Materials and Methods

Study sites and system: The study was carried out late April to mid-May 2011 and 2012 in western and central New York State, USA. The study region spans roughly 5,000 km2 and ranges from Newfield in the south (42.351524°, -76.564604°) to the southern shore of Lake Ontario (43.282155°, -77.121445°) in the north. Sites were spread across five counties: Cayuga, Ontario, Schuyler, Seneca, Tompkins, and Wayne counties. Annual rainfall is approximately 1,000 mm. Average monthly temperatures range from 0 °C and 27.5 °C. The study landscape is heterogeneous, marked by fragmented deciduous woodlands and mixed agriculture, and included three study regions: southern Fingerlakes, Geneva area and southern Lake Ontario. Apple production intensifies as one moves north from the southern Fingerlakes to Lake Ontario, the primary apple producing region of New York State, which is the second largest producer of apple in the United States (USDA National Agricultural Statistics Service 2008). Study sites included U-pick, experimental and commercial orchards, ranging in size from 0.4 to 162 ha.

Apple is a perennial, mass-flowering crop that requires cross-pollination by insects, primarily bees (1). The general practice for managing pollination in our study region is to rent honey bee hives, particularly for large orchards (Park, *pers. obs*). In our study, 74% of orchards rented honey bees, at average density 0.42 hives per acre but ranged from 0.16 to 1.14 hives per acre. Apple is visited by a diverse and abundant wild bee community (2); it is an attractive and accessible floral resource for wild pollinators due to its open flower morphology and production of substantial nectar and pollen rewards (3). Although orchards in our study displayed a wide range of pesticide use, managing a successful crop requires a relatively intense spray regime compared to other crops (4). Bactericides are applied almost exclusively before bloom, with copper formulations acting as both a bactericide and fungicide. Fungicides are applied throughout the season, especially before and during bloom. Growers protect pollinators from insecticide sprays by not applying them during the bloom; however, their precautions are traditionally based on timing of hive placement in the orchard just before the bloom and removal at petal fall. Insecticides are commonly applied before bloom to kill aphid and mite eggs, and at petal fall, the end of peak bloom when petals start to fall, to control lepidopteran pests. Conventional apple growers ubiquitously apply thinning sprays to reduce the fruit load of trees in order to maximize fruit size and prevent alternate bearing among years. Thinners, including Carbaryl an insecticidal compound that also stresses apple trees and plant growth regulators, are typically applied at petal fall after honey bee hives have been removed. Depending on the fruit load, up to 25% of blossoms may remain on trees when thinners are applied (5). Therefore, in spite of grower efforts to protect pollinators from pest management, if active in the orchard before or near the end of bloom, wild bees are exposed to fungicides, bactericides, insecticides and plant growth regulators.

