Electronic Supplementary Information (ESM)

Supplementary Methods

Analysis 1: frequency of pollinator limitation

To measure the frequency of pollinator limitation across all locations for a given crop, we used AIC to choose between three models that relate the number of pollinators observed to our crop-specific yield or production variable (see Fig. 1): 1) a linear positive relationship, implying that all locations were pollination-limited, 2) no relationship (an intercept only model), implying that no locations were limited, or 3) an asymptotic (piecewise) regression model in which production increases with visitation to a certain visit rate breakpoint, then remains flat, implying that the crop is pollination-limited in some locations and not others. If the third model was selected, we estimated the frequency of pollinator limitation as the fraction of locations falling below the breakpoint.

For all models, we used the transect as the unit of analysis for the flower visitation-yield relationship, because this was the most highly resolved scale at which observations of visitation and subsequent production measurements could be paired. In principle, within a given crop in our study, pollination could be limiting at all transects, at a subset of transects, or at no transects. Linear regressions and intercept-only models were performed using the glm() function in R version 3.3.2 (R Core Team 2016). Piecewise regressions were performed using the segmented() function in the segmented package (Muggeo 2003, 2008) in R. The breakpoint between the linear and intercept-only portions of the curve was not specified beforehand, but was estimated automatically by the segmented() function to maximize the model fit. For this analysis, we selected the model with the lowest AIC, even in cases where another model was close, because the different structure of the three models meant model averaging would not be appropriate. Tart cherry in Pennsylvania was not included in this analysis due to insufficient data. Investigation of temporal effects in pollinator limitation is beyond the scope of this manuscript. It should also be noted that site and cultivar are necessarily confounded in this analysis because a large number of cultivars are grown for many of our crops, and because cultivar must be matched to the environmental conditions at a given farm. From our perspective this is not necessarily undesirable because we simply intended our data to be a representative sample of what exists in each growing region, and did not intend to make inferences about particular cultivars. Our goal was to make our sample as representative as possible by spreading sampling over many locations in each region.

All crop regions were analyzed separately except for northern highbush blueberry (i.e. transects from British Columbia, Michigan, and Oregon), where the data from all three regions was pooled together in order to extend the range of bee visitation values on the x-axis as widely as possible, given that transects with low bee visitation were only present in British Columbia (Fig. S6). We felt this was appropriate given that our sampling methods were exactly the same across all three regions and that all bushes were of the same cultivar (Bluecrop), and because estimation across the full range of visitation values should result in a more reliable breakpoint value than if each dataset were analyzed separately. Results for each blueberry region analyzed separately are reported in Supplementary analysis 2. The Florida blueberry dataset was not combined with the other regions because it is a different species (southern highbush blueberry).

For blueberry in all four regions, as a check on the patterns of pollinator limitation suggested by our analysis, we performed an additional parallel analysis using the data from hand-pollination experiments. These experiments were performed in the same transects where open-pollinated bushes were measured, such that each transect had individual measurements for open, bagged, and hand-pollinated bushes. The results of this analysis are reported in Supplementary analysis 3.

Analysis 2: contribution of honey bees versus wild bees

For each crop, the fraction of total pollen grains deposited by honey bees and each species group of wild bee was estimated by multiplying flower visits by that group with an estimate of relative pollen grains deposited per visit (pollinator efficiency), then dividing by the total to give a proportion:

$$P_{pollinator} = \frac{R_{pollinator} \cdot E_{pollinator}}{\sum(R_{pollinator} \cdot E_{pollinator})} \tag{S1}$$

where $P_{pollinator}$ is the proportion of pollen grains deposited by each pollinator group, $R_{pollinator}$ is the visitation rate (expressed as a proportion of total observed visits contributed by a given pollinator group), and $E_{pollinator}$ is the number of pollen grains deposited per visit (by that pollinator group; expressed as a fraction of pollen grains deposited by the honey bee). Table S1 illustrates these calculations for one of our study systems.

Table S1. An example of pollinator contribution calculations based on Florida watermelon.

pollinator	R	E	R x E	P
Honey_bee	0.561	1.0	0.561	0.480
Tiny_bee	0.287	1.2	0.344	0.295
Green_bee	0.102	1.1	0.112	0.096
Bumble_bee	0.029	3.6	0.104	0.089
Large_bee	0.010	0.9	0.009	0.008
Small_bee	0.009	2.0	0.018	0.015
Xylocopa	0.002	12.1	0.019	0.017
Megachilid	0.0004	1.4	0.001	0.000
sum	1		1.169	1

Values of E (pollinator efficiency, i.e., pollen deposition per visit) were taken from the following literature sources (see Table S2): watermelon (Winfree et al. 2007, Winfree et al. 2015), pumpkin (Artz and Nault 2011), almond (Thomson and Goodell 2001), apple (Park et al. 2016), and blueberry (Javorek et al. 2002, Benjamin et al. 2014). Values of E for the wild bee groups were expressed as relative to the E of the honey bee for comparative purposes. For bee species with no available PPV estimates in the literature, we assumed that E was the same as for the honey bee in order to create a conservative estimate of the differences between honey bee and wild bees. No PPV estimates for tart cherry were available in the literature, so the values for sweet cherry (Eeraerts et al. 2019) were substituted.

Analysis 3: Economic valuation

There are multiple methods for valuing pollination services and these vary in their assumptions and data requirements (Winfree et al. 2011, Melathopoulos et al. 2015, Hanley et al. 2015, Breeze et al. 2016). Most studies to date have used the production value method, which starts with the total value of the crop yield and multiplies it by the fraction of total yield that would be lost if pollinators were completely absent (Gallai et al. 2009, Calderone 2012). We used the production value method in order to make our results comparable to previous studies that have calculated the value of honey bee and/or wild bee pollination (Losey and Vaughn 2006, Morse and Calderone 2000). Another potential valuation method is the replacement value method, which values the cost of substituting native pollinators with additional honey bees (e.g. Winfree et al. 2011) or hand pollination (Allsopp et al. 2008). Replacement with honey bees is not relevant for our study, as the value contribution of honey bees is one of our measurements of interest. Furthermore, our analysis is best interpreted over a relatively short time scale over which large-scale economic factors remain constant, and the future development of mechanical pollination technologies is not relevant.

Using the production value method, the economic value delivered to each crop in each state was calculated for wild pollinators and honey bees using the following equation, as described in the main text (as equation 1):

$$V_{pollinator} = V_{crop} \cdot D \cdot P_{pollinator} \tag{S2}$$

Where $V_{pollinator}$ is the annual economic value attributable to a particular pollinator group (either wild bees or honey bee), V_{crop} is the annual production value of the crop, D is the pollinator dependency value for the crop (the proportion by which yield is reduced in the absence of pollination; from Klein et al. 2007), and $P_{pollinator}$ is the fraction of total pollination of the crop provided by the pollinator group. Production values for each crop-state combination (from 2013-2015) were obtained from the USDA-NASS database (USDA-NASS 2017). It is important to note that there remains considerable uncertainty in this equation. For instance, the data used by Klein et al. (2007) to specify pollinator dependency values do not account for some factors that affect pollinator dependence and may differ by farm, such as the crop cultivar used.

As discussed in the main text, our approach updates previous national-scale estimates of the value of wild and honey bee pollination (Losey and Vaughn 2006, Calderone 2012) by incorporating both relative visitation rates and per-visit efficiency by each pollinator group, and by using sites that were within the main production regions for the crop.

To extrapolate our state values up to the national level, we followed two steps. First, we needed to estimate the fraction of total pollination for each crop attributable to each pollinator group at the national level ($P_{pollinator,US}$). These fractions were calculated using the proportion of pollination done by each pollinator group ($P_{pollinator}$) and the value of each crop (V_{crop}), both at the state level.

$$P_{pollinator,US} = \sum \left[P_{pollinator,i} \cdot \frac{V_{crop,i}}{\sum V_{crop,i}} \right] \tag{S3}$$

Equation S3 estimates the national value of each type of pollinator by averaging the values $P_{pollinator}$ for each available state i, weighted by the proportion of the national production of that crop that comes from that state $\left(\frac{V_{crop,i}}{\sum V_{crop,i}}\right)$. If only one state was studied for a given crop (e.g. almond), then no averaging was done.

Lastly, we calculated the total production value attributable to each pollinator group at the national level by substituting our fractions from equation S3, along with national-scale crop values, into equation S2, such that

$$V_{pollinator,US} = V_{crop,US} \cdot D \cdot P_{pollinator,US} \tag{S4}$$

where $V_{crop,US}$ is the total national production value for that crop and $P_{pollinator,US}$ is the fraction of pollen deposited by the pollinator group. Total production values for each crop at national scale (from 2013-2015) were obtained from the USDA-NASS database (USDA-NASS 2017).

