Pollinator Dependence values of animal pollinated crops – an updated compilation and discussion on methodological approaches

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Abstract

1. Pollinator dependence (PD) of a crop is a key estimate for assessing pollinator's contribution to agriculture, guiding management plans and policies for sustainable crop production. However, currently available global compilations of crops PD are outdated and neglect variability between accessions (variety/cultivar) and information on pollen deposition limitation.

2. Here, we gathered PD values of animal pollinated crops, using data from pollination experiments. We also tested methodological aspects of pollination experiments to assess how they affect PD values to define suitable guidelines for future pollination studies.

3. We provide an updated list of PD values for 119 crops, including 290 crop accessions and 35 crops not listed in previous assessments. We found that globally, 80% of the animal pollinated crops depend highly on pollinators, with more than 40% of their production being associated with animal pollination. Pollen deposition limitation was detected in 52% of the dataset entries, indicating that pollinator community in those cases was insufficient to fully provide pollination services.

4. As most crop PD values published are based on natural pollination levels, pollinator's contribution to most crops is underestimated. Pollen supplementation treatments should hence be incorporated into future studies. This study provides valuable data for future evaluations of pollinator's importance for local and global economies as well as guidelines for future crop pollination studies.

Keywords: Agriculture, pollinator dependence, crop yield, ecosystem service, hand pollen supplementation, pollen limitation, pollination.

Introduction

Biotic pollination is a crucial biodiversity-dependent ecosystem service that contributes to crop yield, supporting food provision and other resources important for humans (Dicks et al., 2021; Power, 2010). Together with managed pollinators, diverse and abundant pollinator communities ensure the reproduction of pollinator-dependent crops, with increased yields and/or higher quality of fruit and seeds, even in self-compatible crops (Klatt et al., 2014; Klein et al., 2003).

The ability of a given crop field to achieve its maximum production potential depends on numerous factors, such as nutrient and water availability, environmental conditions, biotic interactions, and pest levels (Licker et al., 2010). For pollinator-dependent crops that have as their primary product fruits or seeds, pollination is directly linked with crop yield. In these crops, yield is mainly the result of two components (Fig. 1): (1) crop selfing ability (i.e. the ability to produce fruits and/or seeds in the absence of pollination vectors, Fig. 1 - SELF bar); (2) pollination services available in each place and time (natural pollination, Fig. 1 - NAT bar). Altogether, they result in yields that, in optimal conditions, are equal to (3), the production under optimal levels of pollination (Fig. 1 - OPT bar).

The difference between natural and optimal yields is known as pollen deposition limitation (PL; Fig. 1), caused by insufficient and/or inefficient pollination services (Bartomeus et al., 2014; Toledo-Hernández et al., 2017). Following Liebig's law of the minimum (Liebig, 1840), crop yield is determined by the most limiting factor. In pollinator-dependent crops, when no other factors limit yield, as expected in optimized agricultural systems, pollen deposition (associated with pollinator availability) is the limiting factor (Tamburini et al., 2019), being PL defined as the quantitative and qualitative inadequate pollen receipt that limits agricultural output in yield or economic terms (Vaissière et al. 2011).

Indeed, pollinator's contribution to crop yields (Fig. 1) can vary significantly due to spatial, temporal, and biotic factors (Bishop & Nakagawa, 2021; Mallinger et al., 2021; Webber et al., 2020). Pollinator communities, the services they provide, and, consequently, crop yield, are largely impacted by factors such as regional biodiversity, landscape conservation status, environmental conditions during flowering, and local management practices (Holland et al., 2017; Mota et al., 2022; Potts et al., 2010; Senapathi et al., 2017).

The relative difference in yield resulting from crop selfing ability (SELF) and optimal pollination (OPT) corresponds to the potential pollinator’s contribution to production, i.e. the true level of PD, a metric highly used to endorse the importance of pollinators to humans (Fig. 1). Indeed, estimates of pollinator’s contribution to agricultural production provide valuable information for guiding both farm management practices and policymaking regarding pollinator conservation (Potts et al., 2016a). Furthermore, by combining crops’ PD with their economic value, we can assess the direct economic impact of pollinators on crop production and crop markets (Gallai et al., 2009; Potts et al., 2016b; Silva et al., 2021).

Studies such as Free (1993) and Klein et al. (2007) widely assessed pollinator's dependence of crops. Klein et al. (2007), the most comprehensive and currently used study to date, evaluated and compiled PD values in four categories (i.e. “little”, “modest”, “high”, and “essential”) for 91 major crops produced worldwide. This index shows the importance of evaluating crop pollination services and constitutes the base for economic assessments of pollination value, opening discussions and facilitating conservation actions and initiatives concerning pollinators and their importance. However, due to the continuous emergence of crops and new studies being available, an update on PD levels of crops is currently needed. Recent syntheses after the seminal work of Klein et al. (2007) include PD values for emergent crops; however, they are usually focused on a few economically important crops or specific regions of the globe (see Bishop & Nakagawa, 2021; Giannini et al., 2015; Mallinger et al., 2021; Olhnuud et al., 2022). Additionally, within a crop, different accessions (plants that share similar and/or selected traits, including cultivars, varieties and other infraspecific taxonomic levels) may differ greatly in self-compatibility and selfing ability (e.g. Kendall et al., 2020; Klatt et al., 2014) and, hence, different PD levels are expected (e.g. Bishop & Nakagawa, 2021; Carvalheiro et al., 2010; Marini et al., 2015). However, detailed information about PD levels in crop’s accessions is scattered in the literature, making it difficult to compile this data, and, to our knowledge, it is seldom accounted for in global studies.

Despite the growing availability of studies quantifying PD, there are challenges with the currently used methodologies, which could be underrepresenting the importance of pollinators and their associated economic value. Crops’ PD literature usually evaluates crop production after natural pollination (i.e. pollination provided by locally available pollinator communities), comparing it with the output after pollinators' exclusion (Fig. 1). Consequently, PD values using natural pollination will vary according to the local pollinator’s communities. Hence, we propose that a hand pollen supplementation treatment is more suitable to estimate the true level of PD since natural pollination may lead to underestimations of PD values. For example, for the same plant species, a natural pollination estimation based on an experiment run in an impoverished landscape with unfavourable conditions for pollinators will generate lower PD values than a similar experiment run in a landscape with rich and abundant pollinator communities able to provide suitable pollination services. Being pollination services often limited in nature (Bennett et al., 2018; Knight et al., 2005) and in crops (Garibaldi et al., 2011; Olhnuud et al., 2022; Potts et al., 2016a; Castro et al., 2021; Sáez et al., 2022), we expect that estimates of PD using natural pollination will be lower than PD values generated with hand-pollination. Moreover, as flower manipulations may affect flower and fruit development, we expect different methodologies associated with hand pollen supplementations to impact PD estimates negatively. Finally, as pollen supplementation may lead to directed resource allocation to treated structures, PD values are expected to be higher when pollination treatments are performed at smaller scales (e.g. flower level) than at larger ones (e.g. plant level).

We gathered information on pollination experiments for animal pollinated crops to test the abovementioned expectations and propose a methodological framework to estimate the PD of crops under optimal pollination. Finally, we provide an updated list of continuous PD values for animal pollinated crops, including crop accessions whenever available. This updated list will significantly contribute to more accurate future studies on the importance of pollinators for local and global economies associated with food and agricultural production.

Material and Methods

Literature search

To gather data on the contribution of animal pollination to crops production, a systematic search was conducted using Web of Science, Scopus and Google Scholar bibliographic databases (from January 1st 1900, to March 1st 2022). The search was focused solely on experiments performed in agricultural contexts and open conditions, excluding assessments on natural populations or closed greenhouses. The search was based on a list of animal pollinated crops from which fruit and/or seeds are used as food and goods (based on FAO list of worldwide produced crops in 2021; list of taxa given in Supporting Information) performing a literature search focused on species or common names as search terms (list of search terms given in Supporting Information). Different publication formats were considered (e.g. published articles, posters, theses, reports), verifying for duplicates across the different formats. Data was extracted to create PolLimCrop, a global database of pollen deposition limitation in crops (unpublished data).

Data extraction and dataset development

To construct a dataset of crops' PD, studies that included the following treatments were selected: hand pollen supplementation, where pollen was applied to flowers to achieve optimal pollination; natural pollination, where flowers received pollination services naturally present at the study location; and pollinator exclusion, where reproductive structures were excluded from animal pollination through caging or bagging. From these studies, the following information was extracted: 1) production variables associated with experimental pollination treatments, i.e. fruit set, fruit weight, seed set, seed number and/or seed weight; 2) data related to geographical and temporal aspects of the study such as country and year when the experiment was performed; and 3) experimental details as additional treatments performed on supplemental pollination (i.e. H – hand pollen supplementation, only; BH – pollinator exclusion and hand pollen supplementation; EH – emasculation and hand pollen supplementation; BEH – pollinator exclusion, emasculation and hand pollen supplementation), scale of the pollination experiment [i.e. pollination treatment applied to the complete plant, branch, inflorescence (which includes flower clusters) or flower (individual flower)], species and common names of the crop and part of the crop economically used (i.e. fruit or seed). Further details on extracted variables are provided in Table S1.

