations toward IPM, for example [21,54–56]. It should also be noted that farmers may be using agrochemicals incorrectly, not following the technical recommendations for their crops or the product recommendations (included in the information leaflets). If these infringements are indeed occurring, they could be impacting pollinators through excessive use of these products as a result of incorrect dosages, times of day, methods of application and even incorrect mixtures of different products [see 21]. For example, the Brazilian Ministry of the Environment recently published a document on risk assessment of insecticides regarding bees containing instructions and listing bee-friendly practices [57]. Therefore, even if farmers prefer to use insecticides for pest control, they can adopt attitudes that would reduce the risk of serious harm to bees [57].

Brazil has also shown itself to be a major global producer of honey, and this has increased over recent years. As the data show, Brazilian honey production has increased much more than the numbers of hives at the apiaries. The increase in honey production may be due to good public policies providing governmental support and technical training to beekeepers, such as teaching them how to better manage their hives and when to harvest honey from the combs. Even though Brazilian honey production is elevated, it could be greater if farmland was more efficiently managed in consort with beekeeping, since Brazil still has an extensive agricultural area that is both underused and little explored by both beekeepers and farmers. Moreover, such a partnership needs to proceed with caution; since 2010, the growth curve of both the number of hives and honey production in Brazil began to decrease again, while insecticide use continued to increase.

As such, considering that there have also been losses of hives because of the effect of insecticides [24], this creates a conflict of interest between the apiculture industry and agricultural farmers. In other words, these practices could make it difficult for apiaries to remain close to agricultural crops over the long term. These practices can also considerably reduce the benefits of the added economic value attributed to agricultural pollination provided by bees in Brazil [8–10], since the use of insecticides has increased much more (> 150%) than the number of hives (23%) and the volume of honey production (72%) in the country over the last 15 years.
This situation is alarming and needs to be addressed, as local research indicates that keepers of honey bees and stingless bees are reluctant to enter into partnerships with agricultural farmers because of excessive use of agrochemicals in the fields [11–13,24]. Considering the lethal and sublethal effects of insecticides on bees [27,32,58,59] and that a large proportion of the honey eaten worldwide, including in Brazil [41], contains insecticide residues, as does pollen [26,28], it would be unwise for Brazilian beekeepers to adopt partnerships with farmers before any deal.

Agricultural farmers and beekeepers should work in partnership, rather than avoiding each other, because both sides could improve the earnings from their production and increase the financial returns from their businesses. If insecticide use in Brazil could be reduced considerably, at least four major advantages of partnerships between farmers and beekeepers could be reaped: (1) greater growth of honey production, (2) increased profits for beekeepers from hive rental, (3) increased size of harvests in tonnage due to increased weight of fruit and seeds resulting from more effective pollination and (4) expansion and increased value of Brazilian agricultural products (“green card”) in more demanding international markets.

We recognize that agrochemicals can be used successfully to control pests. However, we also have alternative practices that are more friendly to pollinators, such as IPM (e.g., biological control, entomopathogens), crop rotation, recombinant RNA technologies, no-tillage systems, agroforestry and/or organic systems [45–49]. Nevertheless, farmers need to be financially aided by public policies and receive technical knowledge to implement all or most of these changes. Therefore, public agencies and private institutions should allocate more funding and offer technical training to help farmers reliably reduce insecticide use or replace it with other practices.

**Conclusion**

Brazilian agriculture already benefits from pollination by wild bees from the few remaining small forest remnants surrounding cultivated areas [2,60]. However, this could be improved both by expanding the natural areas next to agricultural areas, minimizing the expansion of cultivation to fully take advantage of ecosystem services and managing hives within cultivated areas. More bees in the fields mean less insecticide on the crops. Agriculture and apiculture/meliponiculture are not incompatible businesses. In contrast, they are complementary activities that provide mutual environmental, social and economic value to each other. This issue cannot continue to be ignored. It is therefore suggested that the Brazilian public and private sectors rethink the prevailing model of harmful insect control and create incentives and an environment that stimulates favorable relationships between agricultural farmers and beekeepers in Brazil.