The value V_{crop} represents the gross production value of the crop. There is a potential for this value to result in an overestimate of the value of pollinators, because if pollination failed farmers might be able to mitigate financial losses by reducing input costs (i.e. variable costs of production), or potentially adopting alternative pollination strategies. Most of the crops we studied, however, were woody perennials (trees and shrubs) for which the variable costs of production, such as irrigation, fertilizer, and pest management, would still be needed in order to maintain plant health for future production. A sensitivity analysis on the effect of subtracting the variable input costs from the production value estimates (Winfree et al. 2011) is described below. Estimates referenced by each of the equations above are provided in Table S11.

Supplementary analysis 1: The effect of subtracting variable costs from crop production values

In the event that crops fail due to a lack of pollination, farmers can potentially save money by abandoning expenditures that will no longer create a benefit. Such expenses are often referred to as variable costs of production, because they can vary depending on how much yield is expected or produced. For instance, harvest costs (an important variable cost) can decline to zero if there is no crop to harvest. However, as discussed above, farm management is a complex business, so some variable costs will not be entirely eliminated and hence subtracting the sum of variable costs as we do below will likely result in an underestimate of pollinator value.

The total variable cost associated with the production of a particular crop across the entire USA TVC_{US} is calculated as

$$TVC_{US} = \sum \left[VCA_i \cdot \frac{A_i}{\sum A_i} \right] \cdot A_{US} \tag{S5}$$

where VCA_i is the variable cost per acre for a state i (one of the states in our study), and where A_i is the number of acres under production for that state, and A_{US} is the total area under production of that crop in the USA. The variable input cost estimates used for each crop and state were calculated using sample budgets published by the university cooperative extension program that was the geographically closest to our study farms (see Table S8). Our objective was to create a mean cost per acre for the USA from a weighted average of the states for which data were available. If only one state was studied for a given crop (e.g. almond), then no averaging was done. For states where we had no bee visitation data or variable cost estimates, we assumed that the situation was similar enough to be approximated by the states where we did have data.

The net production value of a particular crop at the national scale, NPV_{US} , is calculated as

$$NPV_{US} = TPV_{US} - TVC_{US} \tag{S6}$$

where TPV_{US} is the total (gross) production value at the national scale, and TVC is the extrapolated total variable cost from above. Total production values and total acres bearing at the state and national level for 2013-2015 were obtained from the USDA-NASS database (USDA-NASS 2017). The quantity TPV_{US} is equivalent to the quantity $V_{crop,US}$ from equation S4 above.

The fraction of total pollination of each crop nationwide that is attributable to each pollinator group $P_{pollinator,US}$ was calculated as

$$P_{pollinator,US} = \sum \left[P_{pollinator,i} \cdot \frac{NPV_{crop,i}}{\sum NPV_{crop,i}} \right] \tag{S7}$$

an average of the values P_i for each available state, weighted by the relative net production values NPV_i calculated for that state. This matches equation S3 above, but now with net production value substituted for total production value.

Lastly, we calculated the net production value attributable to each pollinator group at the national level by substituting our fractions from equation S7 into equation S2 where V_{crop} is now the net national production value NPV_{US} for that crop from equation S6.

$$V_{pollinator,US} = NPV_{US} \cdot D \cdot P_{pollinator,US} \tag{S8}$$

Result: As a percentage of gross production value, variable input costs averaged 62% (range 29-87%) across the crop-state combinations in our study (Table S8), often leaving less than half of gross production value to be attributed to pollinators. Nevertheless, the remaining net value represented a very large amount at the scale of the state or nation, especially for the higher value crops such as almond and apple. Results of this analysis compared with the version from the main text where variable costs were not subtracted are summarized in Fig. S5.

Our estimates of wild bee pollination value for the USA were higher than previous studies in four of the seven crops studied, and within the range of previous studies in the other 3 crops (Fig. 4). If all of the variable costs were subtracted (see Fig. S5), these higher estimates would persist in only one crop (apple), and three crops would show lower values than previous estimates because on average, subtracting variable production costs would reduce our estimated values by about 70%. Our higher valuations for wild bees were driven by both higher rates of flower visitation and higher pollen deposition per visit compared with the numbers used in previous studies (Losey and Vaughn 2006). Correspondingly, our valuation for honey bees was often lower (four of the crops) than estimated by previous studies and would have been even further reduced if we had subtracted variable production costs.

Supplementary analysis 2: Analysis of the frequency of pollinator limitation for separate regions of northern blueberry.

When the three regions of northern highbush blueberry were analyzed separately, the segmented model was only clearly preferred by AIC in the British Columbia data (deltaAIC=8.7). A linear increasing model was slightly preferred over a segmented model for Oregon (deltaAIC = 1.4) and Michigan (deltaAIC=0.6), but the slopes of these increasing relationships were very shallow. Breakpoints for the separately analyzed regions were 14.4 bees/10 min (BC), 26.7 bees/10 min (MI), and 43.4 bees/min (OR), compared with an estimated breakpoint of 26.3 bees/10 min when analyzed together. Taken together, these results appear reasonably consistent with the results of the main analysis, and reinforce our decision to combine the three regions.

Supplementary analysis 3: Assessing the frequency of pollen limitation using hand pollination experiments in blueberry

For blueberry in British Columbia, Michigan, Oregon, and Florida, we collected crop production data from plants in each transect that had been pollinated by hand, in addition to the plants used in the main analysis that were either open-pollinated or bagged. For these plants, we added pollen to open clusters of flowers multiple times during bloom to ensure maximum pollination. Thus, the pollen we added was in addition to any pollen provided by bees. If pollination were limiting, we would expect hand-pollinated plants to have higher average berry weight than open-pollinated plants. To analyze the frequency of limitation across farms, we followed the same methods described for the main analysis of pollinator limitation, but with a new crop production variable: the difference in average berry weight between hand- and open-pollinated bushes. For this variable, a larger value would represent a larger effect of hand pollination, and thus potentially lower bee visitation. As before, three models were compared by AIC: 1) a linear relationship between bee visitation and the effect of hand pollination, 2) no relationship, and 3) a segmented relationship in which the effect of hand pollination declines with increased bee visitation to a breakpoint, then remains flat.

Result: As in the main analysis, the segmented relationship was strongly preferred by AIC over the linear relationship (deltaAIC = 19.1) and no relationship models (deltaAIC = 52.3) for northern blueberry (OR, MI, BC) (see Fig. S7). Also consistent with the main analysis, the no relationship model was slightly preferred for southern highbush blueberry in Florida (deltaAIC = 1.7). For northern highbush blueberry, the estimated breakpoint occurred at a somewhat lower value of bee visitation than we found in the main analysis (16.7 bees/10 min compared to 26.3 bees/10 min). This discrepancy may be related to a greater difficulty in detecting differences in production between open and hand pollinated bushes when more bees are present, because simultaneous limitation by other factors becomes more likely. The lower breakpoint would lead to lower estimates of pollen/pollinator limitation across farms than reported in the main analysis (see Table S9).