Estimates of pollinator dependence

Pollinator dependence (PD) value was calculated using the following equation:

PD = 1 – [pollinator exclusion production / pollinator-associated production]

where *pollinator exclusion production* refers to the production in the absence of pollinators, and *pollinator-associated production* refers to the production associated with animal pollinator visitation (i.e. natural pollination or hand pollen supplementation).

For PD estimates, fruit and seed variables available were used depending on which part of the crop is economically used (i.e. seed or fruit). In fruit crops, fruit-related production variables were used for PD calculation, i.e. fruit set and fruit weight. For seed crops, seed set, and seed number and weight were used, in addition to fruit set. When several production variables were provided, a mean value of the obtained PD values was calculated and used. In four entries (out of 564), pollinator exclusion production was 25% higher than pollinator-associated production and were likely related with methodological problems with the pollinator exclusion methodology. Therefore, PD value was not calculated for those four entries. When pollinator exclusion production was higher than pollinator-associated production, but the difference was below 25%, PD estimates were considered to be zero. The PD value was calculated for each entry that met the abovementioned conditions. PD ranged between 0 and 1, 0 representing the absence of PD and 1 representing maximum PD. Two PD values were calculated for each entry, one using hand pollen supplementation and pollinator exclusion treatments (PD-SUP) and the other using natural pollination and pollinator exclusion treatment (PD-NAT).

A final PD value was obtained for each entry (defined here as PD-final), using either hand pollen supplementation or natural pollination treatment, by selecting the maximum value obtained. Variation in production variables is expected, and thus, cases where natural pollination overcomes hand pollen supplementation may occur. Cases where production of natural pollination is much higher than after hand pollination might reflect methodological issues or lack of efficiency or success in hand pollen supplementation; such cases may affect the data and lead to misleading conclusions. Here, entries in which PD-NAT was 25% higher than PD-SUP were not used in statistical analyses. These represented only 11 entries (out of 564) and did not significantly affect overall conclusions (see Supporting Information). For every database entry, PD-SUP, PD-NAT and PD-final was added to the dataset for further analyses.

Statistical analyses

A total of 166 studies contained hand pollen supplementation, natural pollination and pollinator exclusion and were included in statistical analyses. To evaluate for differences between PD levels after natural pollination and hand pollen supplementation treatment, General Linear Mixed-Effects Models (GLMMs) were performed, using PD values obtained after the two treatments, including “treatment type” as an explanatory variable. To account for variation associated with crop identity, “crop” was included as a random variable in all models. Similarly, “article code” was also used as a random variable to remove confounding effects of within-study aspects.

To evaluate if PD values depended on specific aspects of the methodologies used, analyses were performed using PD-final obtained in our dataset. In particular, GLMMs were performed to analyse the effects of hand pollen supplementation methodology and scale of the pollination experiment on PD values. Hand pollen supplementation methodology included four techniques (see Table S3, ‘supplement type’). Scale included four experimental scales (see Table S3, ‘scale’). Again, “crop” and “article code” were used as random factors. GLMMs were performed using function “lmer” of the R package “lme4” (Bates et al., 2014), with logit transformation of adjusting factor of 0.01 of the R package “car” (Fox & Weisberg, 2019). Wald chi-square analyses were used to calculate the effect of tested variables on PD values. We then ran post hoc pairwise comparisons to test for differences within treatments of supplement type and scale, using R package “emmeans” (Lenth et al., 2018). The studies on apples contributed with 33% of PD values in all performed analyses (see Table S2, Crop “Apple”). To test if such a large contribution influenced our conclusions, all analyses without apple's entries were reran to evaluated if similar trends were observed.

Although PD values are presented as a continuous variable, for comparisons with previous global studies, PD values obtained here were translated into the same classes of PD as in Klein et al. (2007; little: 0–0.09 PD, modest: 0.10–0.39, high: 0.40–0.89, essential: 0.90–1.00). 2-sample tests for equality of proportions were performed using R package "stats", to compare class distribution obtained here with those in Klein et al. (2007). Differences within our results were tested by performing a 4-sample test, enabling us to evaluate significant differences in the proportions among classes. All analyses and graphs were obtained in R software (version 4.2.1).

Pollinator dependence of animal pollinated crops – Final table

A comprehensive final table was compiled using data collected from the 166 studies used in statistical analyses. An additional set of 52 studies bearing only hand-pollen supplementation or natural pollination (thus, excluded from statistical analyses) were added to the final table to provide the most comprehensive list of PD values for animal pollinated crops and their accessions (list of studies given in Supporting Information). In these cases, PD values were calculated based solely on the available treatment.

Mean PD values for a crop were obtained and assembled in a complete list of available crops (Table S2). Mean values were obtained using PD-final from each entry available, plus PD-final of the additional studies. Treatments that contributed to mean PD values (either hand pollen supplementation treatment, natural pollination, or both) are indicated in the dataset. Similarly, mean PD values were obtained and assembled for all the available accessions within crops (Table S3).

Results

Natural pollination versus hand pollen supplementation

A total of 166 studies, corresponding to 91 individual crops, were used in statistical analyses, including 549 entries with PD values (representing different crops, accessions, years and experimental sites). Crops with most entry values of PD were apple, oilseed rape and almond (representing 33.1%, 6.4% and 4.2% of total entries, respectively). Twenty-seven crops were represented by one value of PD only.

PD values estimated after hand pollen supplementation-associated production were significantly higher (ca. 5.7% higher on average) than using natural pollination-associated production (χ^2 = 38.5260, P < 0.0001; Fig. 2a; Table S4). In 51.5% of the entries, hand pollen supplementation treatment presented higher PD values than natural pollination (Figs 2b-2c). Also, for 23.9% of the entries, natural pollination and hand pollen supplementation treatment presented similar PD values (Figs 2b-2c). Finally, for 24.6% of the data entries, natural pollination led to higher PD values than hand pollen supplementation treatment (Figs 2b-2c).

Methodological constraints of the hand pollen supplementation treatment

No significant differences were found in PD values among different pollen supplementation techniques (χ^2 = 4.4784, P = 0.2142; Fig. S1a; Table S4). However, signs of resource limitation were observed, with significant differences in PD values among the different scales used in pollination experiments (χ^2 = 10.0600, P = 0.0181; Table S4 and S5). Despite significant *P*-value, no significant differences were observed among scales in post hoc tests (Fig. S1b; Table S6). Similar results were obtained when rerunning analyses without apple studies (Tables S7-S9).

Crop pollinator dependence values – an updated list

Mean PD values are provided for 119 animal pollinated crops, including data for 35 crops not listed previously or with no data in former global assessments (list of taxa with PD estimated values given in Supporting Information) (Table S2). Information on specific PD values of crop accessions (including cultivars, varieties and other infraspecific taxonomic levels) is provided for 86 crops, comprising 290 individual crop accessions (Table S3).

The mean value of PD (PD-final) across all crops of the list was 0.66 ± 0.29 (mean ± SD). Values varied, as expected, from no pollinator dependence (value of 0) to complete pollinator dependence (value of 1); however, a concentration of values around 1 was observed, with 79.8% of the crops having high PD values (i.e. PD ≥ 0.40) (Fig. 3a).

When considering the classes defined by Klein et al. (2007), significant differences in proportion of crops were observed among classes of PD (χ^2 = 77.3890, P < 0.0001). Compared with Klein et al. (2007), we observed evident changes in crop distribution (Fig. 4b). A significant increase in the proportion of crops where pollination needs are classified as "high" (χ^2 = 7.0277, P = 0.0080) and "essential" (χ^2 = 5.4494, P = 0.0196) was observed, with both categories having, in our study, more than the double of crops when compared with Klein et al. (2007) (Fig. 3b), representing 51.7% and 28.5% of the crops, respectively. The proportion of crops where pollination needs were classified as "little" (χ^2 = 19.112, P < 0.0001) and "modest" (χ^2 = 4.2276, P = 0.0398) decreased significantly in comparison with Klein et al. (2007), representing 3.5% and 16.4% of the crops, respectively (Table S10).

Discussion

Crop pollinator dependence values – an updated list

This study provides a new compilation of pollinator dependence (PD) values for animal pollinated crops. Compared with previous approaches, the list comprises, for the first time, continuous PD values for 119 worldwide crops, including 290 crop accessions, estimates for 35 crops not listed previously and detailed data for several crops that were once merged in large groups. As examples of the latter, we considered *Citrus* species individually while previously they were grouped as "citrus"; also, *Phaseolus vulgaris* (common bean) and *Phaseolus coccineus* (runner bean) that were previously grouped under "beans" were now regarded as individual species. By providing PD values discriminated for individual crop species and their accessions, our study contributes with vital and, until now, neglected information.

For several crop species, PD values given here differ from previous global assessments (Klein et al., 2007), with many crops having higher PD values than previously. This has resulted in an increased number of crops classified as having "high" or "essential" PD, from 47% (43 out of 91 animal pollinated crops, Klein et al. 2007) to 80% of the animal pollinated crops (95 out of 119 crops). These differences are mainly explained by the fact that we used hand pollen supplementation instead of natural pollination (primary treatment used in previous estimates) to obtain final PD value. As hand pollen supplementation accounts for effects of pollen limitation (PL), it provides more accurate measures of PD. Once PD estimations are usually based on natural levels of pollination, previous studies and compilations are substantially underestimating animal pollinator's importance for crop production.