**Supporting information**

**S1 Fig. Insecticides recently approved in Brazil that are toxic to bees.** Ministério da Agricultura, Pecuária e Abastecimento [MAPA]. Sistema de Agrotóxicos Fitossanitários [AGROFIT]. In: AGROFIT. Consulta aberta [Internet]. Brasília/ Brazil; 2017. Available: http://agrofit.agricultura.gov.br/agrofit_cons/principal_agrofit_cons. (PNG)

**S1 Table. Country-reported information on insecticide use, 2010–2015. Are countries sending data about agrochemical use equally?.** United Nations Food and Agriculture Organization (http://www.fao.org/faostat/en/#data). (XLSX)
S2 Table. Worldwide insecticide use, 2010–2015. United Nations Food and Agriculture Organization (http://www.fao.org/faostat/en/#data).
(XLSX)

S3 Table. Total agricultural area and total area allocated to organic agriculture in countries for which data about insecticide use are available. Reference year, 2015. United Nations Food and Agriculture Organization (http://www.fao.org/faostat/en/#data).
(XLSX)

Acknowledgments
The authors are grateful to the committee of the VI Simpósio de Biodiversidade of the Universidade Federal de Santa Maria, especially to Andressa Paladini PhD, whose invitation to CFS for a talk about bee extinction led to the development of this manuscript. CFS is grateful to the Programa Nacional de Pós-Doutorado (PNPD) from Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES). AO is grateful to the Programa de Bolsas Pesquisa Alunos da PUCRS/BPA (N° 01/2017). BB is grateful to the Produtividade em Pesquisa do Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq).

Author Contributions
Conceptualization: Charles Fernando dos Santos, Betina Blochtein.
Data curation: Charles Fernando dos Santos, Alex Otesbelgue.
Formal analysis: Charles Fernando dos Santos.
Funding acquisition: Charles Fernando dos Santos, Alex Otesbelgue.
Investigation: Charles Fernando dos Santos, Alex Otesbelgue.
Methodology: Charles Fernando dos Santos.
Supervision: Charles Fernando dos Santos, Betina Blochtein.
Validation: Charles Fernando dos Santos, Betina Blochtein.
Visualization: Charles Fernando dos Santos, Betina Blochtein.
Writing – original draft: Charles Fernando dos Santos, Betina Blochtein.
Writing – review & editing: Charles Fernando dos Santos, Betina Blochtein.

References
1. Ricketts TH, Regetz J, Steffan-Dewenter I, Cunningham SA, Kremen C, Bogdanski A, et al. Landscape effects on crop pollination services: are there general patterns? Ecol Lett. 2008; 11: 499–515. https://doi.org/10.1111/j.1461-0248.2008.01157.x PMID: 18294214
2. Garibaldi LA, Steffan-Dewenter I, Winfree R, Aizen MA, Bommarco R, Cunningham SA, et al. Importance of pollinators in changing landscapes for world crops. Science. 2007; 274: 1–7. https://doi.org/10.1086/519634
3. Potts SG, Biesmeijer JC, Kremen C, Neumann P, Schweiger O, Kunin WE. Global pollinator declines: trends, impacts and drivers. Trends Ecol Evol. Elsevier Ltd; 2010; 25: 345–353. https://doi.org/10.1016/j.tree.2010.01.007 PMID: 20188434
4. Aizen MA, Harder LD. The global stock of domesticated honey bees is growing slower than agricultural demand for pollination. Curr Biol. Elsevier Ltd; 2009; 19: 915–918. https://doi.org/10.1016/j.cub.2009.03.071 PMID: 19427214
5. Oliver TH, Isaac NJB, August TA, Woodcock BA, Roy DB, Bullock JM. Declining resilience of ecosystem functions under biodiversity loss. Nat Commun. Nature Publishing Group; 2015; 6: 1–8. https://doi.org/10.1038/ncomms10122 PMID: 26646209

6. Woodcock BA, Harrower C, Redhead J, Edwards M, Vanbergen AJ, Heard MS, et al. National patterns of functional diversity and redundancy in predatory ground beetles and bees associated with key UK arable crops. J Appl Ecol. 2014; 51: 142–151. https://doi.org/10.1111/1365-2664.12171

7. Freitas BM, Nunes-Silva P. Polinização agrícola e sua importância no Brasil. In: Imperatriz-Fonseca VL, Canhos DAL, Alves DA, Saraiva AM, editors. Polinizadores no Brasil—contribuição e perspectivas para a biodiversidade, uso sustentável, conservação e serviços ambientais. São Paulo: EDUSP; 2012. pp. 103–118.