Supplementary References

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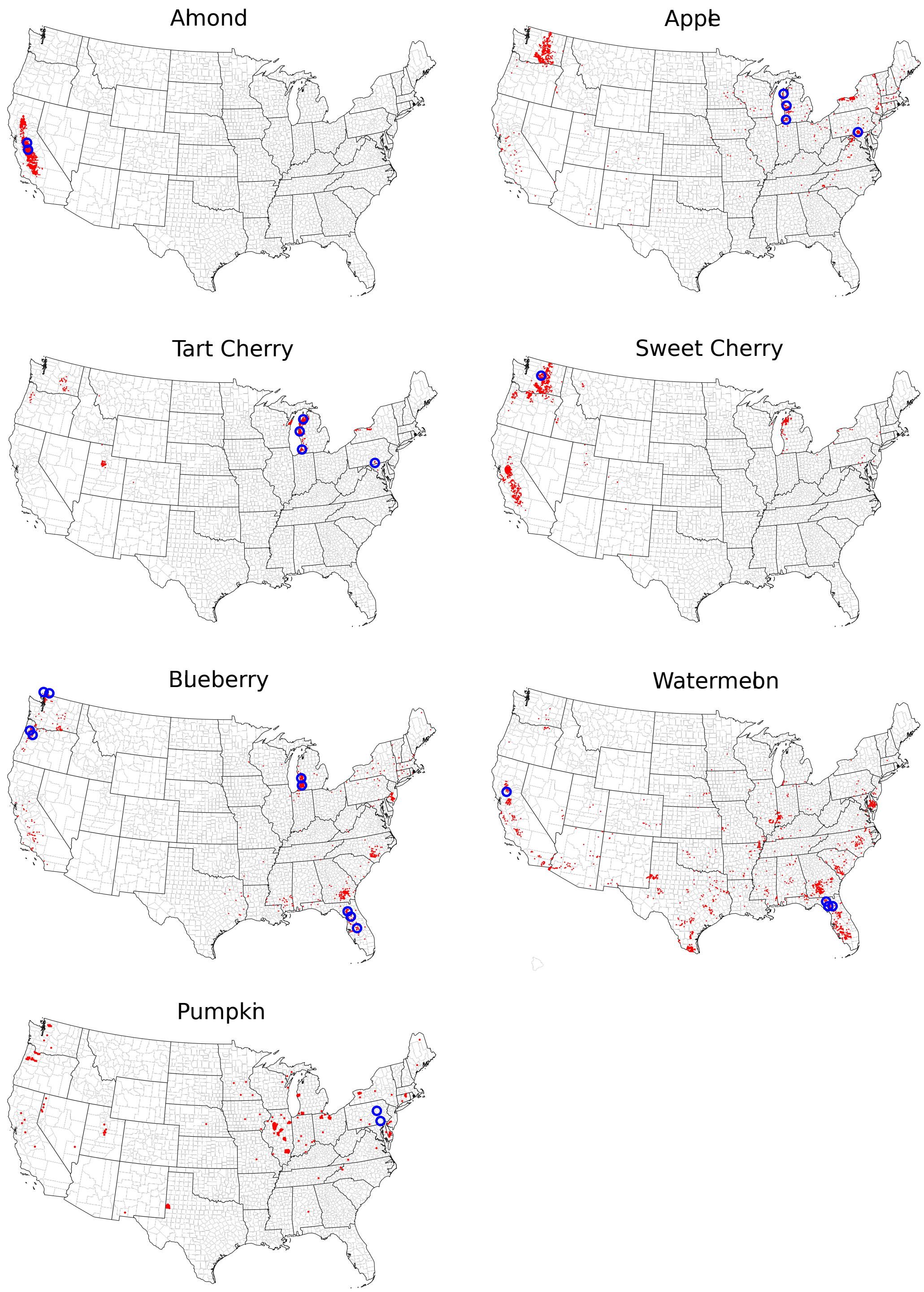

Figure S1. Maps showing the location of our study farms with respect to the major production areas for each crop in the United States. Study farms are marked with a blue circle (often, multiple study farms were located within the same county, so in these cases only a single circlewas drawn for clarity). Crop-specific maps were based on data provided by the United States Department of Agriculture National Agricultural Statistics Service 2012 Census of Agriculture. Each red dot represents 100 acres of a given crop, except in the case of apple where each dot represents 500 acres and almond where each dot represents 1000 acres.

Figure S2 (page 1/4)

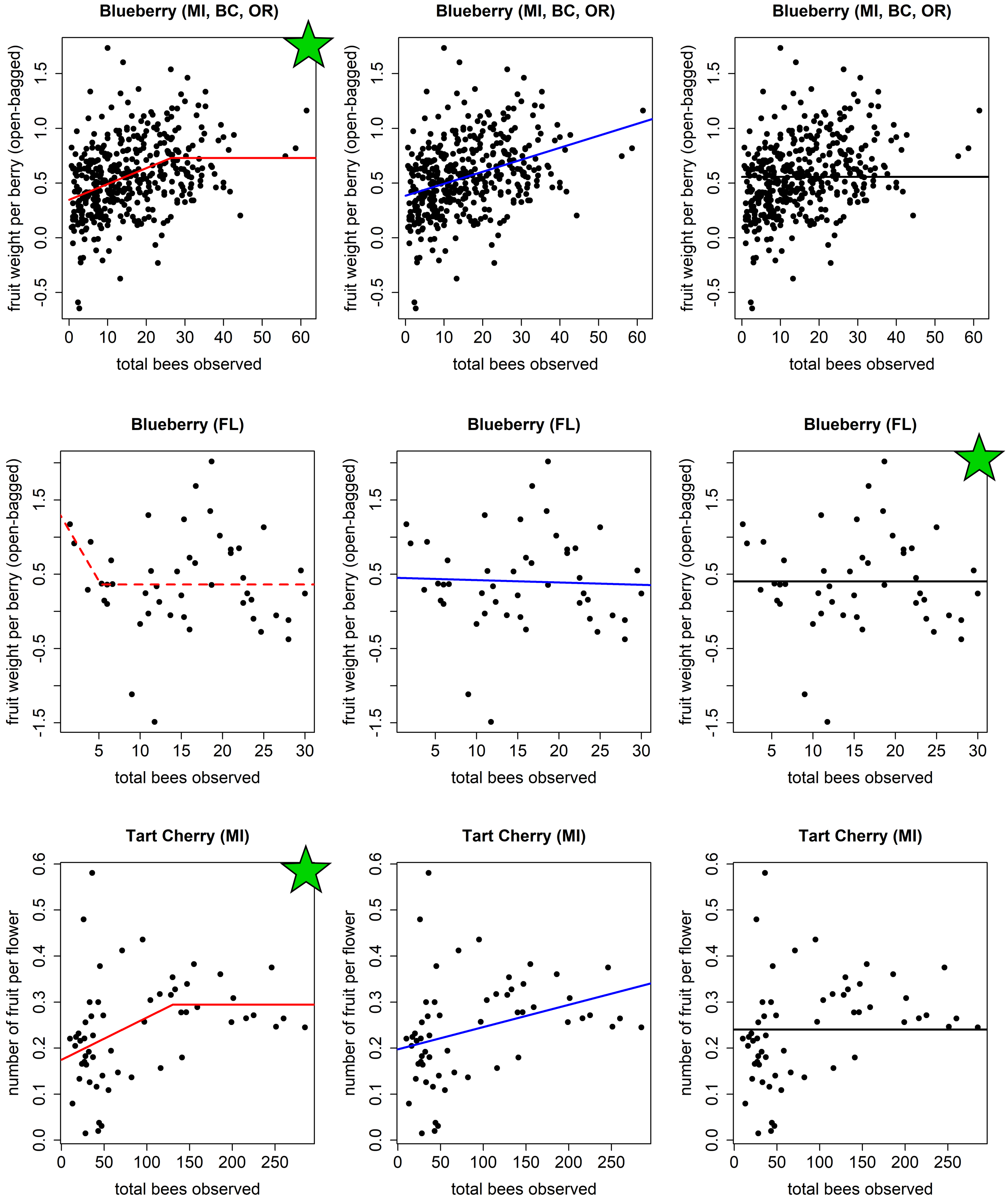

Figure S2 (page 2/4)