The large variability of PD values observed here within crops was expected since the degree of selfing ability and self-compatibility is known to vary among accessions of crops (e.g. sunflower, Carvalheiro et al., 2011, oilseed rape, Hudewenz et al., 2014). Knowledge on pollination requirements of crops' accessions is crucial for suitable management decisions (Hudewenz et al., 2014). For example, in impoverished locations, when pollinator communities are insufficient to provide the needed pollination services to a crop, selecting accessions less dependent on pollinator communities may be a suitable solution to ameliorate production losses. Unfortunately, 29% of the studies analysed here did not provide information about crop accessions (or any other infraspecific taxonomic level, such as cultivar, variety, forma or clone), hindering the compilation of precise data. Considering the importance of this information (Hudewenz et al., 2014), we recommend that future works should always provide information and data for each accession of the crop under study.

The "optimal pollination level" from the plant perspective (i.e. plant fitness) differs from that of farmers perspective (i.e. agronomic and economic yield). To follow farmers' perspective, PD value was calculated using different production variables, depending on the part of the crop economically used (fruit or seed). Likewise, quantity (e.g. fruit set) and quality (e.g. fruit weight) production traits were used to calculate PD values, to accurately account for the impact of animal pollination at both levels. Studies on PD often focus on quantitative variables, with mixed responses between these and qualitative variables (e.g. Bartomeus et al. 2014; Stein et al. 2017). Here, however, only 30% of the dataset entries presented quantity and quality variables. Hence, we recommend that future experiments evaluate production variables related to both levels.

Natural pollination vs. hand pollen supplementation to calculate PD values

Hand pollen supplementation led to higher PD values than natural pollination in 51.5% of datapoints that had information in both treatments. These results are consistent with our predictions and indicate that PL is common, reducing yield level and, consequently, underestimating potential pollinator's contribution. Therefore, in locations where pollination services are inadequate and/or impoverished, such as landscapes of poor quality due to high levels of fragmentation and/or simplification (Aizen & Feinsinger, 2003, Nicholson et al., 2017), hand pollen supplementation is a more suitable treatment to achieve optimal crop yield and obtain an accurate estimate of PD value. However, despite the importance of accurate PD estimates to value pollinator's contribution to production systems, and even though hand pollen supplementation is widely used to study pollen limitation in wild plants (e.g. Bennett et al., 2018; Castro et al., 2015; Knight et al., 2005), in crops, its use for the calculation of PD has been rare (but see Bishop & Nakagawa, 2021; Garibaldi et al., 2011; Garratt et al., 2021). Therefore, based on the results obtained here, we recommend that hand pollen supplementation is included in pollination experiments that aim to assess the contribution of animal pollination to crops. A complete experimental design for such purposes is provided below and in Box 1.

Methodological guidelines for hand pollen supplementations

When performing hand pollen supplementations, assuring efficiency is critical (see Box 1). However, in plant families with complex flower structures or with flowers sensitive to manipulation, this can be challenging to achieve. In such cases, animal pollinators may perform better at pollinating than hand pollen supplementation by humans since animals are adapted to exploit floral resources. Thus, the fact that hand pollen supplementation produced lower production values in 24.6% of the data points compared with natural pollination is not entirely unexpected. It is possible that in these studies, the supplementation of pollen was not ideal or that over-pollination led to reduced yield. Indeed, technical approaches used in hand pollen supplementation, such as type of supplementation, scale at which pollination experiments are done and pollen source, are known to affect yield in certain crops (e.g. Webber et al., 2020).

Emasculation of flowers prior to hand pollen supplementation and bagging plants after hand pollination are practices often performed on pollination experiments to exclude production associated with self-pollination and/or avoid undesirable external pollen, respectively (e.g. Chacoff & Aizen, 2007; Kendall et al., 2020). Here, no significant differences were obtained between standard hand pollen supplementation and supplementation with some of the techniques detailed above, indicating that supplementations with these methodological approaches provide reliable estimates of PD or, at least, estimates comparable to hand pollinations.

PD values are expected to be higher when pollination treatments are performed at smaller scales (e.g. flower level) than at higher ones (e.g. plant level), as resources for fruit development in a plant are usually limited and will be preferentially (re)allocated to fruits with higher pollination quality (Webber et al., 2020). Although no significant differences were observed among different scales, higher PD values were obtained in experiments that used flower as a scale, with marginal *p*-values obtained when comparing flower vs. plant scales and flower vs. inflorescence scales ($P = 0.0646$ and $P = 0.0639$, respectively). Therefore, despite lack of a scale effect in analyses, future pollination experiments should be performed at the largest scale possible, avoiding using individual flowers as scale measurements.

Hand pollen supplementation should be included in crop pollination experiments as it accounts for PL, providing a more accurate method to calculate PD values and assess total pollinator's contribution to crop production. Yet, it should be bear in mind that the inclusion of hand pollen supplementation increases the time and complexity of crop pollination experiments, particularly in mass flowering or self-pruning crops (where sample size needs to be significantly increased to compensate for self-pruning losses) or in plants with complex and sensible flower structures (where hand pollen supplementation of flowers requires more time). Therefore, when designing a pollination experiment for a given crop, all factors linked with crop reproductive traits should be considered (Young & Young, 1992), acknowledging the limitations and advantages of selected treatments (see Box 1).

Conclusions

Our results highlight the importance of recognizing that the commonly applied method of assessing PD (comparing fruit set in plants exposed vs isolated from pollinators) can lead to an underestimation of PD values. Given that most published studies on pollinator's contribution to crops use PD values obtained through methodologies that did not account for pollen limitation, it is probable that pollinator's contribution to crops' local and global production (e.g. Klein et al., 2007), international trade markets (e.g. Silva et al. 2021), and economic value of pollinators (e.g. Gallai et al., 2009; Gianinni, 2015) are substantially undervalued. As a quantitative evaluation, this study brings significant input for future assessments of the economic value of pollination in crops.

Authors’ contributions

CS, LGC and SC developed initial hypothesis and statistical methods, which were discussed with HC and JL. CS and HC led literature search and data extraction. CS, HC and SC performed data revision and validation. CS wrote the first draft, and all remaining authors edited and commented on earlier versions of the manuscript.

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Conflict of Interest

None declared.

Data accessibility statement

Additional supporting information can be found online in Supporting Information section at the end of this article. Upon acceptance of the manuscript, data will be available via Dryad Digital Repository, with a provided DOI.

Supporting Information

Supporting information can be found online in Supporting Information section.

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Figures

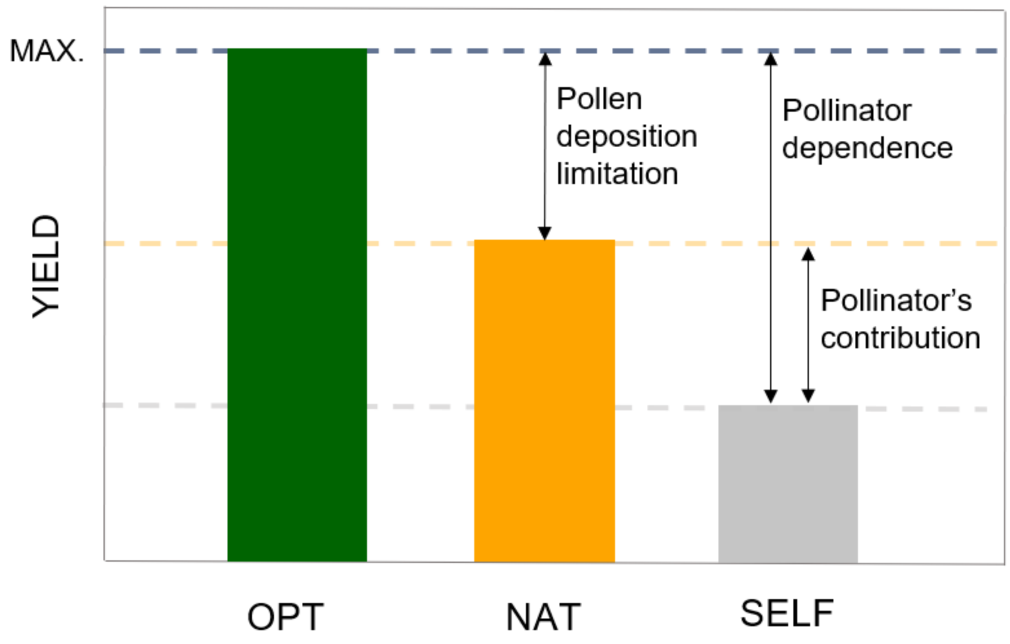


Figure 1. Theoretical representation of pollination components associated with yield in pollinator-dependent crops: optimal pollination levels for local study conditions (OPT), natural levels of pollination (NAT), and autonomous self-pollination levels (SELF). Associated indexes are also presented: (1) **pollen deposition limitation**, yield loss associated with limited pollen deposition levels; (2) **pollinator dependence**, yield directly dependent on pollinators (for simplification, here we considered a crop with negligible wind contribution for pollination) and (3) **pollinator's contribution**, yield associated with existing pollination services. See Box 1 for methodologies associated with estimations of each component and index.