Bee sampling: At each site, multiple transects of 15-minute timed, aerial netting were conducted along blooming tree rows. During each 15 minute transect, collectors walked a steady pace along 50 m of each side of two adjacent tree rows, and netted all observed bees visiting apple blossoms. In 2011 and 2012, temperature data were recorded for each transect from the nearest weather station (< 1 km up to 14 km away) and hand-held temperature meter, respectively. In 2011, we randomly placed three pairs of transects at two edges and at the center of the orchard, for a total of six transects. Transects were spaced at least 50 meters apart. To maintain the 50 m distance between transects, in our smallest orchard we conducted 2 transects per collection event and in two other small orchards, we conducted 4 transects. If an orchard had an edge flanked by natural habitat, we selectively placed a pair of transects there. The location of each transect was marked using GPS. To inform the importance of transect placement, we used ArcGIS 10 to map transects onto county orthophotos to calculate transect distance from orchard edge. In order to control for the effects of bloom display on bee visitation, we systematically counted the number of flower clusters (normally comprised of 5 flowers) and number of open flowers per cluster at the first, middle and last tree in a transect row. An estimate of the total number of blossoms per transect was then calculated by the product of number of trees per transect, average number of clusters per tree and percent open flowers. We also categorized the bloom stage at the orchard level as "early" (1-2 flowers open per cluster on average), "peak" (3-5 flowers open per cluster on average) or "past" (petal fall had begun), and the percentage of the orchard in bloom as 0-25%, 26-50%, 51-75% or 76-100%. The fixed effect of distance to edge, density of flowers in bloom per transect and their interaction were tested against wild bee abundance and richness per transect (both ln+1 transformed) in a mixed linear model with the covariate temperature and orchard as a random variable. Because sampled bees were not influenced by distance from edge (abundance: $t = 0.92$, $d.f. = 84$, $p = 0.36$; richness: $t = 1.76$, $d.f. = 84$, $p = 0.082$) or bloom density within a transect (abundance: $t = -0.28$, $d.f. = 84$, $p = 0.78$; richness: $t = 0.17$, $d.f. = 84$, $p = 0.87$) in 2011, we simplified our sampling protocol the following year. First, we reduced the number of transects per collecting event from six to two and placed them opportunistically throughout the orchard within 150 m of orchard edge, where trees were most in bloom. We maintained 50 m between transects whenever possible (if not, it was because bloom was limited or because orchard was too small). Second, we assessed bloom stage as described above, but did not count clusters per tree. Instead of calculating flowers per transect, we developed an index of bloom display for the orchard that incorporates the proportion flowers open per cluster within transects and the proportion of the orchard in bloom. This index, therefore, estimated total floral display based on the bloom stage (relative to peak) of the trees and the spatial extent across the orchard. The simpler protocol enable us to survey each orchard in 2012 twice, while in 2011 50% or orchards were surveyed twice. Given unequal sample sizes among orchards within and between years, an average of timed netting trials was calculated per site per collection day and used in statistical analyses. Bee specimens were pinned, labeled and identified to species. Specimens reside in Cornell University's Entomology Collection (http://cuic.entomology.cornell.edu/).

Scale of percent natural habitat: To inform the appropriate scale at which to use percent natural habitat in our main analyses, we determined the scale at which percent natural area in the landscape provided the best model fit (i.e. lowest akaike information criterion [AIC] score). Five mixed linear models were conducted with the response variables abundance and richness of wild bee species, each, and included the fixed covariates percent natural area, year and temperature, with orchard as a random variable. The radius of percent natural area changed with each model and included 300 m, 500 m, 1000 m, 1500 m and 2000 m. The scale that provided the model with the lowest AIC score was chosen (table S6). Dominated by deciduous and mixed forest, percent natural habitat was negatively correlated with percent land in agriculture ($t = -3.9203$, df $= 17$, $p = 0.001$, Pearson's product momentum).

References

1. Free JB (1993) *Insect pollination of crops* (Academic Press, London, UK). 2nd Ed.
2. Bartomeus I et al. (2013) Biodiversity ensures plant–pollinator phenological synchrony against climate change. *Ecol Lett*:1331–1338.
3. McGregor SE (1976) *Insect pollination of cultivated crop plants* (U.S. Department of Agriculture, Agricultural Research Service).
4. Mates SG, Perfecto I, Badgley C (2012) Parasitoid wasp diversity in apple orchards along a pest-management gradient. *Agric Ecosyst Environ* 156:82–88.
5. Eve Consulting (2013) *personal communication*.

Table S1. Cover types included in classification of natural and agricultural areas in landscape-level analyses. Mean percent composition of each class as well as their range (min-max) are provided within a 2km radius of study orchards

Class category	Cover type	Mean % composition (range)
Natural	Deciduous forest	23.0 (9.1 – 46.0)
	Wood wetland	6.1 (2.6 – 15.0)
	Shrubland	3.7 (1.1 – 8.3)
	Mixed forest	2.9 (0.9 – 6.9)
	Evergreen forest	0.6 (0.1 – 1.6)
	Herbaceous wetland	0.12 (0.0 – 0.1)
	Grassland/herbaceous	0.04 (0.0 – 0.34)
Agricultural	Annual row crops	15.0 (1.5 – 38.3)
	Pasture/fallow fields	11.5 (4.3 – 23.6)
	Apple	10.8 (0.2 – 38.0)
	Perennial row crops	6.3 (0.4– 19.7)
	Non-apple tree fruit	0.5 (0.0 – 1.8)
	Vineyard	0.03 (0.0 – 0.1)