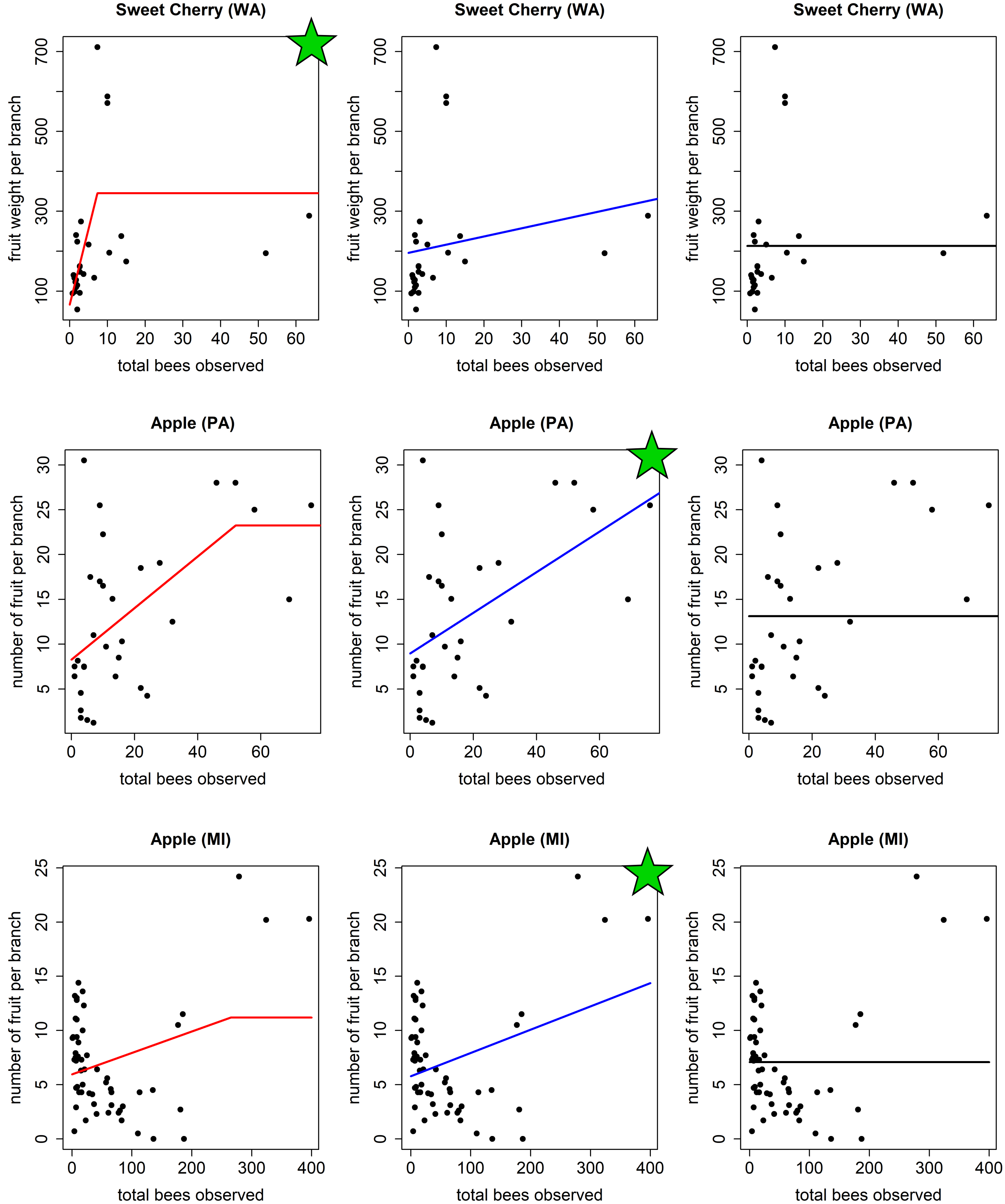

Figure S2 (page 3/4)

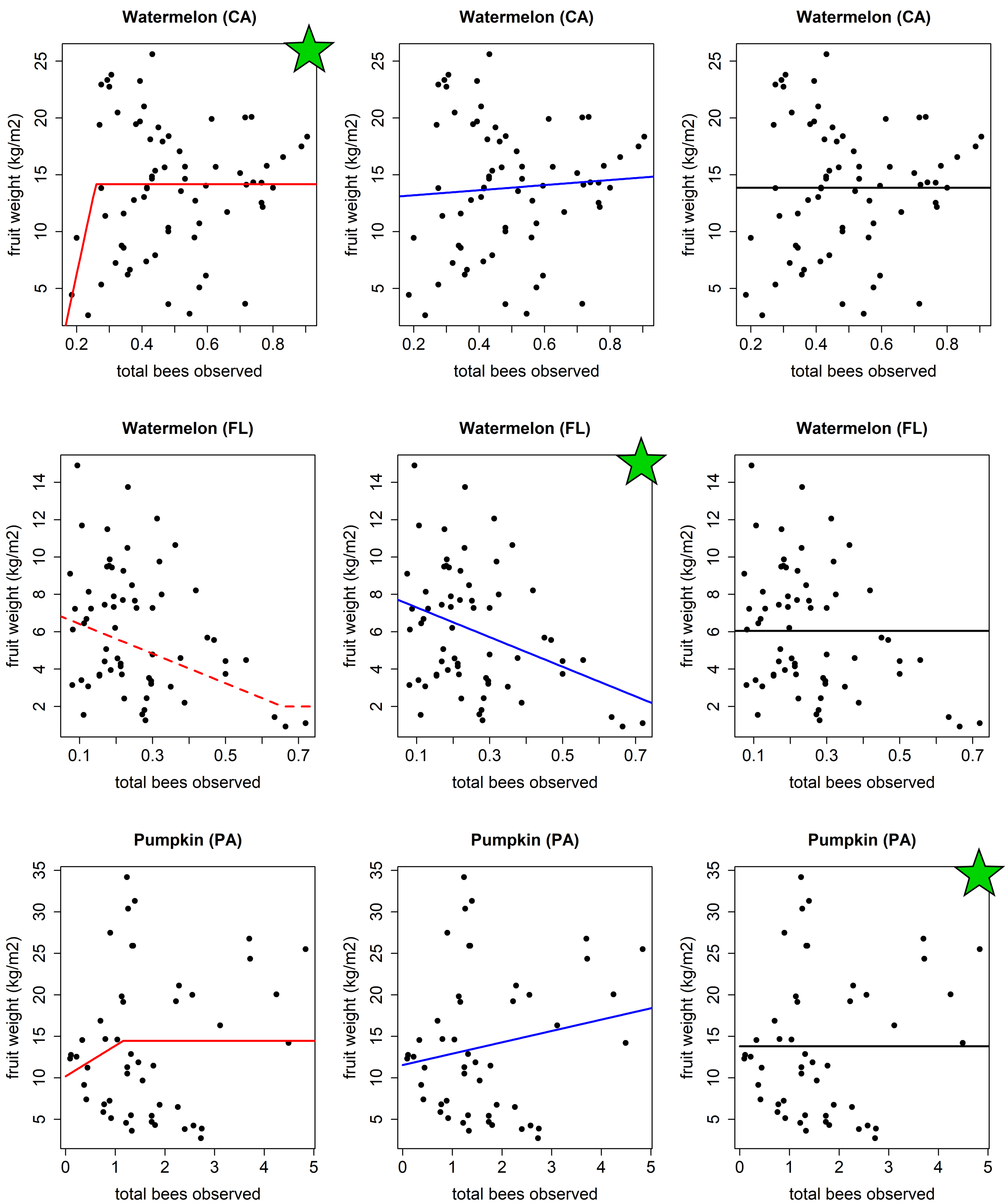

Figure S2 (page 4/4)

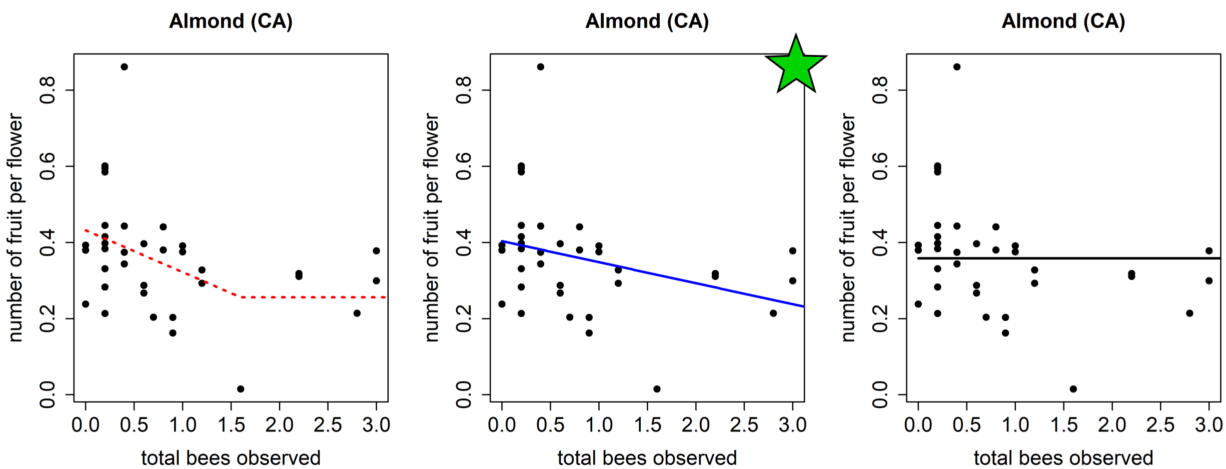

Figure S2. Plots of different potential relationships between visits and yield or production for each crop. In each row, the plots correspond to models of a) a segmented relationship between visits and crop productionwhere there is initially a positive relationship, but after an estimated breakpoint there is no relationship, B) a linear relationship between visits and crop productionacross all sampled locations c) no relationship. AIC model selection was used to select the best model of the three. The green star in the corner denotes which model was selected for a given crop.