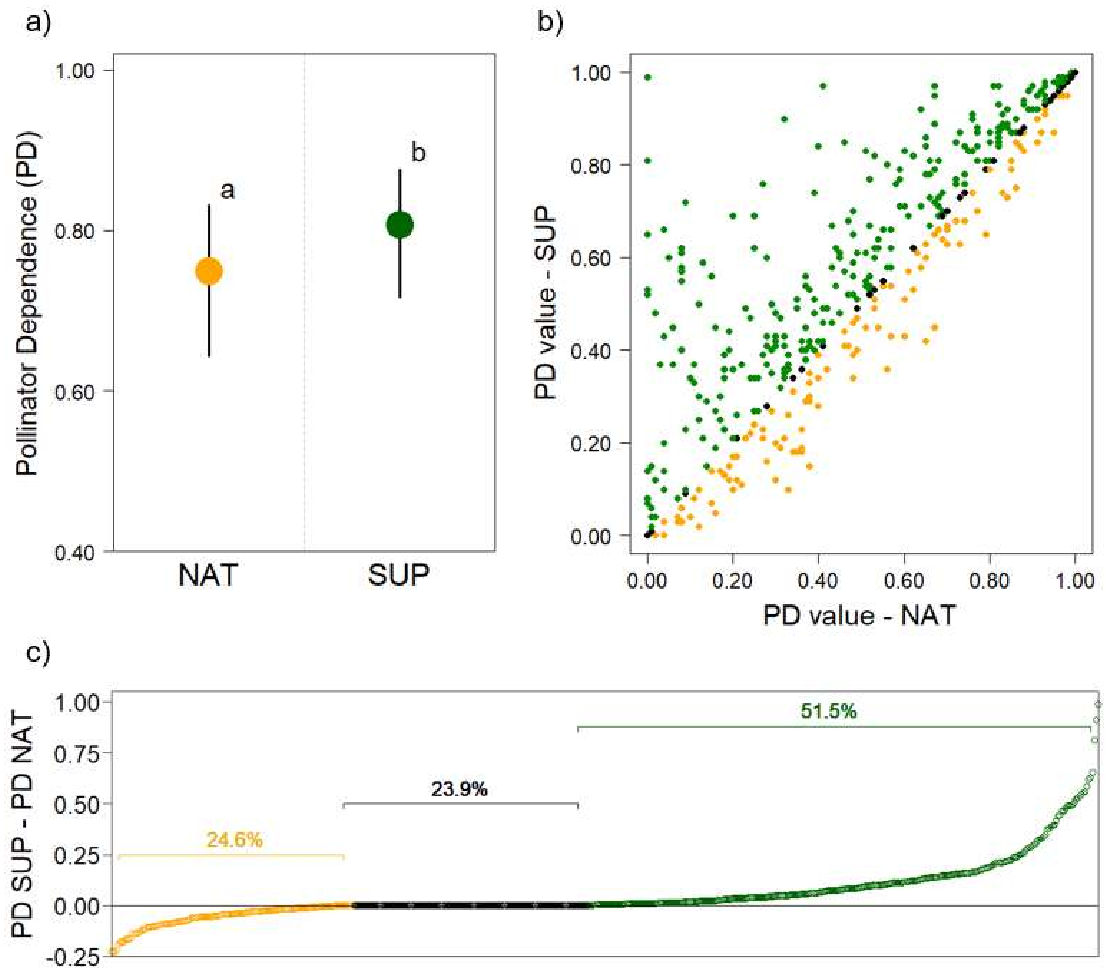


Figure 2 a) Estimated means and 95% confidence interval values for pollinator dependence (PD) estimates obtained with natural pollination (NAT) and hand pollen supplementation (SUP) treatment (χ^2 = 38.5260, P < 0.0001). Different letters indicate significant differences at P < 0.05. b) Scatterplot of PD values obtained through hand-supplementation treatment (SUP, y-axis) in relation to that obtained through natural pollination (NAT, x-axis); PD values in which PD-SUP > PD-NAT are represented as green dots, when PD-SUP < PD-NAT are represented as yellow dots and when PD-SUP = PD-NAT are represented as black dots. c) Difference between PD value from hand pollen supplementation and natural treatment (PD-SUP – PD-NAT) for each given entry; values range from -0.25 to 1.00 (differences lower than -0.25 were considered to result from methodological errors); negative differences, where PD-NAT was the highest value, are represented as yellow dots; values where PD-SUP = PD-NAT are represented by black dots; positive values, where PD-SUP was the highest value, are represented as green dot

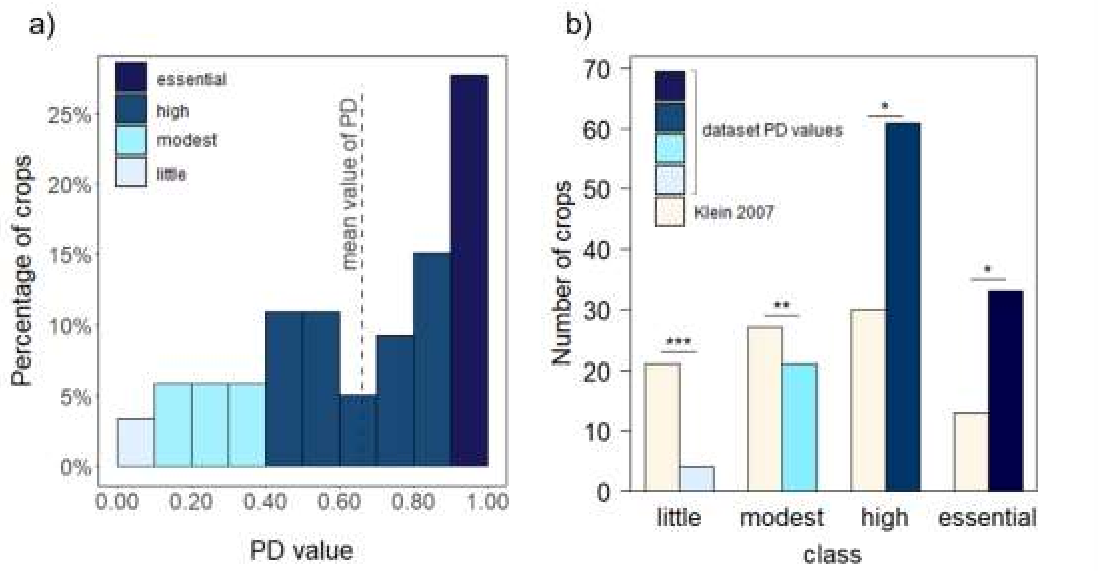
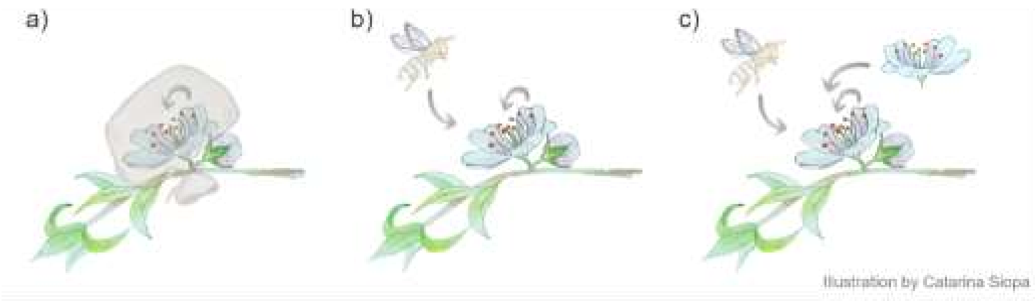


Figure 3. a) Percentage of crops along PD values (interval range of 0.10). Final PD was used for each crop (values given in Table S2). Overall mean PD is indicated through a dashed line. Different colour bars represent classes as defined by Klein et al. (2007); b) Number of crops on each PD class: “little” (PD values between 0-0.09), “modest” (0.10-0.39), “high” (0.40-0.89) and “essential” (0.90-1.00). Beige bars represent distribution of crops among classes of Klein et al. (2007), and different blue bars represent crops’ distribution in this study. Significant differences between current and Klein et al. (2007) for each PD class represented as *** for $P < 0.001$, ** for $0.001 < P < 0.01$ and * for $0.01 < P < 0.05$. Classes “no increase” and “unknown” in Klein et al. (2007) were excluded for the comparisons.

Box 1: Guidelines for pollination experiments when studying animal pollination contribution.

An experimental design should include the following treatments:



a) **pollinator exclusion:** a bagged treatment, without biotic visits. In crops also pollinated by wind, the experimental design should also evaluate its contribution using two bagging treatments, one using a mesh fabric that allows wind contribution, excluding only biotic interactions, and another using a mesh that restrains pollen movement by both wind and biotic agents. Wind contribution is given by the difference between the two bagged treatments.

b) **natural pollination:** a treatment without any manipulation of the reproductive units where flowers are naturally pollinated.

c) **optimal pollination** (or pollen supplementation)**:** a treatment where flowers are naturally pollinated and to which a hand pollen supplementation is provided. Pollen applications should be performed once or multiple times, depending on the crop's requirements. The use of compatible pollen is crucial, and several sources of compatible pollen should be applied.

Additional notes:

- Bigger scales are preferred (i.e. branch or plant scales).
- Hand pollen supplementations without additional treatments, as bagging or emasculation, are advised but, if additional treatments are essential for the experiment, they can be considered.
- All relevant details should be provided (e.g. studied accessions), additionally to details surrounding agricultural management (e.g. application of reproductive hormones, presence of managed pollinators).