Table S2. List of pesticides applied across study orchards. For study analyses, bactericides were classified as fungicides (F) and miticides as insecticides (I). Pesticide application frequency and rate ranges are for the entire study. All rates were converted to lb/ac or pt/ac for index calculations. The bee impact quotient (BIQ) is a relative impact score based on honey bee toxicity and plant surface half-life of a pesticide. Herbicides, adjuvants and penetrants were not included in index calculations and are not shown here.

Classification	Study class	Active ingredient	Times applied	Min rate (lb or pt/ac)	Max rate (lb or pt/ac)	BIQ
Fungicide	F	*Bacillus subtilis*	8	2	2	3
Fungicide/Bactericide	F	Basic Copper Sulfate	13	2	6	9.3
Fungicide	F	Boscalid	2	0.1875	0.225	9.3
Fungicide/Miticide	F	Calcium Polysulfide	4	8	8	9.3
Fungicide	F	Captan	140	0.25	5	3
Fungicide/Bactericide	F	Copper Hydroxide	5	1.5	4	9.3
Fungicide	F	Cyprodinil	30	0.125	0.75	9.3
Fungicide	F	Difenoconazole	27	0.25	0.8	15
Fungicide	F	Dodine	2	2	2	9
Fungicide	F	Fenarimol	7	0.0375	0.75	3
Fungicide	F	Fenbuconazole	3	0.375	0.5	9.3
Fungicide	F	Kresoxim-methyl	12	0.09375	0.375	3
Fungicide	F	Mancozeb	85	0.5	6	9.3
Fungicide	F	Myclobutanil	21	0.0625	0.3125	9.3
Fungicide	F	Phosphorous Acid	6	1	1.75	3
Fungicide	F	Pyraclostrobin	2	0.1875	0.225	9.3
Fungicide	F	Pyrimethanil	3	0.4	0.6	3
Bactericide	F	Streptomycin sulfate	31	0.2	1.5	10.23
Fungicide	F	Sulfur	28	1.5	6	9.3
Fungicide	F	Tebuconazole	1	0.15625	0.15625	15
Fungicide	F	Thiophanate-Methyl	33	0.03125	5.6	9.3
Fungicide	F	Trifloxystrobin	27	0.025	2	9.3
Fungicide	F	Triflumizole	3	0.3125	0.3125	3
Fungicide	F	Ziram	1	1.875	1.875	3
Insecticide/Miticide	I	Abamectin	3	0.125	0.625	28.5
Miticide	I	Acequinocyl	1	0.875	0.875	3
Insecticide	I	Acetamiprid	47	0.15625	0.5	17.1
Insecticide	I	*Bacillus thuringiensis Kurstaki*	22	0.4	1.5	5.7
Insecticide	I	Beta-cyfluthrin	2	0.1	0.1	28.5
Insecticide/Miticide	I	Bifenazate	1	0.2	0.2	17.1
Insecticide	I	Carbaryl	26	0.09375	4	15
Insecticide	I	Chlorantraniliprole	10	0.15625	0.25	18.81
Insecticide	I	Chlorpyrifos	1	1	1	15
Insecticide	I	Emamectin Benzoate	2	0.15	0.3	15
Insecticide/Miticide	I	Fenpyroximate	9	0.09375	2	3