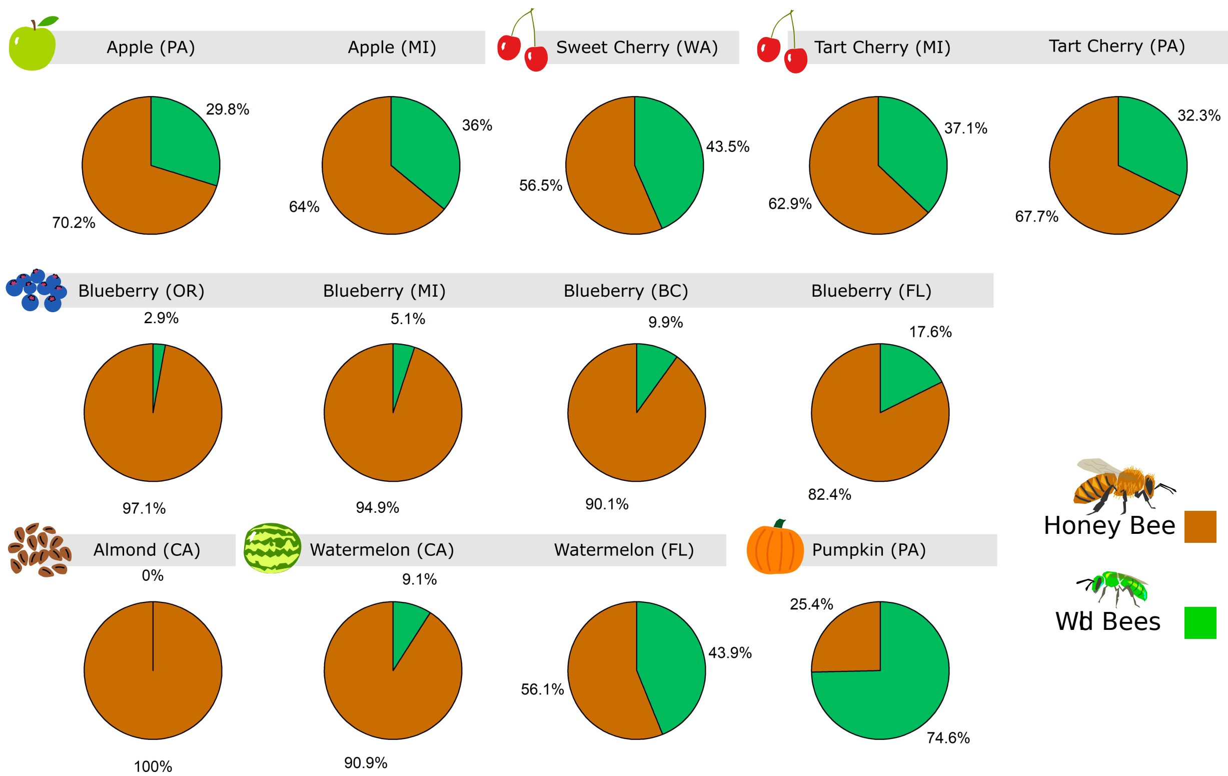

Figure S3. Relative visitation rates of honey beeand wild bees across the crop-region combinations in our study. Percentages were calculated by averaging the number of visits by each pollinator across all the farm-years within that crop. The number of farms and years differed by crop (see Table S3).

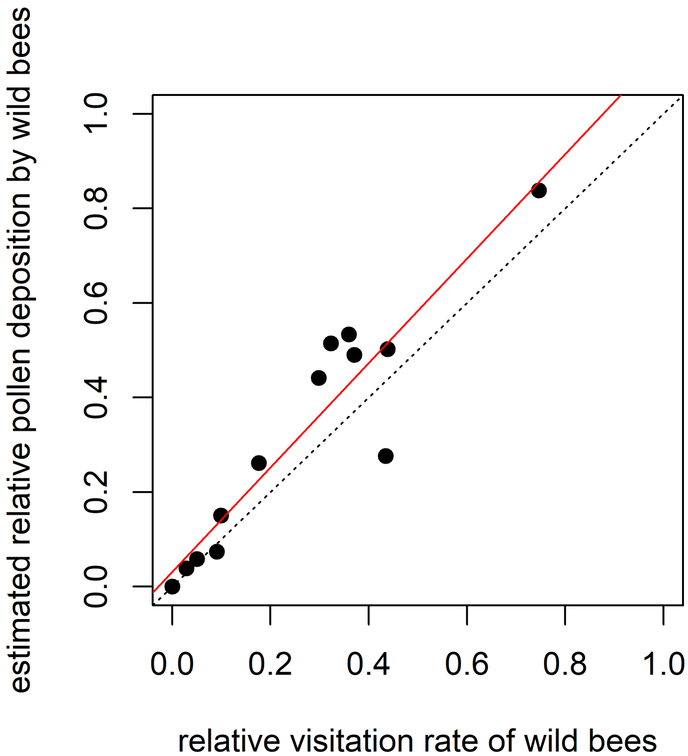

Figure S4. Regression between percent of pollen deposition and percent of visitation by wild bees (where the remainder is provided by the honey bee). Each data point is a crop-state combination from our study. (R^2=0.87, p<0.01) If all bee visits carried the same PPV, the regression would fall along the 1:1 line (dotted). Overall pollen deposition for most crops was somewhat greater than predicted by visit rate alone, hence the regression line (red, slope: 1.10) is somewhat above the 1:1 line. In other words, visitation predicts pollen deposition very well, but there is a positive multiplier of associated with wild bee visitation such that each wild bee visit (on average) results in more pollen deposition than each honey bee visit. The outlier below the line is sweet cherry, where many of the wild bee pollinators were bumble bees (see Table S2) that are not currently thought to be effective pollinators of cherry (Eeraerts et al 2019).

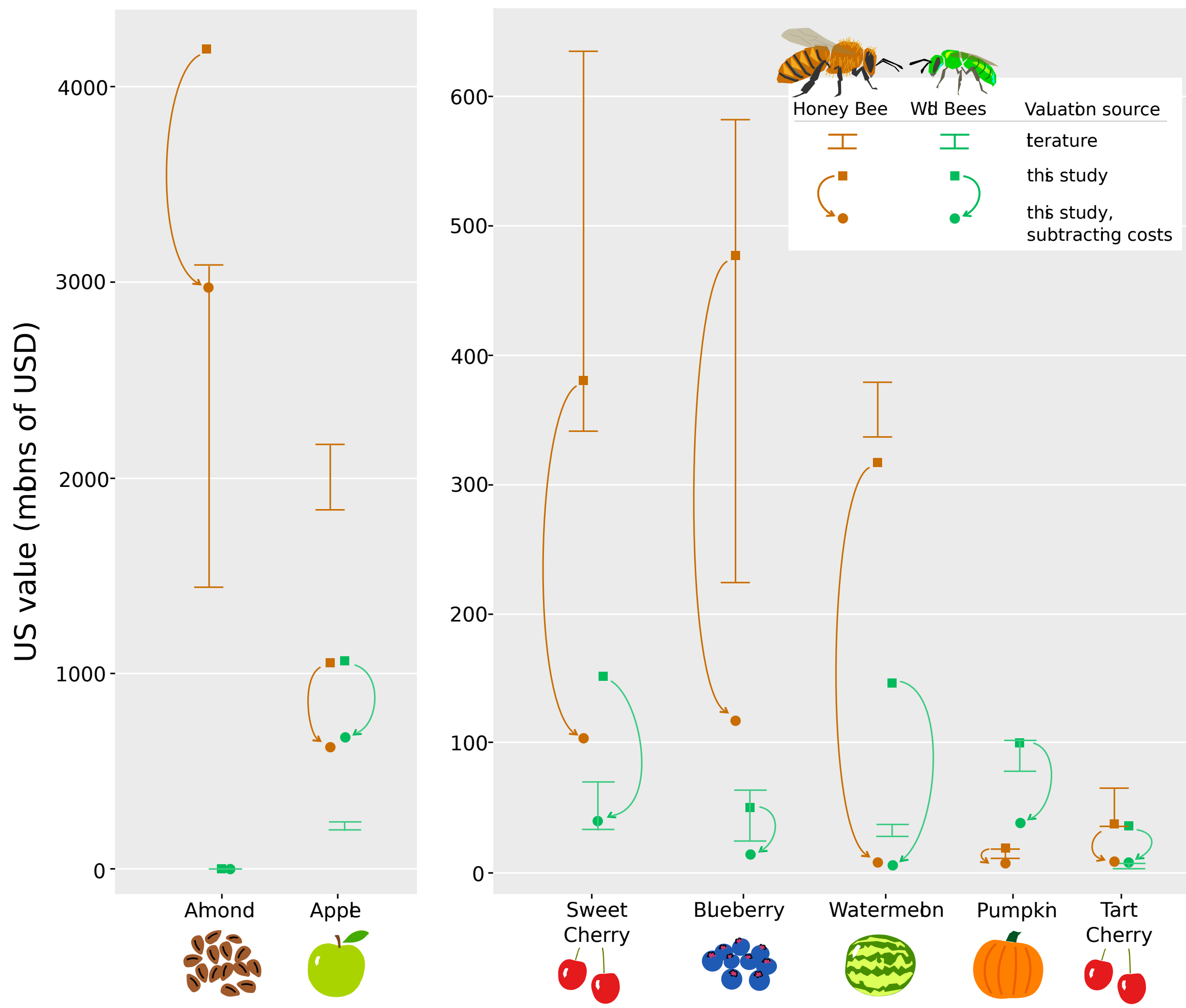

Figure S5. Comparison of valuations before and after subtracting variablecosts of production. Points represent value estimates for honey bee (orange) and wild bees (green), extrapolated to the level of the United States. Bars encompass the range of estimates in the published literature (Losey and Vaughn 2006 and Calderone 2012). Square points show total value estimates, equivalent to those shown in Fig. 4 of the main text. Circle points show net value estimates, following the methods in this supplementary analysis. Arrows are included to indicate the magnitude and direction of value change as a result of subtracting variable costs. All values have been adjusted to 2015 dollars.