Table S2. Pollinator dependence values of crops. The overall mean, standard error (SE), minimum (min) and maximum (max) values of pollinator dependence are provided, along with the number of accessions with information and the number of entries for each crop. NA denotes no available information.

Species	Crop common name	Number of accessions with information	Pollinator dependence value				Number of entries
			mean	SE	min	max	
Abelmoschus esculentus	Okra	2	0.14	0.08	0.00	0.36	4
Acca sellowiana	Feijoa	7	0.95	0.03	0.79	1.00	7
Actinidia chinensis	Golden kiwifruit	3	0.73	0.11	0.47	0.94	4
Actinidia chinensis var. *deliciosa*	Kiwifruit	7	0.59	0.09	0.10	1.00	14
Anacardium occidentale	Cashew	2	1.00	0.00	1.00	1.00	4
Annona cherimola	Cherimoya	1	1.00	NA	1.00	1.00	1
Annona crassiflora	Marolo	NA	1.00	0.00	1.00	1.00	2
Annona squamosa	Sugar apple	NA	1.00	NA	1.00	1.00	1
Annona spp.*	Custard apple	1	1.00	0.00	1.00	1.00	5
Artocarpus heterophyllus	Jackfruit	2	0.84	0.05	0.79	0.88	2
Asimina parviflora	Pawpaw	NA	1.00	0.00	1.00	1.00	2
Averrhoa carambola	Carambola	1	0.93	NA	0.93	0.93	1
Bertholletia excelsa	Brazil nut	NA	1.00	NA	1.00	1.00	1
Bixa orellana	Annatto	NA	0.98	NA	0.98	0.98	1
Brassica juncea	Mustard seed	NA	0.40	0.03	0.34	0.48	4
Brassica napus	Oilseed rape	8	0.27	0.03	0.00	0.69	35
Brassica rapa	Canola	2	0.39	0.04	0.30	0.51	4
Cajanus cajan	Pigeon pea	NA	0.17	0.01	0.15	0.19	6

Camellia oleifera	Camellia	NA	0.87	0.04	0.81	0.94	3
Capparis spinosa	Caper	NA	0.83	NA	0.83	0.83	1
Capsicum annuum	Chilli	2	0.48	0.07	0.10	0.93	14
Capsicum chinense	Habanero pepper	1	0.85	NA	0.85	0.85	1
Carica papaya	Papaya	1	0.91	NA	0.91	0.91	1
Carthamus tinctorius	Safflower	NA	0.58	NA	0.58	0.58	1
Carum carvi	Caraway seed	NA	0.20	NA	0.20	0.20	1
Castanea crenata	Japanese chestnut	2	0.77	0.09	0.59	0.86	3
Castanea mollissima	Chinese chestnut	1	0.06	0.03	0.02	0.12	3
Castanea sativa	European chestnut	6	0.35	0.07	0.04	0.63	8
Castanea sativa × *C. crenata*	Chestnut	7	0.76	0.05	0.55	0.94	10
Cicer arietinum	Chickpea	1	0.27	NA	0.27	0.27	1
Citrullus lanatus	Watermelon	2	0.90	0.05	0.84	1.00	3
Citrus clementina	Clementine	3	0.82	0.07	0.67	1.00	5
Citrus limon	Lemon	NA	0.80	NA	0.80	0.80	1
Citrus paradisi	Grapefruit	5	0.67	0.04	0.53	1.00	14
C. paradisi × *C. reticulata*	Tangelo	2	1.00	0.00	1.00	1.00	2
Citrus reticulata	Mandarin, tangerine	2	0.67	0.34	0.33	1.00	2
Citrus sinensis	Orange	4	0.19	0.04	0.06	0.31	7
Coffea arabica	Arabic coffee	2	0.31	0.05	0.21	0.37	3
Coffea canephora	Coffee	NA	0.63	0.32	0.00	1.00	3
Coriandrum sativum	Coriander	1	0.47	0.33	0.14	0.80	2

Cucumis melo	Melon	2	1.00	0.00	1.00	1.00	4
Cucumis sativus	Cucumber	2	0.56	0.10	0.26	0.81	5
Cucurbita moschata	Gourd	2	0.90	0.08	0.70	1.00	3
Cucurbita pepo	Squash	4	1.00	0.00	1.00	1.00	5
Cucurbita pepo	Courgette	NA	0.31	0.06	0.21	0.40	1
Cuminum cyminum	Cumin	1	0.29	NA	0.29	0.29	1
Dimocarpus longan	Longan	NA	0.50	NA	0.50	0.50	1
Diospyros kaki	Persimmon	4	0.60	0.10	0.21	1.00	9
Durio zibethinus	Durian	1	0.92	0.09	0.83	1.00	2
Elaeis guineensis	Oil palm	NA	0.81	NA	0.81	0.81	1
Elettaria cardamomum	Cardamom	2	0.99	0.02	0.97	1.00	2
Eriobotrya japonica	Loquat	1	0.75	0.02	0.73	0.76	2
Euterpe oleracea	Açaí	NA	0.84	NA	0.84	0.84	1
Ficus carica	Fig	1	0.32	NA	0.32	0.32	1
Foeniculum vulgare	Fennel	1	0.87	NA	0.87	0.87	1
Fragaria × ananassa	Strawberry	2	0.54	0.09	0.42	0.74	3
Glycine max	Soybean	4	0.19	0.06	0.00	0.37	5
Gossypium hirsutum	Cottonseed	2	0.20	0.05	0.07	0.37	6
Helianthus annuus	Sunflower	7	0.54	0.09	0.08	0.93	8
Jatropha curcas	Jatrofa	NA	0.58	0.07	0.19	0.87	8
Linum usitatissimum	Linseed	1	0.03	0.03	0.00	0.04	2
Litchi chinensis	Lychee	9	0.80	0.08	0.14	1.00	15

Lonicera caerulea	Honeysuckle	2	0.64	0.02	0.62	0.65	2
Luffa acutangula	Chinese okra	2	1.00	0.00	1.00	1.00	2
Luffa aegyptiaca	Smooth gourd	4	1.00	0.00	1.00	1.00	4
Macadamia spp.***	Macadamia	2	0.66	0.23	0.07	1.00	8
Macadamia integrifolia	Macadamia	2	0.80	0.11	0.56	1.00	4
Malpighia emarginata	Acerola cherry	3	0.86	0.07	0.66	1.00	5
Malus domestica	Apple	25	0.73	0.02	0.02	1.00	182
Mangifera indica	Mango	2	0.71	0.18	0.53	0.88	2
Manilkara zapota	Sapodilla	1	0.90	NA	0.90	0.90	1
Momordica charantia	Bitter melon	2	0.95	0.05	0.68	1.00	7
Nephelium lappaceum	Rambutan	1	0.54	0.02	0.52	0.56	2
Nigella sativa	Black cumin	NA	0.47	0.01	0.46	0.47	2
Opuntia ficus-indica	Cactus pear	1	0.41	0.07	0.17	0.57	5
Paeonia ostii	Peony	1	0.52	NA	0.52	0.52	1
Papaver somniferum	Poppy seed	NA	0.41	NA	0.41	0.41	1
Passiflora edulis	Passion fruit	NA	1.00	0.00	0.97	1.00	8
Passiflora ligularis	Granadilla	NA	0.99	NA	0.99	0.99	1
Persea americana	Avocado	1	0.86	NA	0.86	0.86	1
Phaseolus coccineus	Runner bean	4	0.78	0.08	0.44	1.00	8
Phaseolus vulgaris	Bean	3	0.19	0.11	0.00	0.37	2
Physalis angulata	Camapu	NA	1.00	NA	1.00	1.00	1
Physalis peruviana	Goldenberry	NA	0.34	0.02	0.32	0.35	2

Pimpinella anisum	Anise	NA	0.45	0.02	0.43	0.47	2
Polaskia chichipe	Chichituna	NA	0.67	NA	0.67	0.67	1
Prunus armeniaca	Apricot	1	0.95	0.04	0.87	1.00	3
Prunus avium	Sweet cherry	1	0.82	0.17	0.49	1.00	3
Prunus cerasus	Sour cherry	5	0.75	0.06	0.36	0.97	9
Prunus dulcis	Almond	13	0.86	0.03	0.38	1.00	23
Prunus persica	Peach, nectarine	43	0.37	0.03	0.08	0.73	43
Psidium guajava	Guava	1	0.08	NA	0.08	0.08	1
Punica granatum	Pomegranate	3	0.40	0.02	0.37	0.44	3
Pyrus communis	Pear	6	0.74	0.10	0.15	1.00	8
Ribes rubrum	Currant	1	0.42	NA	0.42	0.42	1
Ribes uva-crispa	Gooseberry	5	0.45	0.06	0.27	0.65	7
Ricinus communis	Castor bean	NA	0.81	NA	0.81	0.81	1
Rubus fruticosus	Blackberry	2	0.45	0.06	0.39	0.51	2
Rubus idaeus	Raspberry	5	0.55	0.07	0.07	0.70	8
Selenicereus undatus	White-fleshed pitaya	1	0.22	NA	0.22	0.22	1
Selenicereus spp.**	Red-peel pitaya	3	1.00	0.00	1.00	1.00	3
Sesamum indicum	Sesame seed	2	0.25	0.24	0.01	0.49	2
Solanum lycopersicum	Tomato	2	0.40	0.12	0.28	0.52	2
Solanum melongena	Eggplant	3	0.83	0.04	0.74	1.00	8
Spondias mombin	Hog plum	1	0.78	NA	0.78	0.78	1
Theobroma cacao	Cocoa	NA	1.00	NA	1.00	1.00	1