Insecticide	I	Imidacloprid	5	0.125	0.375	28.5
Insecticide	I	Indoxacarb	13	0.1	0.375	28.5
Insecticide	I	Lambda-Cyhalothrin	2	0.25	0.25	28.5
Insecticide	I	Methoxyfenozide	3	0.75	0.8	15
Insecticide	I	Phosmet	7	0.7	2.5	28.5
Insecticide/Miticide	I	Pyridaben	2	0.125	0.6625	28.5
Insecticide	I	Pyriproxyfen	2	0.3125	0.3125	3
Insecticide	I	Spinetoram	11	0.28125	0.40625	18.81
Insecticide	I	Spirotetramat	6	0.15	0.46875	5.7
Insecticide	I	Thiacloprid	16	0.05	0.5	9
Insecticide	I	Thiamethoxam	8	0.28125	0.3125	28.5
Insecticide/Fungicide	Excluded	Petroleum oil	2	5.12	8	18.81
Plant growth regulator	P	6-benzyladenine	2	1	1	3
Plant growth regulator	P	Gibberellin A4, Gibberllin A7	4	1	1.25	3

Table S3. Species list and frequency of female bees surveyed in Spring 2011 and 2012 in orchards across Central New York State.

Species	**Count**
Agapostemon sericeus (Förster, 1771)	3
Andrena barbilabris (Kirby, 1802)	5
Andrena carlini Cockerell, 1901	49
Andrena commoda Smith, 1879	3
Andrena crataegi Robertson, 1893	168
Andrena cressonii Robertson, 1891	18
Andrena dunningi Cockerell, 1898	16
Andrena erythronii Robertson, 1891	3
Andrena forbesii Robertson, 1891	31
Andrena hippotes Robertson, 1895	75
Andrena imitatrix Cresson, 1872	5
Andrena mandibularis Robertson, 1892	12
Andrena milwaukeensis Graenicher, 1903	9
Andrena miserablis Cresson, 1872	114
Andrena morrisonella Viereck, 1917	13
Andrena nasonii Robertson, 1895	67
Andrena nivalis Smith, 1853	1
Andrena nuda Robertson, 1891	1
Andrena perplexa Smith, 1853	22
Andrena pruni Robertson, 1891	16
Andrena regularis Malloch, 1917	254
Andrena rugosa Cockerell, 1906	42
Andrena vicina Smith, 1853	141
Andrena w-scripta Viereck, 1904	8
Andrena wilkella (Kirby, 1802)	1
Apis mellifera Linnaeus, 1758	1820
Augochlorella aurata (Smith, 1853)	4
Augochlorella pura (Say, 1837)	32
Bombus bimaculatus Cresson, 1863	20
Bombus fervidus (Fabricius, 1798)	1
Bombus griseocollis (DeGeer, 1773)	13
Bombus impatiens Cresson, 1863	155
Bombus perplexus Cresson, 1863	14
Bombus ternarius Say, 1837	3
Bombus terricola Kirby, 1837	1
Ceratina calcarata Robertson, 1900	12
Ceratina dupla Say, 1837	1
Colletes inaequalis Say, 1837	29
Halictus confusus Smith, 1853	11
Halictus rubicundus (Christ, 1791)	10
Lasioglossum cinctipes (Provancher, 1888)	12
Lasioglossum coeruleum (Robertson, 1893)	5

Table S3. Species list and frequency of female bees surveyed in Spring 2011 and 2012 in orchards across Central New York State.

Species	**Count**
Lasioglossum coriaceum (Smith, 1853)	2
Lasioglossum cressonii (Robertson, 1890)	4
Lasioglossum ephialtum Gibbs, 2010	1
Lasioglossum foxii (Robertson, 1895)	17
Lasioglossum imitatum (Smith, 1853)	1
Lasioglossum laevissimum (Smith, 1853)	6
Lasioglossum lineatulum (Crawford, 1906)	13
Lasioglossum hitchensi Gibbs, 2012	38
Lasioglossum nigroviride (Graenicher, 1911)	1
Lasioglossum obscurum (Robertson, 1892)	1
Lasioglossum oceanicum (Cockerell, 1916)	8
Lasioglossum paradmirandum (Knerer and Atwood, 1966)	9
Lasioglossum perpunctatum (Ellis, 1913)	1
Lasioglossum planatum (Lovell, 1905)	3
Lasioglossum quebecense (Crawford, 1907)	13
Lasioglossum truncatum (Robertson, 1901)	1
Lasioglossum versans (Lovell, 1905)	1
Lasioglossum versatum (Robertson, 1902)	16
Lasioglossum weemsi (Mitchell, 1960)	6
Lasioglossum zonulum (Smith, 1848)	8
Nomada cressonii Robertson, 1893	3
Nomada ovata (Robertson, 1903)	1
Nomada pygmaea Cresson, 1863	1
Osmia conjuncta Cresson, 1864	2
Osmia cornifrons (Radoszkowski, 1887)	18
Osmia pumila Cresson, 1864	1
Xylocopa virginica (Linnaeus, 1771)	23