8. Giannini TC, Cordeiro GD, Freitas BM, Saraiva a. M, Imperatriz-Fonseca VL. The dependence of crops for pollinators and the economic value of pollination in Brazil. J Econ Entomol. 2015; 1–9. https://doi.org/10.1093/jee/tov093 PMID: 26470203

9. Giannini TC, Boff S, Cordeiro GD, Carlotano EA, Veiga a. K, Imperatriz-Fonseca VL, et al. Crop pollinators in Brazil: a review of reported interactions. Apidologie. 2014; https://doi.org/10.1007/s13592-014-0316-z

10. Novais SMA, Nunes CA, Santos NB, D’Amico AR, Fernandes GW, Quesada M, et al. Effects of a possible pollinator crisis on food crop production in Brazil. PLoS One. 2016; 11: 1–12. https://doi.org/10.1371/journal.pone.0167292 PMID: 27902787

11. Morais MM, De Jong D, Message D, Gonçalves LS. Perspectivas e desafios para o uso das abelhas Apis mellifera como polinizadores no Brasil. In: Imperatriz–Fonseca VL, Canhos DAL, Alves DA, Saraiva MA, editors. Polinizadores no Brasil—contribuição e perspectivas para a biodiversidade, uso sustentável, conservação e serviços ambientais. 1st ed. São Paulo: Editora da Universidade de São Paulo; 2012. p. 488.

12. Venturieri GC, Alves DA, Villas-Bôas J, de Carvalho CAL, Menezes C, Vollet-Neto A, et al. Meliponiculture no Brasil: situação atual e perspectivas futuras para o uso na polinização agrícola. In: Imperatriz–Fonseca VL, Canhos DAL, Alves DA, Saraiva AM, editors. Polinizadores no Brasil—contribution and perspectives for a biodiversity, use sustainable, conservation and services environmental. 1a. São Paulo: Editora da Universidade de São Paulo; 2012. p. 488.

13. Jaffé R, Pope N, Carvalho AT, Maia UM, Blochtein B, Carvalho CAL, et al. Bees for development: Brazilian survey reveals how to optimize stingless beekeeping. PLoS One. 2015; 10: e0121157. https://doi.org/10.1371/journal.pone.0121157 PMID: 25826402

14. FAO. FAOSTAT—Food and Agriculture Organization of the United Nations. In: Data. 2017.

15. Scott-Dupree C, Winston M, Hergert G, McKenzie K, Murrel D, Dixon D, et al. A guide to: managing bees for crop pollination. Aylesford: Canadian Association of Professional Apiculturists; 1995.

16. Woodcock TS. Pollination in the agricultural landscape: best management practices for crop pollination. University of Guelph: Canadian Pollination Initiative (NSERC-CANPOLIN); 2012.

17. Calderone NW. Insect pollinated crops, insect pollinators and US agriculture: trend analysis of aggregate data for the period 1992–2009. PLoS One. 2012; 7: e37235. https://doi.org/10.1371/journal.pone.0037235 PMID: 22629374

18. Klatt BK, Holzschuh A, Westphal C, Clough Y, Smit I, Pawelzik E, et al. Bee pollination improves crop quality, shelf life and commercial value. Proc R Soc B Biol Sci. 2014; 281. Available: http://rspb.royalsocietypublishing.org/content/281/1775/20132440.short

19. Klatt B, Klaus F, Westphal C, Tschamntke T. Enhancing crop shelf life with pollination. Agric Food Secur. 2014; 3: 14. https://doi.org/10.1186/2048-7010-3-14

20. Devkota K, Dhakal SC, Thapa RB. Economics of beekeeping as pollination management practices adopted by farmers in Chitwan district of Nepal. Agric Food Secur. 2016; 5: 6. https://doi.org/10.1186/s40066-016-0053-9

21. Brazil. Pesticides and related products commercialized in Brazil 2009: an environmental approach. Brasilia/Brazil: IBAMA: Brazilian Institute for the Environment and Renewable Natural Resources; 2010.

22. Dasgupta S, Mamingi N, Meisner C. Pesticide use in Brazil in the era of agroindustrialization and globalization. Environ Dev Econ. 2001; 6: 459–482. https://doi.org/10.1017/S1355770X01000262

23. Bellotti AC, Cardona C, Lapointe SL. Trends in pesticide use in Colombia and Brazil. J Agric Entomol. 1990; 7: 191–201.

24. Cerqueira A, Figueiredo RA. Percepção ambiental de apicultores: Desafios do atual cenário apícola no interior de São Paulo. Acta Bras. 2015; 1: 17–21.