Trichosanthes cucumerina	Snake gourd	3	0.91	0.06	0.73	1.00	4
Trichosanthes dioica	Pointed gourd	1	1.00	0.00	1.00	1.00	2
Trifolium alexandrinum	Berseem	NA	0.24	0.04	0.20	0.27	2
Vaccinium corymbosum	Highbush blueberry	6	0.53	0.04	0.28	0.92	20
Vaccinium macrocarpon	Cranberry	1	0.58	NA	0.58	0.58	1
Vaccinium myrtillus	Bilberry	NA	0.93	NA	0.93	0.93	1
Vaccinium virgatum	Rabbit-eye blueberry	NA	0.79	0.11	0.60	1.00	4
Vaccinium vitis-idaea	Linganberry	NA	0.88	NA	0.88	0.88	1
*Vanilla planifolia*ꝉ	Vanilla	NA	1.00	NA	1.00	1.00	1
Vicia faba	Broad bean	1	0.05	0.03	0.02	0.08	2
Vigna unguiculata	Cowpea	2	0.22	0.11	0.04	0.42	3
Vitellaria paradoxa	Karite nut	1	0.54	0.20	0.08	1.00	6
Ziziphus jujuba	Jujube	NA	0.97	NA	0.97	0.97	1

Notes: Our study extends the existing data; however, because we only used studies with pollination experiments, some species previously reported and for which we could not find relevant publications may be missing from our list.

**Annona* spp. includes Annona hybrids (e.g. *Annona squamosa* × *Annona cherimola*)

** *Selenicereus* spp. was not always given at the species level by included studies. Difficulties in separating species and accessions are present due to high intra- and/or inter-specific hybridization. Here, we considered two crops: *Hylocereus* spp. (including red-peel pitayas) and *Hylocereus undatus* (white-peel pitaya).

****Macadamia* spp. is adopted for studies in which species level was not given, or hybrids were studied.

ꝉ*Vanilla planifolia* was included in this list, although a complete pollination experiment was not found in the literature (due to the lack of a pollinator exclusion treatment). Once vanilla species possess a rostellum membrane that physically divides female and male flower structures, self-pollination is prevented (Rodolphe et al. 2011), and the crop depends entirely on pollinators.

Rodolphe, G., Séverine, B., Michel, G., & Pascale, B. (2011). Biodiversity and evolution in the Vanilla genus. In: *The dynamical processes of biodiversity-case studies of evolution and spatial distribution*), 1-27.

Table S3. Pollinator dependence values of accessions for each species/crop. The mean, standard error (SE), minimum (min) and maximum (max) values of pollinator dependence, along with the total number of entries for each included accession (i.e. cultivar, variety, and other infraspecific taxonomic levels), are provided. NA denotes no available information.

Species	Crop / Plant genotype	Pollinator dependence value				Number of entries
		mean	SE	min	max	
Abelmoschus esculentus	Okra					
	var. *Clemson spineless*	0.10	0.02	0.07	0.12	2
	var. *Shakthi*	0.36	NA	0.36	0.36	1
Acca sellowiana	Feijoa					
	clone “51”	0.79	NA	0.79	0.79	1
	clone “101”	1	NA	1	1	1
	clone “453 N.2”	1	NA	1	1	1
	clone “454 N.2”	1	NA	1	1	1
	clone “456 N.2”	1	NA	1	1	1
	clone “457 N.2”	1	NA	1	1	1
	clone “458 N.2”	0.84	NA	0.84	0.84	1
Actinidia chinensis	Golden Kiwifruit					
	cv. “Golden Sunshine”	0.62	NA	0.62	0.62	1
	cv. “Gulf Coast Gold”	0.87	NA	0.87	0.87	1
	cv. “Haegeum”	0.94	NA	0.94	0.94	1
Actinidia chinensis var. *deliciosa*	Kiwifruit					
	cv. “Allison”	1.00	NA	1.00	1.00	1
	cv. “BoErica”	0.61	NA	0.61	0.61	1
	cv. “Bruno”	1.00	NA	1.00	1.00	1
	cv. “Early Green”	0.25	NA	0.25	0.25	1
	cv. “Hayward”	0.50	0.11	0.10	1.00	8
	cv. “Monty”	1.00	NA	1.00	1.00	1
	cv. “Tsechelidis”	0.41	NA	0.41	0.41	1
Anacardium occidentale	Cashew					
	cv. “CCP 1001”	1.00	0.00	1.00	1.00	2
	cv. “CCP76”	1.00	0.00	1.00	1.00	2
Annona sp.	Custard Apple					
	cv. “Hillary White”	1.00	0.00	1.00	1.00	5
Annona cherimola	Cherimoya					

	cv. “Big Sister”	1.00	NA	1.00	1.00	1
Artocarpus heterophyllus	Jackfruit					
	cv. “Chee”	0.79	NA	0.79	0.79	1
	cv. “Dang Rasimi”	0.88	NA	0.88	0.88	1
Averrhoa carambola	Carambola					
	cv. “Mih Tao”	0.93	NA	0.93	0.93	1
Brassica napus	Oilseed rape					
	cv. “CTC-4”	0.16	NA	0.16	0.16	1
	cv. “DK Exquisite”	0.12	NA	0.12	0.12	1
	cv. “Hyola 420”	0.20	NA	0.20	0.20	1
	cv. “Hyola 61”	0.42	0.21	0.21	0.62	2
	cv. “Sherlock”	0.24	NA	0.24	0.24	1
	cv. “Traviata”	0.25	NA	0.25	0.25	1
	cv. “Treffer”	0.42	NA	0.42	0.42	1
	cv. “Visby”	0.36	NA	0.36	0.36	1
Brassica rapa	Canola					
	cv. “Arlo”	0.38	NA	0.38	0.38	1
	cv. “Pragati”	0.37	NA	0.37	0.37	1
Capsicum annuum	Chilli					
	cv. “All Big”	0.10	NA	0.10	0.10	1
	var. *Samn*	0.4	NA	0.4	0.4	1
Capsicum chinense	Habanero pepper					
	cv. “Habanero”	0.85	NA	0.85	0.85	1
Carica papaya	Papaya					
	cv. “Maradol”	0.91	NA	0.91	0.91	1
Castanea crenata	Japanese chestnut					
	cv. “Ishizuki”	0.73	0.14	0.59	0.86	2
	cv. “Tsukuba”	0.85	NA	0.85	0.85	1
Castanea mollissima	Chinese chestnut					
	cv. “Zaodali”	0.06	0.03	0.02	0.12	3
Castanea sativa	European chestnut					
	cv. “Judia”	0.40	NA	0.40	0.40	1
	cv. “Longal”	0.19	0.15	0.04	0.34	2
	cv. “Marillac”	0.63	NA	0.63	0.63	1
	cv. “Marrone di Lusern”	0.39	NA	0.39	0.39	1
	cv. “Martainha”	0.45	0.04	0.41	0.49	2

	cv. “Verdeal”	0.08	NA	0.08	0.08	1
Castanea sativa × C. crenata	Chestnut					
	cv. “Bellefer”	0.72	NA	0.72	0.72	1
	cv. “Betizac”	0.86	NA	0.86	0.86	1
	cv. “Florifer”	0.55	NA	0.55	0.55	1
	cv. “Maraval”	0.60	NA	0.60	0.60	1
	cv. “Marigoule”	0.85	0.07	0.64	0.94	4
	cv. “OG19”	0.64	NA	0.64	0.64	1
	cv. “Vignols”	0.79	NA	0.79	0.79	1
Cicer arietinum	Chickpea					
	cv. “Desi”	0.27	NA	0.27	0.27	1
Citrullus lanatus	Watermelon					
	cv. “Malali”	0.87	NA	0.87	0.87	1
	cv. “Samara F1”	0.84	NA	0.84	0.84	1
Citrus clementina	Clementine					
	cv. “Afourer”	0.67	NA	0.67	0.67	1
	cv. “Fi Sodea”	0.97	NA	0.97	0.97	1
	cv. “Nules”	1.00	NA	1.00	1.00	1
Citrus paradisi	Grapefruit					
	cv. “Franks”	0.95	NA	0.95	0.95	1
	cv. “Mcgain”s”	1.00	NA	1.00	1.00	1
	cv. “Minneola”	0.58	0.01	0.53	0.62	11
	cv. “Rio Red”	0.94	NA	0.94	0.94	1
	cv. “Rouge la Toma”	0.79	NA	0.79	0.79	1
C. paradisi × C. reticulata	Tangelo					
	cv. “Lee”	1.00	NA	1.00	1.00	1
	cv. “Nova”	1.00	NA	1.00	1.00	1
Citrus reticulata	Mandarin, tangerine					
	cv. “Criolla”	0.33	NA	0.33	0.33	1
	cv. “Fairchild”	1.00	NA	1.00	1.00	1
Citrus sinensis	Orange					
	cv. “Early Gold”	0.15	0.05	0.09	0.20	2
	var. “Pera ro”	0.06	NA	0.06	0.06	1
	cv. “Rhod-e-Red”	0.21	0.07	0.14	0.28	2
	cv. “Trovita”	0.30	0.02	0.28	0.31	2
Coffea arabica	Arabic Coffee					