Table S4. Fixed effects of pest management, percent natural habitat, year, and temperature on abundance and species richness of bees visiting apple blossoms in 2011 and 2012, with a random orchard nested within region effect. All response variables except social bees were ln(y +1) transformed. Temperature was ln(x) transformed. Percent natural habitat and Pesticide Use Index (PUI) were mean centered. Non-transformed coefficients (SE) are presented with *p*-values indicated by asterisks: * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$. Blanks represent variables dropped following backwards stepwise deletion. Hive density, local orchard diversity, floral display, and Phosmet use had no effect on bees, and are not included. ΔAIC from null to final model included. N = 19 orchards total.

	Abundance				**Species richness**		
Fixed Effects	Wild bee	Solitary	Social	Honey bee	Wild bee	Solitary	Social
% Natural habitat	0.027 (0.0061) ***	0.021 (0.0069) **	0.065 (0.013) ***		0.022 (0.0040) ***	0.017 (0.0046) **	0.052 (0.014) ***
Pesticide Use Index (PUI)	0.00071 (0.0015)	0.0018 (0.0016)			-0.0015 (0.00072)	-0.00030 (0.0010)	
Year Ref = 2011	-0.64 (0.14) ***	-0.54 (0.14) ***	-1.38 (0.30) ***		-0.46 (0.098) ***	-0.36 (0.092) ***	-1.07 (0.25) ***
Temp (C°)	1.20 (0.41) **	1.35 (0.41) **	2.27 (0.93) *	1.00 (0.41) *	1.00 (0.29) **	0.060 (0.013) *	2.02 (1.03) *
% Natural × PUI	0.00024 (8.5×10^{-5}) *	0.00030 (9.8×10^{-5}) **			0.00016 (5.5×10^{-5}) *	0.00019 (6.4×10^{-5}) **	
PUI × Year	-0.0038 (0.0017) *	-0.0053 (0.0017) **				-0.0023 (0.0012) *	
ΔAIC	33.34	33.53	27.70	3.41	43.15	40.32	17.80

Table S5. Pesticides effects, according to class (fungicide v. insecticide) and application timing (before, during or after bloom), on wild bee abundance (2012) and species richness (2011 and 2012), surveyed on blossoms in orchards. Response variables were ln(y+1) transformed. All fixed effects were mean centred except for temperature, which was ln(x) transformed. Non-transformed coefficients (SE) are presented with *p*-values indicated by asterisks: * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$. Blanks represent variables dropped following backwards stepwise deletion. Results with and without Phosmet are provided for post-bloom analyses, the period in which Phosmet was applied. There were no significant effects of whether a farm used Phosmet in analyses without Phosmet, nor were there significant insecticide × natural area interactions on bees. Total orchard N=19.

	Bloom			
Fixed effect	Before	During	After (without Phosmet)	After (with Phosmet)
Abundance				
Natural Habitat (%)	0.0080 (0.0071)	0.023 (0.0082) *		0.020 (0.0087) *
Fungicide Use Index (FUI)	-0.0044 (0.0015) **	-0.0071 (0.0037)		
Insecticide Use Index (IUI)			-0.061 (0.014) ***	
% Natural x FUI	0.00032 (0.00010) **			
Temperature	1.34 (0.46) **	1.37 (0.48) **	1.73 (0.44) **	1.39 (0.49) *
Species richness				
Natural Habitat (%)	0.011 (0.0050)	0.019 (0.0054) **		0.019 (0.0053) **
Fungicide Use Index (FUI)	-0.0026 (0.00093) *			
Insecticide Use Index (IUI)			-0.040 (0.010) **	
% Natural x FUI	0.00019 (6.9×10^{-5}) *			
Temperature	1.02 (0.29) **	1.16 (0.30) ***	1.23 (0.29) ***	1.16 (0.30) ***
Year	-0.48 (0.10) ***	-0.48 (0.10) ***	-0.45 (0.10) ***	-0.48 (0.10) ***