25. Desneux N, Decourtey A, Delpuech J-M. The sublethal effects of pesticides on beneficial arthropods. Annu Rev Entomol. 2007; 52: 81–106. https://doi.org/10.1146/annurev.ento.52.110405.091440 PMID: 16842032
26. Lundin O, Rundlöf M, Smith HG, Fries I, Bommarco R. Neonicotinoid insecticides and their impacts on bees: a systematic review of research approaches and identification of knowledge gaps. PLoS One. 2015; 10: e0136928. https://doi.org/10.1371/journal.pone.0136928 PMID: 26313444
27. Pisa L, Goulson D, Yang EC, Gibbons D, Sánchez-Bayo F, Mitchell E, et al. An update of the worldwide integrated assessment (WIA) on systemic insecticides. Part 2: impacts on organisms and ecosystems. Environ Sci Pollut Res. Environmental Science and Pollution Research; 2017; 1–49. https://doi.org/10.1007/s11356-017-0341-3 PMID: 29124633
28. Tosi S, Costa C, Vesco U, Quaglia G, Guido G. A 3-year survey of Italian honey bee-collected pollen reveals widespread contamination by agricultural pesticides. Sci Total Environ. Elsevier B.V.; 2018; 615: 208–218. https://doi.org/10.1016/j.scitotenv.2017.09.226 PMID: 28968582
29. Henry M, Béguin M, Requier F, Rollin O, Odoux J-F, Aupinel P, et al. A common pesticide decreases foraging success and survival in honey bees. Science. 2012; 336: 348–350. https://doi.org/10.1126/science.1215039 PMID: 22461498
30. Mommaerts V, Reynerts S, Boulet J, Besard L, Sterk G, Smaggh G. Risk assessment for side-effects of neonicotinoids against bumblebees with and without impairing foraging behavior. Ecotoxicology. 2010; 19: 207–215. https://doi.org/10.1007/s10646-009-0406-2 PMID: 19757031
31. Ciereszko A, Wilde J, Dietrich GJ, Siuda M, Bąk B, Judycka S, et al. Sperm parameters of honeybee drones exposed to imidacloprid. Apidologie. 2016; 48: 211–222. https://doi.org/10.1007/s13592-016-0466-2
32. dos Santos CF, Acosta AL, Dorneles AL, dos Santos PDS, Blochtein B. Queens become workers: pesticides alter caste differentiation in bees. Sci Rep. 2016; 6: 31605. https://doi.org/10.1038/srep31605 PMID: 27530246
33. Thompson HM, Wilkins S, Batterby AH, Waite RJ, Wilkinson D. The effects of four insect growth-regulating (IGR) insecticides on honeybee (Apis mellifera L.) colony development, queen rearing and drone sperm production. Ecotoxicology. 2005; 14: 757–769. https://doi.org/10.1007/s10646-005-0024-6 PMID: 16106749
34. Sandrock C, Tanadini M, Tanadini LG, Fauser-Misslin A, Potts SG, Neumann P. Impact of chronic neonicotinoid exposure on honeybee colony performance and queen supersEDURE. PLoS One. 2014; 9: e103592. https://doi.org/10.1371/journal.pone.0103592 PMID: 25084279
35. Alaux C, Brunet JL, Dussaubat C, Mondet F, Tchamitchan S, Cousin M, et al. Interactions between Nosema microspores and a neonicotinoid weaken honeybees (Apis mellifera). Environ Microbiol. 2010; 12: 774–802. https://doi.org/10.1111/j.1462-2920.2009.02123.x PMID: 20050872
36. Auffauvre J, Misme-Acoutourier B, Viguès B, Texier C, Delbac F, Blot N. Transcriptome analyses of the honeybee response to Nosema ceranae and insecticides. PLoS One. 2014; 9: e91866. https://doi.org/10.1371/journal.pone.0091686 PMID: 24646894
37. Spurgeon D, Hesketh H, Lahive E, Svendsen C, Baas J, Robinson A, et al. Chronic oral lethal and sublethal toxicities of different binary mixtures of pesticides and contaminants in bees (Apis mellifera, Osmia bicornis and Bombus terrestris). EFSA Support Publ. 2016; EN-1076. https://doi.org/10.2903/SP.EFSA.2016.EN-1076
38. Tosi S, Nieh JC, Sgoalastra F, Cabbri R, Medrzycki P. Neonicotinoid pesticides and nutritional stress synergistically reduce survival in honey bees. Proc R Soc B Biol Sci. 2017; 284: 20171711. https://doi.org/10.1098/rspb.2017.1711 PMID: 29263280
39. Sgoalastra F, Medrzycki P, Bortolotti L, Renzi MT, Tosi S, Bogo G, et al. Synergistic mortality between a neonicotinoid insecticide and an ergosterol-biosynthesis-inhibiting fungicide in three bee species. Pest Manag Sci. 2017; 73: 1236–1243. https://doi.org/10.1002/ps.4449 PMID: 27685544
40. Goulson D, Nicholls E, Botias C, Rotheray EL. Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. Science. 2015; 348: 347–348. https://doi.org/10.1126/science.1255957 PMID: 26251506
41. Mitchell EAD, Mulhauer B, Mulot M, Aebi A. A worldwide survey of neonicotinoids in honey. Science. 2017; 111: 109–111. https://doi.org/10.1126/science.aan3684 PMID: 28983052
42. MAPA. AGROFIT—Sistema de Agrotóxicos Fitossanitários. In: AGROFIT. Consulta aberta. Brasília/ Brazil; 2017.
43. Urban D, Melo GAR. Catalogue of bees (Hymenoptera, Apoidea) in the neotropical region. Curitiba: Sociedade Brasileira de Entomologia; 2007.
44. Oliveira CM, Auad AM, Mendes SM, Frizzas MR. Crop losses and the economic impact of insect pests on Brazilian agriculture. Crop Prot. Elsevier Ltd; 2014; 56: 50–54. https://doi.org/10.1016/j.cropro.2013.02.022
45. Guedes RNC, Smaggh G, Stark JD, Desneux N. Pesticide-induced stress in arthropod pests for optimized integrated pest management programs. Annu Rev Entomol. 2016; 61: 43–62. https://doi.org/10.1146/annurev-ento-010715-023646 PMID: 26473315
46. Zotti MJ, Smaggh e G. RNAi technology for insect management and protection of beneficial insects from diseases: lessons, challenges and risk assessments. Neotrop Entomol. 2015; 44: 197–213. https://doi.org/10.1007/s13744-015-0291-8 PMID: 26013264