	cv. “Maragogipe”	0.21	NA	0.21	0.21	1
	cv. “Mundo Novo”	0.37	NA	0.37	0.37	1
Coriandrum sativum	Coriander					
	cv. “Waltahi”	0.14	NA	0.14	0.14	1
Cucumis melo	Melon					
	var. *agrestis*	1.00	0.00	1.00	1.00	2
	cv. “HM-43”	1.00	0.00	1.00	1.00	2
Cucumis sativus	Cucumber					
	var. *Ashley*	0.52	0.10	0.42	0.62	2
	cv. “Swam Ageti”	0.81	NA	0.81	0.81	1
Cucurbita moschata	Gourd					
	var. *Jacarezinho*	1.00	NA			1
	cv. “Meni Brasileira”	1.00	NA			1
Cucurbita pepo	Squash					
	cv. “Chamatkar”	1.00	NA	1.00	1.00	1
	cv. “Chandra”	1.00	NA	1.00	1.00	1
	cv. “Gold Queen”	1.00	NA	1.00	1.00	1
	cv. “Parikrama”	1.00	NA	1.00	1.00	1
Cucurbita pepo	Courgette					
	var. *Tosca*	0.31	0.06	0.21	0.4	2
Cuminum cyminum	Cumin					
	var. *GC-4*	0.29	NA	0.29	0.29	1
Diospyros kaki	Persimmon					
	cv. “Fuyu”	0.42	0.05	0.21	0.56	5
	cv. “Giant Fuyu”	1.00	NA	1.00	1.00	1
	cv. “O”Gosho”	1.00	NA	1.00	1.00	1
	cv. “Tabebashi”	0.39	NA	0.39	0.39	1
Durio zibethinus	Durian					
	cv. “Monthong”	1.00	NA	1.00	1.00	1
Elettaria cardamomum	Cardamom					
	cv. “Malabar”	0.97	NA	0.97	0.97	1
	cv. “Njellani”	1.00	NA	1.00	1.00	1
Eriobotrya japonica	Loquat					
	cv. “Akko13”	0.75	0.02	0.73	0.76	2
Ficus carica	Fig					
	var. *Nabout*	0.32	NA	0.32	0.32	1

Foeniculum vulgare	Fennel					
	var. *Jupiter*	0.87	NA	0.87	0.87	1
Fragaria × ananassa	Strawberry					
	cv. "Honeoye"	0.42	NA	0.42	0.42	1
	var. *Jewel*	0.60	0.11	0.49	0.71	2
Glycine max	Soybean					
	var. *BRS-113*	0.37	NA	0.37	0.37	1
	cv. "BRS Carnaúba"	0.06	NA	0.06	0.06	1
	var. *IRAT 278*	0.27	0.01	0.26	0.28	2
	var. *Nidera A 4990 RG*	0.08	0.08	0.00	0.15	2
Gossypium hirsutum	Cottonseed					
	cv. "CNPA-7MH"	0.27	NA	0.27	0.27	1
	var. *FK37*	0.37	NA	0.37	0.37	1
Helianthus annuus	Sunflower					
	clone NDSH-1	0.53	NA	0.53	0.53	1
	cv. "5009"	0.48	NA	0.48	0.48	1
	cv. "9530"	0.08	NA	0.08	0.08	1
	cv. "9592"	0.54	NA	0.54	0.54	1
	cv. "Hysun 30"	0.93	NA	0.93	0.93	1
	cv. "Jaguar II"	0.31	NA	0.31	0.31	1
	cv. "Royal Hybrid 843"	0.61	NA	0.61	0.61	1
Hylocereus undatus	White-fleshed pitaya					
	cv. "VN White"	0.22	NA	0.22	0.22	1
Hylocereus spp.	Red-peel pitaya					
	cv. "Chaozhou 5"	1.00	NA	1.00	1.00	1
	cv. "F11"	1.00	NA	1.00	1.00	1
	cv. "Orejona"	1.00	NA	1.00	1.00	1
Linum usitatissimum	Linseed					
	cv. "Antares"	0.03	0.03	0.00	0.04	2
Litchi chinensis	Lychee					
	cv. "Ajhauli"	0.39	NA	0.39	0.39	1
	cv. "Dehradoon"	0.14	NA	0.14	0.14	1
	cv. "Dehra Rose"	1.00	NA	1.00	1.00	1
	cv. "Deshi"	1.00	NA	1.00	1.00	1
	cv. "Ellaichi"	1.00	NA	1.00	1.00	1
	cv. "Late Large Red"	1.00	NA	1.00	1.00	1
	cv. "Rose Scented"	0.17	NA	0.17	0.17	1

	cv. “Shahi”	0.78	0.22	0.56	1.00	2
	cv. “Trikolia”	1.00	NA	1.00	1.00	1
Lonicera caerulea	Honeysuckle					
	cv. “Gerda”	0.65	NA	0.65	0.65	1
	cv. “Viola”	0.62	NA	0.62	0.62	1
Luffa acutangula	Chinese Okra					
	cv. “Arka sujath”	1.00	NA	1.00	1.00	1
	cv. “Arka sumeet”	1.00	NA	1.00	1.00	1
Luffa aegyptiaca	Smoth gourd					
	cv. “C-2016”	1.00	NA	1.00	1.00	1
	cv. “Hirat”	1.00	NA	1.00	1.00	1
	cv. “Pusa Chickni”	1.00	NA	1.00	1.00	1
	cv. “Ragini”	1.00	NA	1.00	1.00	1
Macadamia spp.	Macadamia					
	cv. “246”	0.69	0.20	0.69	0.69	4
	cv. “A4”	0.82	0.20	0.82	0.82	3
Macadamia integrifolia	Macadamia					
	cv. “741”	0.97	NA	0.97	0.97	1
	cv. “A268”	1.00	NA	1.00	1.00	1
Malpighia emarginata	Acerola cherry					
	cv. “Flor Branca”	0.66	NA	0.66	0.66	1
	cv. “Okiwa”	0.74	NA	0.74	0.74	1
	cv. “Sertaneja”	0.88	NA	0.88	0.88	1
Malus domestica	Apple					
	cv. “Amanda”	0.82	0.06	0.76	0.88	2
	cv. “Aport”	1.00	0.00	1.00	1.00	2
	cv. “Aroma”	0.51	0.06	0.27	1.00	16
	cv. “Boskoop”	1.00	NA	1.00	1.00	1
	cv. “Braeburn”	0.75	0.05	0.36	1.00	21
	cv. “Bramley”	0.58	0.13	0.41	0.96	4
	cv. “Cox”	0.46	0.06	0.15	1.00	11
	cv. “Elstar”	0.65	0.12	0.15	1.00	8
	cv. “Fuji”	0.51	NA	0.51	0.51	1
	cv. “Gala”	0.56	0.03	0.23	1.00	39
	cv. “Gilly”	0.86	0.04	0.82	0.90	2
	cv. “Golden”	0.89	0.03	0.34	1.00	26
	cv. “Hastings”	0.85	0.04	0.76	0.97	4

	cv. “Idared”	0.56	0.16	0.40	0.71	2
	cv. “Ingrid-Marie”	1.00	NA	1.00	1.00	1
	cv. “Jogold”	0.72	0.10	0.60	0.91	3
	cv. “Kandil”	1.00	NA	1.00	1.00	1
	cv. “Kirgizski zimni”	1.00	NA	1.00	1.00	1
	cv. “Iivka”	0.40	NA	0.40	0.40	1
	cv. “Montuan”	1.00	NA	1.00	1.00	1
	cv. “Pink Lady”	0.99	0.01	0.97	1.00	5
	cv. “Renet zolotoi”	1.00	NA	1.00	1.00	1
	cv. “Rubinola”	0.84	NA	0.84	0.84	1
	cv. “Starkrimson”	1.00	NA	1.00	1.00	1
	cv. “Topaz”	0.97	0.03	0.94	1.00	2
Mangifera indica	Mango					
	cv. “Chok An”	0.88	NA	0.88	0.88	1
	cv. “Sala”	0.53	NA	0.53	0.53	1
Manilkara achras	Sapodilla					
	cv. “Jantung”	0.90	NA	0.90	0.90	1
Momordica charantia	Bitter melon					
	var. *neelam 105*	1.00	0.00	1.00	1.00	3
	var. *raja*	1.00	NA	1.00	1.00	1
Nephelium lappaceum	Rambutan					
	var. “CERI61”	0.54	0.02	0.52	0.56	2
Opuntia ficus-indica	Cactus pear					
	cv. “Gialla”	0.41	0.07	0.17	0.57	5
Paeonia ostii	Peony					
	cv. “Feng Dan”	0.52	NA	0.52	0.52	1
Persea americana	Avocado					
	cv. “West Indian”	0.86	NA	0.86	0.86	1
Phaseolus coccineus	Runner bean					
	cv. “Achievement”	0.67	0.12	0.56	0.79	2
	cv. “Bianco di Spagna”	0.71	0.27	0.44	0.97	2
	cv. “Kelvedon Marvel”	0.95	0.03	0.90	1.00	3
	cv. “Streamline”	0.61	NA	0.61	0.61	1
Phaseolus vulgaris	Bean					
	cv. “Kariasii”	0.19	NA	0.19	0.19	1
	cv. “Lyamungo 90”	0.00	NA	0.00	0.00	1