Table S6. AIC results for mixed-model regressions of wild bee abundance and species richness by percent natural habitat in the surrounding landscape, year and temperature. Bold indicates radius resulting in the lowest AIC and used for all analyses.

Wild bee	**Radius (m)**	**AIC**
Abundance	300	283.36
	500	281.64
	1000	277.60
	1500	276.95
	2000	**275.76**
Species richness	300	154.84
	500	153.18
	1000	149.10
	1500	148.20
	2000	**146.12**

Figure S1. Study orchards (N = 19) lay along two continuous gradients: index of pesticide use intensity and percent natural area, making it possible to look at the interaction between the two.

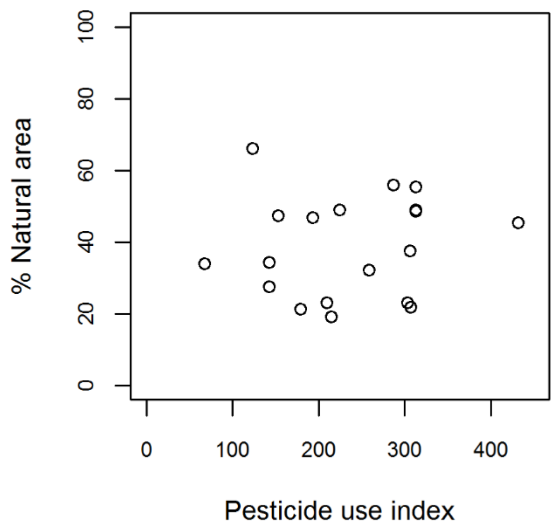

Figure S2. Bivariate relationships between surrounding natural habitat (2km scale) of wild solitary and social bee abundance and species richness in apple orchards in 2011 (n= 16, open circles, hatched regression line) and 2012 (n=19, closed circles, solid regression line). Percent natural area had a significant positive association with all wild bees regardless of sociality across years. Simple linear regression lines indicate significant relationships.

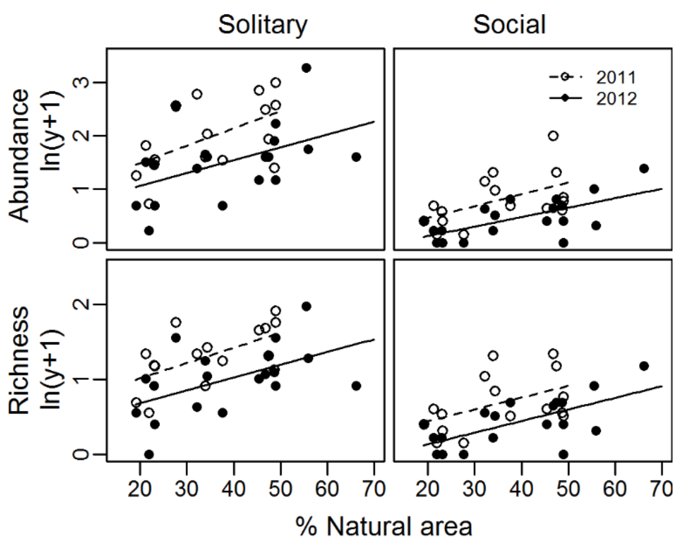

Figure S3. Bivariate relationships between intensity of conventional pesticide use in 2011 and surveyed wild solitary and social bee abundance and species richness in apple orchards in 2011 (open circles, hatched regression line, n = 16) and 2012 (closed circle, solid regression line, n = 19). Pesticide use in 2011 had a negative effect on wild solitary bee richness across years and on abundance in 2012. Simple linear regression lines indicate significant relationships.