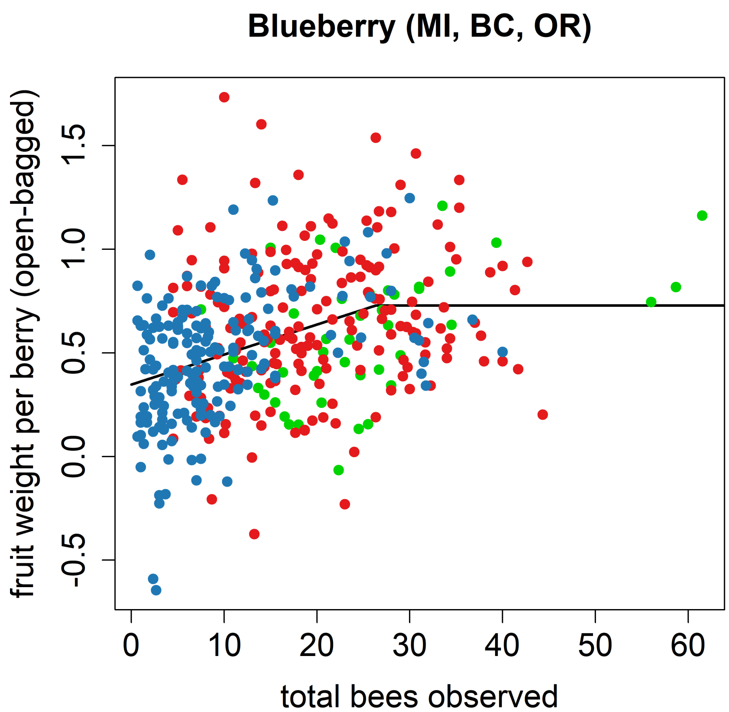

Figure S6. Plot of the relationship between visits and crop production for each northern highbush blueberry site (in MI, BC, and OR) showing how the distribution of bee visitation values differs across region. Note that more of the transects with low visitation occur in the British Columbia data (blue), than in the Michigan (red) or Oregon (green) data. For reference, the segmented model relationship as selected in Fig. S2 is plotted in black.

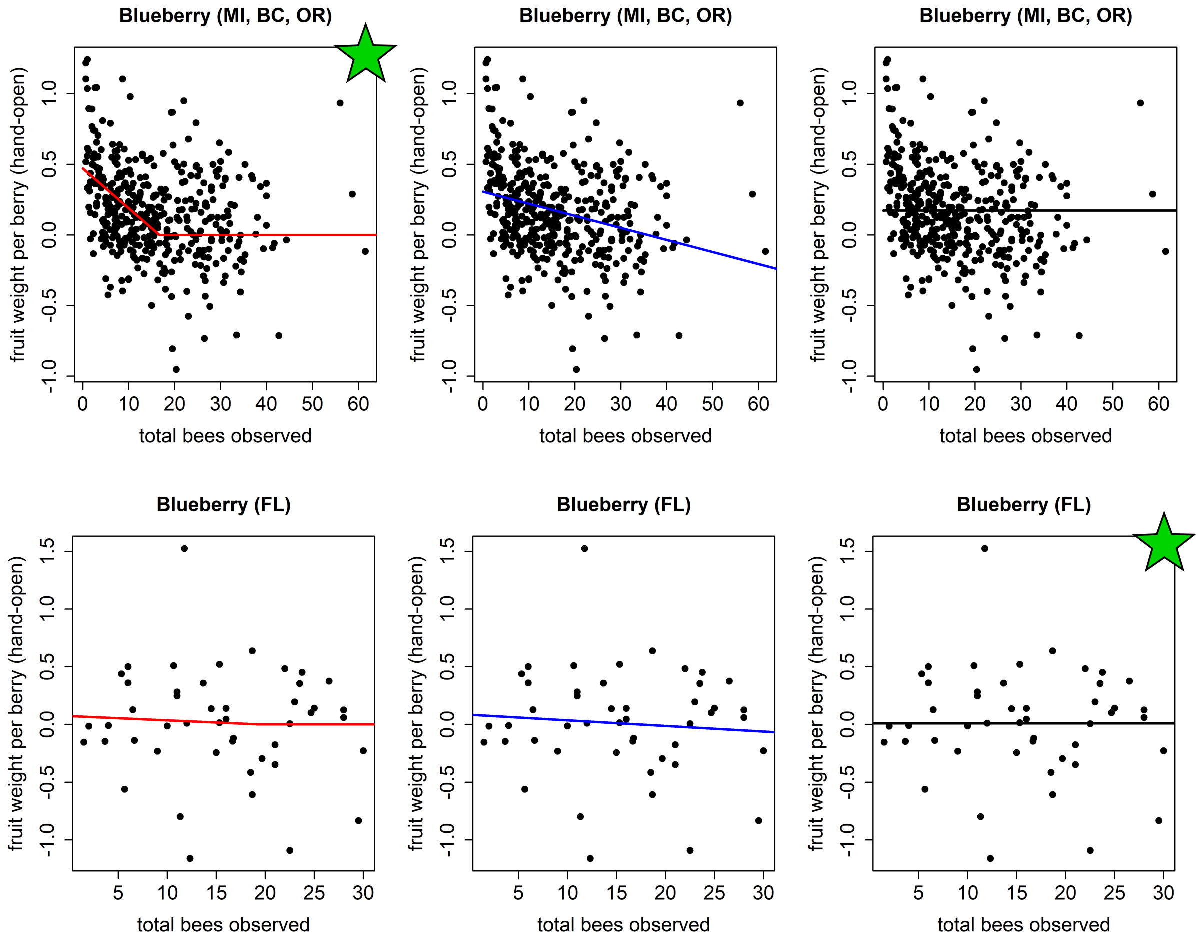

Figure S7. Plots of different potential relationships between visits and the effect of hand-pollination for blueberry. In these plots, a larger y-axis value corresponds to more pollen limitation, thus a negative slope indicates pollenlimitation across transects (the opposite of Fig. S2). The first row of plots correspond to modelsfor northern highbush blueberryof a) a segmented relationship between visits and the effect of hand pollination where there is initially a negative relationship, but after an estimated breakpoint there is no relationship, b) a linear relationship between visits and the effect of hand pollination across all sampled locations and c) no relationship. The second row shows the results of the same models for southern highbush blueberry (Florida). AIC model selection was used to select the best model of the three. The green star in the corner denotes which model was selected.

Table S2. Relative visit rates (% of total visits) by each species group from our study, pollen deposition per visit (PPV) estimates collected from the literature for each species group, and PPV values relative to that of the honey bee (PPV of species group divided by PPV of honey bee).

species_group	crop_state	visits (%)	PPV (pollen grains)	relative PPV	PPV reference (state)	reference species group (PPV sample size)
honey_bee	watermelon_fl	56.1	40	1.0	Winfree et al. 2007 (NJ)	honey_bee (44)
tiny_bee	watermelon_fl	28.7	49	1.2	Winfree et al. 2015 (NJ)	tiny_dark_bee (33)
green_bee	watermelon_fl	10.2	43	1.1	Winfree et al. 2015 (NJ)	mean of small_green_bee and large_green_bee (54)
Bombus	watermelon_fl	2.9	142	3.6	Winfree et al. 2015 (NJ)	Bombus (79)
large_bee	watermelon_fl	1.0	37	0.9	Winfree et al. 2015 (NJ)	large_dark_striped_bee (6)
small_bee	watermelon_fl	0.9	79	2.0	Winfree et al. 2015 (NJ)	small_dark_bee (67)
Xylocopa	watermelon_fl	0.2	479	12.1	Winfree et al. 2015 (NJ)	Xylocopa (1)
megachilid	watermelon_fl	0.04	56	1.4	Winfree et al. 2015 (CA)	Melissodes_megachile_dia dasia (56)
honey_bee	watermelon_ca	90.9	40	1.0	Winfree et al. 2007 (NJ)	honey_bee (44)
Dialictus_Hylaeus	watermelon_ca	6.5	19	0.5	Winfree et al. 2015 (CA)	Lasioglossum_dialictus_hyl aeus (66)
Halictus_tripartitus	watermelon_ca	1.9	46	1.2	Winfree et al. 2015 (CA)	Halictus tripartitus (61)
Halictus_ligatus	watermelon_ca	0.5	73	1.8	Winfree et al. 2015 (CA)	Halictus ligatus (30)
Anthophora	watermelon_ca	0.1	275	6.9	Winfree et al. 2015 (CA)	Anthophora urbana (22)
Peponapis	watermelon_ca	0.04	54	1.4	Winfree et al. 2015 (CA)	Peponapis (39)
Melissodes	watermelon_ca	0.03	56	1.4	Winfree et al. 2015 (CA)	Melissodes_megachile_dia dasia (56)
Tripeolus	watermelon_ca	0.02	3	0.1	Winfree et al. 2015 (CA)	Triepeolus (4)
other_bee	watermelon_ca	0.02	185	4.6	Winfree et al. 2015 (CA)	mean of Lasioglossum_large and Agapostemon (41)
Bombus	pumpkin_pa	53.5	170	2.5	Artz and Nault 2011 (NY)	Bombus impatiens (20)
honey_bee	pumpkin_pa	25.4	68	1.0	Artz and Nault 2011 (NY)	Apis mellifera (20)
squash_bee	pumpkin_pa	17.7	63	0.9	Artz and Nault 2011 (NY)	Peponapis pruinosa (20)