	cv. "Processor"	0.37	NA	0.37	0.37	1
Prunus armeniaca	Apricot					
	cv. "Sundrop"	0.95	0.04	0.87	1.00	3
Prunus avium	Sweet cherry					
	cv. "Royal Ann"	0.49	NA	0.49	0.49	1
Prunus cerasus	Sour cherry					
	cv. "Csengodi"	0.87	0.01	0.86	0.87	2
	cv. "Eva"	0.83	0.02	0.81	0.84	2
	cv. "Pandy 279"	0.97	NA	0.97	0.97	1
	cv. "Petri"	0.55	0.19	0.36	0.73	2
	cv. "Ujfehertoi furtos"	0.67	0.03	0.64	0.70	2
Prunus dulcis	Almond					
	cv. "Guara"	0.85	NA	0.85	0.85	1
	cv. "Nonpareil"	0.95	NA	0.95	0.95	1
	selection "A-10-2"	0.91	0.05	0.86	0.95	2
	selection "A-10-6"	0.99	0.00	0.99	0.99	2
	selection "B-4-2"	0.72	NA	0.72	0.72	1
	selection "B-5-2"	1.00	0.01	0.99	1.00	2
	selection "B-5-9"	0.98	0.01	0.97	0.98	2
	selection "C-11-1"	1.00	0.01	0.99	1.00	2
	selection "D-3-5"	0.59	NA	0.59	0.59	1
	selection "D-4-15"	0.99	0.02	0.97	1.00	2
	selection "E-5-7"	0.38	NA	0.38	0.38	1
	selection "G-5-2"	0.70	0.02	0.66	0.72	3
	selection "A-10-8"	0.80	0.02	0.78	0.81	2
Prunus persica	Peach, nectarine					
	cv. "Aurora 1"	0.11	NA	0.11	0.11	1
	var. *Baby Gold 5*	0.48	NA	0.48	0.48	1
	var. *Baby Gold 6*	0.53	NA	0.53	0.53	1
	var. *Baby Gold 7*	0.34	NA	0.34	0.34	1
	var. *Blazing Gold*	0.08	NA	0.08	0.08	1
	var. *Champion*	0.21	NA	0.21	0.21	1
	var. *Dixired*	0.47	NA	0.47	0.47	1
	var. *Early Redhaven*	0.09	NA	0.09	0.09	1
	var. *Elberta*	0.14	NA	0.14	0.14	1
	var. *Flavortop*	0.53	NA	0.53	0.53	1
	var. *Frederica*	0.41	NA	0.41	0.41	1

	var. *Fusador*	0.56	NA	0.56	0.56	1
	cv. “Golden Queen”	0.23	NA	0.23	0.23	1
	var. *Hale Haven*	0.43	NA	0.43	0.43	1
	var. *Independence*	0.62	NA	0.62	0.62	1
	var. *J.H. Hale*	0.73	NA	0.73	0.73	1
	var. *Jerseyland*	0.08	NA	0.08	0.08	1
	var. *La Fayette*	0.24	NA	0.24	0.24	1
	var. *Lexington*	0.40	NA	0.40	0.40	1
	var. *Loadel*	0.38	NA	0.38	0.38	1
	var. *Merril Sundance*	0.46	NA	0.46	0.46	1
	var. *Michelini*	0.31	NA	0.31	0.31	1
	var. *Morton*	0.53	NA	0.53	0.53	1
	var. *Nectaheart*	0.50	NA	0.50	0.50	1
	var. *Nectared 4*	0.37	NA	0.37	0.37	1
	var. *Nectared 6*	0.13	NA	0.13	0.13	1
	var. *Nectarose*	0.38	NA	0.38	0.38	1
	var. *Pocahontas*	0.32	NA	0.32	0.32	1
	var. *Red June*	0.43	NA	0.43	0.43	1
	var. *Redchief*	0.28	NA	0.28	0.28	1
	var. *Redhaven*	0.48	NA	0.48	0.48	1
	var. *Redtop*	0.54	NA	0.54	0.54	1
	var. *Redwing*	0.53	NA	0.53	0.53	1
	var. *Robin*	0.59	NA	0.59	0.59	1
	var. *Shasta*	0.39	NA	0.39	0.39	1
	var. *Springcrest*	0.36	NA	0.36	0.36	1
	var. *Springgold*	0.53	NA	0.53	0.53	1
	var. *Springtime*	0.58	NA	0.58	0.58	1
	var. *Starking Delicious*	0.25	NA	0.25	0.25	1
	var. *Sudanell*	0.10	NA	0.10	0.10	1
	var. *Suncrest*	0.15	NA	0.15	0.15	1
	var. *Troubador*	0.34	NA	0.34	0.34	1
	var. *Vesuvio*	0.16	NA	0.16	0.16	1
Psidium guajava	Guava					
	cv. “Kimju guava”	0.08	NA	0.08	0.08	1
Punica granatum	Pomegranate					
	cv. “Gorch-e-dadashi”	0.39	NA	0.39	0.39	1
	cv. “Poost ghermez-e-aliaghaei”	0.37	NA	0.37	0.37	1

	cv. "Zagh-e-yazdi"	0.44	NA	0.44	0.44	1
Pyrus communis	Pear					
	cv. "Conference"	0.56	0.42	0.15	0.98	2
	cv. "Rocha"	0.96	0.04	0.92	0.99	2
	cv. "Sebri"	0.61	NA	0.61	0.61	1
	cv. "Shahmiveh"	0.69	NA	0.69	0.69	1
	cv. "Tanzi"	0.57	NA	0.57	0.57	1
Ribes uva-crispa						
	cv. "White Triumph"	0.27	NA	0.27	0.27	1
	cv. "Lady Delamere"	0.27	NA	0.27	0.27	1
	cv. "Resistenta"	0.65	NA	0.65	0.65	1
	cv. "Shanon"	0.36	NA	0.36	0.36	1
	cv. " Careless"	0.45	0.07	0.35	0.64	3
Ribes rubrum	Currant					
	cv. "Rovada"	0.42	NA	0.42	0.42	1
Rubus fruticosus	Blackberry					
	cv. "Black Satin"	0.51	NA	0.51	0.51	1
	cv. "Hull Thornless"	0.39	NA	0.39	0.39	1
Rubus idaeus	Raspberry					
	cv. "Cowichan"	0.69	0.01	0.69	0.69	1
	cv. "La Amelia"	0.07	NA	0.07	0.07	1
	cv. "Latham"	0.66	0.01	0.65	0.66	2
	cv. "Polka"	0.59	NA	0.59	0.59	1
	cv. "Royalty"	0.57	0.07	0.45	0.70	3
Selenicereus undatus	White-fleshed pitaya					
	cv. "VN White"	0.22	NA	0.22	0.22	1
Selenicereus spp.	Red-peel pitaya					
	cv. "Chaozhou 5"	1.00	NA	1.00	1.00	1
	cv. "F11"	1.00	NA	1.00	1.00	1
	cv. "Orejona"	1.00	NA	1.00	1.00	1
Sesamum indicum	Sesame seed					
	cv. "CNP G2"	0.01	NA	0.01	0.01	1
	var. *S-42*	0.49	NA	0.49	0.49	1
Solanum lycopersicum	Tomato					
	var. *NS 25*	0.52	NA	0.52	0.52	1
	var. *SunGold*	0.28	NA	0.28	0.28	1

Solanum melongena	Eggplant					
	var. *Aruki 25*	0.78	NA	0.78	0.78	1
	var. *Kathri 25*	0.76	NA	0.76	0.76	1
	cv. "Poli"	0.87	0.07	0.74	1.00	4
	var. *Shiva*	0.81	0.03	0.77	0.88	3
Spondias mombin	Hog plum					
	cv. "Lagoa Redonda"	0.78	NA	0.78	0.78	1
Trichosanthes cucumerina	Snake gourd					
	var. *Bhuvan*	0.92	NA	0.92	0.92	1
	var. *Lakshmi 7*	0.73	NA	0.73	0.73	1
	var. *S25*	1.00	0.00	1.00	1.00	2
Trichosanthes dioica	Pointed gourd					
	cv. "Damodar"	1.00	0.00	1.00	1.00	2
Vaccinium corymbosum	Highbush blueberry					
	cv. "Bluecrop"	0.47	0.07	0.33	0.64	5
	cv. "Duke"	0.46	0.12	0.34	0.58	2
	cv. "Emerald"	0.76	NA	0.76	0.76	1
	cv. "Liberty"	0.53	0.07	0.34	0.80	6
	cv. "Northland"	0.66	0.05	0.61	0.70	2
	cv. "Patriot"	0.31	0.03	0.28	0.33	2
Vaccinium macrocarpon	Cranberry					
	cv. "Stevens"	0.58	NA	0.58	0.58	1
Vicia faba	Broad bean					
	cv. "Tiffany"	0.05	0.03	0.02	0.08	2
Vigna unguiculata	Cowpea					
	cv. "BR3-Tracuateua"	0.04	NA	0.04	0.04	1
	cv. "Ken Kunde"	0.32	0.10	0.21	0.42	2
Vitellaria paradoxa	Karite nut					
	subs. *paradoxa*	0.31	0.22	0.08	0.96	4