47. Willer H, Lemoud J. The world of organic agriculture: summary. The world of organic agriculture. statistics and emerging trends. Bonn: Researcher Institute of Organic Agriculture (FiBL), Frick & IFOAM—Organics International; 2017. https://doi.org/10.4324/9781849775991

48. Rebek EJ, Frank SD, Royer TA, Bográn CE. Alternatives to chemical control of insect pests. In: Soloneski S, editor. Insecticides—basic and other applications. Rijeka (Croatia), Shanghai (China): InTech; 2012. pp. 171–196.

49. Khater HF. EcoSMART biorational insecticides: alternative insect control strategies. In: Perveen F, editor. Insecticides—advances in integrated pest management. Rijeka (Croatia), Shanghai (China): InTech; 2012. pp. 17–60. https://doi.org/10.5772/27852

50. Bates D, Maechler M, Bolker B, Walker S. lme4: Linear mixed-effects models using Eigen and S4 [Internet]. 2015. Available: http://cran.r-project.org/package=lme4

51. Fox J, Weisberg S. An R companion to applied regression. 2011.

52. R Core Team. R: A language and environment for statistical computing [Internet]. Vienna, Austria: The R Foundation for Statistical Computing; 2016. Available: http://www.r-project.org/

53. Sanchez-Bayo F, Goka K. Pesticide residues and bees—a risk assessment. PLoS One. 2014; 9: e94482. https://doi.org/10.1371/journal.pone.0094482 PMID: 24718419

54. Hamerschlag K. More integrated pest management please. New York: Natural Resources Defense Council; 2007.

55. Cullen EM, Stute JK, Raymond KL, Boyd HH. Farmers’ perspectives on IPM field scouting during a period of insect pest range expansion: a case study of variant Western Corn Rootworm (Coleoptera: Chrysomelidae) in Wisconsin. Am Entomol. 2008; 54: 170–178.

56. Mamun MSA, Ahmed M. Integrated pest management in tea: prospects and future strategies in Bangladesh. J Plant Prot Sci. 2011; 3: 1–13.

57. Cham KO, Rebelo RM, Oliveira RP, Ferro AA, Viana-Silva EC V., Borges LO, et al. Manual de avaliação de risco ambiental de agrotóxicos para abelhas. Brasília/Brazil: Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis. Ibama/Diqua; 2017. https://doi.org/10.1590/S0100-67622004000400014

58. Barbosa WF, Tomé HV V., Bernardes RC, Siqueira MAL, Smaggh e G, Guedes RNC. Biopesticide-induced behavioral and morphological alterations in the stingless bee Melipona quadrifasciata. Environ Toxicol Chem. 2015; 34: 2149–2158. https://doi.org/10.1002/etc.3053 PMID: 26190792

59. Dorneles AL, Rosa AS, Blochtein B. Toxicity of organophosphorus pesticides to the stingless bees Scaptotrigona bipunctata and Tetragonisca fiebrigii. Apidologie. 2017; https://doi.org/10.1017/s13592-017-0502-x

60. Halinski R, Dorneles AL, Blochtein B. Bee assemblage in habitats associated with Brassica napus L. Rev Bras Entomol. Elsevier Editora Ltda.; 2015; 59: 222–228. https://doi.org/10.1016/j.rbe.2015.07.001