small_dark_bee	pumpkin_pa	2.0	NA	1.0	no data	
green_bee	pumpkin_pa	1.2	NA	1.0	no data	
small_striped_bee	pumpkin_pa	0.3	NA	1.0	no data	
large_dark_bee	pumpkin_pa	0.04	NA	1.0	no data	
honey_bee	cherry_pa	67.7	15 (num fruit)	1.0	Eeraerts et al 2019 (sweet cherry, Belgium)	Apis mellifera (179)
other_bee	cherry_pa	27.5	58 (num fruit)	3.0	Eeraerts et al 2019 (sweet cherry, Belgium)	solitary and mason bees (231)
Bombus	cherry_pa	4.8	0 (num fruit)	0	Eeraerts et al 2019 (sweet cherry, Belgium)	Bombus (30)
honey_bee	cherry_mi	62.9	15 (num fruit)	1.0	Eeraerts et al 2019 (sweet cherry, Belgium)	Apis mellifera (179)
other_bee	cherry_mi	34.1	58 (num fruit)	3.0	Eeraerts et al 2019 (sweet cherry, Belgium)	solitary and mason bees (231)
Bombus	cherry_mi	3.0	0 (num fruit)	0	Eeraerts et al 2019 (sweet cherry, Belgium)	Bombus (30)
honey_bee	sweet_cherry_wa	56.5	15 (num fruit)	1.0	Eeraerts et al 2019 (sweet cherry, Belgium)	Apis (179)
Bombus	sweet_cherry_wa	42.6	58 (num fruit)	3.0	Eeraerts et al 2019 (sweet cherry, Belgium)	solitary and mason bees (231)
other_bee	sweet_cherry_wa	0.8	0 (num fruit)	0	Eeraerts et al 2019 (sweet cherry, Belgium)	Melandrena (30)
honey_bee	blueberry_or	97.1	12	1.0	Javorek et al. 2002 (NS)	Apis mellifera (10)
other_bee	blueberry_or	1.5	11	0.9	Benjamin et al. 2014 (NJ)	mean of large and medium Andrena (83)
Bombus	blueberry_or	1.3	24	2.0	Benjamin et al. 2014 (NJ)	Bombus (queen) (80)

honey_bee	blueberry_mi	94.9	12	1.0	Javorek et al. 2002 (NS)	Apis mellifera (10)
other_bee	blueberry_mi	3.4	11	0.9	Benjamin et al. 2014 (NJ)	mean of large and medium Andrena (83)
Bombus	blueberry_mi	1.4	24	2.0	Benjamin et al. 2014 (NJ)	Bombus (queen) (80)
Xylocopa	blueberry_mi	0.2	3	0.3	Benjamin et al. 2014 (NJ)	Xylocopa virginica (34)
honey_bee	blueberry_fl	82.4	12	1.0	Javorek et al. 2002 (NS)	Apis mellifera (10)
Habropoda	blueberry_fl	8.4	28	2.3	Benjamin et al. 2014 (NJ)	Habropoda laboriosa (38)
Bombus	blueberry_fl	7.3	24	2.0	Benjamin et al. 2014 (NJ)	Bombus (queen) (80)
other_bee	blueberry_fl	1.2	11	0.9	Benjamin et al. 2014 (NJ)	mean of large and medium Andrena (83)
Xylocopa	blueberry_fl	0.8	3	0.3	Benjamin et al. 2014 (NJ)	Xylocopa virginica (34)
honey_bee	blueberry_bc	90.1	12	1.0	Javorek et al. 2002 (NS)	Apis mellifera (10)
Bombus	blueberry_bc	8.9	24	2.0	Benjamin et al. 2014 (NJ)	Bombus (queen) (80)
other_bee	blueberry_bc	1.0	11	0.9	Benjamin et al. 2014 (NJ)	mean of large and medium Andrena (83)
honey_bee	apple_pa	70.2	34	1.0	Park et al. 2016 (NY)	Apis (46)
other_bee	apple_pa	25.3	73	2.5	Park et al. 2016 (NY)	Melandrena (33)
Bombus	apple_pa	4.4	51	1.5	Park et al. 2016 (NY)	Bombus (8)
honey_bee	apple_mi	64.0	34	1.0	Park et al. 2016 (NY)	Apis (46)
other_bee	apple_mi	31.8	73	2.5	Park et al. 2016 (NY)	Melandrena (33)
Bombus	apple_mi	4.2	51	1.5	Park et al. 2016 (NY)	Bombus (8)
honey_bee	almond_ca	100	18	1.0	Thomson & Goodell 2001 (CA)	Apis mellifera (16)

Table S3. Methods details for bee observations on each crop.

crop	state	years	sites	transects	bee obs dates per year	bee obs times per day	bee obs replicate unit
almond	CA	2013, 2014	6	35	1	1	6.7 min (20 sec x 4 areas per tree x 5 trees). The four areas observed on each tree were bottom exterior, bottom interior, top exterior, and top interior.
apple	MI	2013, 2014, 2015	5	57	1	1	10 min (60 sec per tree x 10 trees). Approximately equal time was spent on both sides of the tree.
apple	PA	2013, 2014	5	32	1	1	10 min (60 sec per tree x 10 trees). Approximately equal time was spent on both sides of the tree.
blueberry	BC	2013, 2014, 2015	17	177	3	1	10 min (20 bushes along transect, 1 side each). Observers walked along the row, observing only the facing half of each bush.
blueberry	MI	2013, 2014, 2015	17	188	3	1	10 min (20 bushes along transect, 1 side each). Observers walked along the row, observing only the facing half of each bush.
blueberry	OR	2014, 2015	6	45	3	1	10 min (20 bushes along transect, 1 side each). Observers walked along the row, observing only the facing half of each bush.
blueberry	FL	2014, 2015	12	47	3	1	10 min (20 bushes along transect, 1 side each). Observers walked along the row, observing only the facing half of each bush.
tart cherry	MI	2013, 2014, 2015	5	58	1	1	10 min (60 sec per tree x 10 trees). Approximately equal time was spent on both sides of the tree.
tart cherry	PA	2015	4	16	1	1	10 min (60 sec per tree x 10 trees). Approximately equal time was spent on both sides of the tree.
sweet cherry	WA	2013, 2014, 2015	11	56	3	1	10 min (60 sec per tree x 10 trees). Approximately equal time was spent on both sides of the tree.
pumpkin	PA	2013, 2014, 2015	13	49	3	2	22.5 min (45 sec x 30 replicates per transect). Each replicate was a patch of flowers small enough to be observed from one location.
watermelon	CA	2013, 2014, 2015	17	68	2	2	16.7 min (25 sec x 40 replicates per transect). Each replicate was a patch of flowers small enough to be observed from one location.
watermelon	FL	2013, 2014, 2015	19	80	2	2	16.7 min (25 sec x 40 replicates per transect). Each replicate was a patch of flowers small enough to be observed from one location.

Table S4. Methods details for yield or production measurements of each crop.

crop	state	crop production variable	replicate unit
almond	CA	number of fruit per flower	5 trees sampled per transect
apple	MI	number of fruit per branch*	10 trees per transect (1 branch sampled per tree)
apple	PA	number of fruit per branch*	2-50 (mean 16) trees per transect (1 branch sampled per tree)
blueberry	BC	fruit weight (per berry, open-bagged)	10 bushes per transect (1 bagged and unbagged branch sampled per bush)
blueberry	MI	fruit weight (per berry, open-bagged)	10 bushes per transect (1 bagged and unbagged branch sampled per bush)
blueberry	OR	fruit weight (per berry, open-bagged)	10 bushes per transect (1 bagged and unbagged branch sampled per bush)
blueberry	FL	fruit weight (per berry, open-bagged)	10 bushes per transect (1 bagged and unbagged branch sampled per bush)
tart cherry	MI	number of fruit per flower	10 trees per transect (1 branch sampled per tree)
tart cherry	PA	number of fruit per flower	10 trees per transect (1 branch sampled per tree)
sweet cherry	WA	fruit weight per branch	10 trees per transect (1 branch sampled per tree)
pumpkin	PA	fruit weight per area	5 (2013), 20 (2014-15) quadrats per transect (1 sq m each)
watermelon	CA	fruit weight per area	20 quadrats per transect (2.25 sq m each)
watermelon	FL	fruit weight per area	10 (2013), 20 (2014-15) quadrats per transect (2.25 sq m each)

*Note: for apple, we additionally explored models that included branch cross -sectional area to control for the possibility that larger branches could produce more fruit. However, the orchards we sampled were of similar cross -sectional area, thus the additional variable was not retained by AIC selection.

Table S5. Percent of national gross production value represented by the states sampled in this study (average of 2013-2015 production values). States that are often the top state in terms of national value are marked with an asterisk. In the case of apple, our data rely on estimates from Michigan and Pennsylvania, which both contain important apple producing regions (see Fig. S1), but sum to only about 10% of national value. However our estimates of honey bee and wild bee visitation rates for apple match very well with literature estimates from New York, which is a higher-value state (Park et al. 2016). Similarly, pumpkin is grown widely across the USA, while our data for this crop come only from Pennsylvania. Although it is reasonable to expect that there may be regional differences in pollination that our analysis will not incorporate, our data nevertheless represent the best information currently available.

Crop	States sampled	Percent of National Value
Almond	California*	100.0
Tart Cherry	Michigan*, Pennsylvania	67.0
Sweet Cherry	Washington*	57.6
Blueberry	Florida, Michigan*, Oregon	48.2
Watermelon	Florida*, California	39.7
Pumpkin	Pennsylvania	12.0
Apple	Michigan, Pennsylvania	10.2

Table S6. Pollinator limitation analysis model results (part 1). Yield or crop production variables used in the models, best model as chosen by AIC, breakpoint (if segmented model was chosen), and estimated percent of transects that were pollination limited are listed for each model.

crop	state	variable	best model	segmented breakpoint	percent limited
almond	CA	number of fruit per flower	linear negative	NA	0
apple	MI	number of fruit per branch	linear positive	NA	100
apple	PA	number of fruit per branch	linear positive	NA	100
blueberry	BC	fruit weight per berry (open-bagged)	segmented	26.3	94
blueberry	MI	fruit weight per berry (open-bagged)	segmented	26.3	72
blueberry	OR	fruit weight per berry (open-bagged)	segmented	26.3	64
blueberry	FL	fruit weight per berry (open-bagged)	flat	NA	0
tart cherry	MI	number of fruit per flower	segmented	131.0	72
tart cherry	PA	number of fruit per flower	NA	NA	NA
sweet cherry	WA	fruit weight per branch	segmented	7.3	74
pumpkin	PA	fruit weight per area	flat	NA	0
watermelon	CA	fruit weight per area	segmented	0.3	9
watermelon	FL	fruit weight per area	linear negative	NA	0

Table S7. Pollinator limitation analysis model results (part 2). AIC values, delta AIC values, and Akaike weights are listed for each model, and the best model for each crop state combination is marked in bold.

crop	states	model	AIC	ΔAIC	*w*
almond	CA	flat model	-31.4	1.7	0.30
almond	**CA**	**linear model (neg)**	**-33.1**	**0**	**0.70**
almond	CA	segmented model	NA	NA	NA
apple	MI	flat model	350.5	5.5	0.06
apple	**MI**	**linear model (pos)**	**345**	**0**	**0.91**
apple	MI	segmented model	351.9	6.9	0.03
apple	PA	flat model	232.7	8.4	0.01
apple	**PA**	**linear model (pos)**	**224.3**	**0**	**0.59**
apple	PA	segmented model	225.1	0.8	0.40
blueberry	MI, OR, BC	flat model	264.7	56.3	0.00
blueberry	MI, OR, BC	linear model (pos)	211.1	2.7	0.21
blueberry	**MI, OR, BC**	**segmented model**	**208.4**	**0**	**0.79**
blueberry	**FL**	**flat model**	**39.2**	**0**	**0.68**
blueberry	FL	linear model (neg)	40.7	1.5	0.32
blueberry	FL	segmented model	NA	NA	NA
tart cherry	MI	flat model	-86.1	4.8	0.05
tart cherry	MI	linear model (pos)	-90.5	0.4	0.43
tart cherry	**MI**	**segmented model**	**-90.9**	**0**	**0.52**
sweet cherry	WA	flat model	353.6	8.7	0.01
sweet cherry	WA	linear model (pos)	354.6	9.7	0.01
sweet cherry	**WA**	**segmented model**	**344.9**	**0**	**0.98**
pumpkin	**PA**	**flat model**	**352.3**	**0**	**0.48**
pumpkin	PA	linear model (pos)	352.7	0.4	0.39
pumpkin	PA	segmented model	354.9	2.6	0.13
watermelon	CA	flat model	432.6	1.7	0.27
watermelon	CA	linear model (pos)	434.3	3.4	0.11
watermelon	**CA**	**segmented model**	**430.9**	**0**	**0.62**
watermelon	FL	flat model	338.3	6.2	0.00
watermelon	**FL**	**linear model (neg)**	**332.1**	**0**	**1.00**
watermelon	FL	segmented model	NA	NA	NA

Table S8. Variable input costs per acre (in USD) for each crop-state used in our value analysis, and reference for best-available local extension publication from which cost estimates were calculated.

crop	state	Variable input cost per acre (USD)	reference	notes	% of gross production value
cherry_tart	MI	$2080	Penn State Cooperative Extension (2014)	variable costs	88%
cherry_tart	PA	$2080	Penn State Cooperative Extension (2014)	variable costs	73%
cherry_sweet	WA	$6495	Washington State University Extension (2007)		49%
watermelon	CA	$6885	University of California Cooperative Extension (2004)	all costs minus land prep	86%
watermelon	FL	$2759	Clemson University Extension (2009)	variable costs	51%
blueberry	MI	$7420	Penn State Cooperative Extension (2014)	variable costs	86%
blueberry	OR	$6052	Oregon State University Extension Service (2011)	variable costs for machine harvest	43%
blueberry	FL	$8017	University of Georgia Cooperative Extension (2004)	total variable + harvesting and marketing	45%
apple	MI	$3794	Penn State Cooperative Extension (2014)	60 40 processing vs fresh market (different input costs)	56%
apple	PA	$3794	Penn State Cooperative Extension (2014)	60 40 processing vs fresh market (different input costs)	82%
almond	CA	$2151	University of California Cooperative Extension (2011)	total operating costs	29%
pumpkin	PA	$1672	Penn State Cooperative Extension (2000)		62%

Table S9. A comparison of the fraction of blueberry transects below the estimated breakpoint for pollinator/pollen limitation in the main analysis and hand-pollination analysis (see Supplementary analysis 2). For Florida blueberry, the no relationship model was preferred by AIC, so we do not apply the breakpoint model and therefore estimate 0% (i.e. no limitation).

blueberry region	main analysis (open-bagged)	hand analysis (hand-open)
British Columbia	0.94	0.88
Michigan	0.72	0.42
Oregon	0.64	0.22
Florida	0 / NA	0 / NA

Table S10. Percentages of agricultural and natural landcover within various radii of the study farms. Within each crop system, values are mean percentages across study farms calculated using the 2016 National Landcover Dataset (Homer et al. 2020).

	percent agriculture				percent natural			
crop	1 km	3 km	5 km	10 km	1 km	3 km	5 km	10 km
almond_ca	80	80	73	67	16	17	22	26
apple_mi	67	61	55	49	29	34	38	43
apple_pa	45	35	35	32	47	58	57	60
blueberry_fl	35	25	21	21	60	69	73	71
blueberry_mi	41	30	29	32	48	55	54	50
blueberry_or	84	77	75	71	9	14	13	13
cherry_sweet_wa	13	18	14	10	81	74	78	76
cherry_tart_mi	66	56	50	45	28	36	42	47
cherry_tart_pa	64	55	50	40	24	34	40	51
pumpkin_pa	52	44	44	41	39	47	47	49
watermelon_ca	92	84	81	72	3	9	13	20
watermelon_fl	58	50	46	39	36	41	46	52

Table S11. (separate .xlsx file) Economic value estimates associated with Analysis 3 and Supplementary analysis 1. Quantities referenced by each equation (equations S3-S8) within the economic value analyses are listed with their associated crop and state. These estimates were used to produce Fig. 4 and Fig. S5.