IPM reduces insecticide applications by 95% while maintaining or enhancing crop yields through wild pollinator conservation

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Pest management practices in modern industrial agriculture have increasingly relied on insurance-based insecticides such as seed treatments that are poorly correlated with pest density or crop damage. This approach, combined with high invertebrate toxicity for newer products like neonicotinoids, makes it challenging to conserve beneficial insects and the services they provide. We used a 4-y experiment using commercial-scale fields replicated across multiple sites in the midwestern United States to evaluate the consequences of adopting integrated pest management (IPM) using pest thresholds compared with standard conventional management (CM). To do so, we employed a systems approach that integrated coproduction of a regionally dominant row crop (corn) with a pollinator-dependent specialty crop (watermelon). Pest populations, pollination rates, crop yields, and system profitability were measured. Despite higher pest densities and/or damage in both crops, IPM-managed pests rarely reached economic thresholds, resulting in 95% lower insecticide use (97 versus 4 treatments in CM and IPM, respectively, across all sites, crops, and years). In IPM corn, the absence of a neonicotinoid seed treatment had no impact on yields, whereas IPM watermelon experienced a 129% increase in flower visitation rate by pollinators, resulting in 26% higher yields. The pollinator-enhancement effect under IPM management was mediated entirely by wild bees; foraging by managed honey bees was unaffected by treatments and, overall, did not correlate with crop yield. This proof-of-concept experiment mimicking on-farm practices illustrates that cropping systems in major agricultural commodities can be redesigned via IPM to exploit ecosystem services without compromising, and in some cases increasing, yields.

Significance

Environmental damage from insecticide overuse is a major concern, particularly for conservation of “good” insects such as pollinators that ensure stable production of food crops like fruits and vegetables. However, insecticides are also necessary for farmers to manage “bad” insects (i.e., pests), and thus, a more holistic view of crop management needs to account for the proper balance between the beneficial and detrimental aspects of pesticides. Here, we used multiyear field experiments with a paired corn–watermelon cropping system to show that insecticide use can be dramatically reduced (by ∼95%) while maintaining or even increasing yields through the conservation of wild bees as crop pollinators. These data demonstrate that food production and ecosystem sustainability are not necessarily conflicting goals.

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in oral toxicity, an effect attributed almost completely to corn and soybean NSTs. These patterns suggest that neonicotinoid inputs in row crops have the potential to profoundly affect pollinator health across landscapes, with potential reverberations in noncorn/soybean habitats.

Most fruits, vegetables, and tree nuts (hereafter “specialty crops”) are at least partially—and, in some cases, entirely—reliant on insect pollinators for yield (40–42). Consequently, NST-mediated impacts have the potential to threaten food production. However, the crops driving neonicotinoid exposure are not the same ones that depend on bees for their services. Corn, soybean, and cotton account for production. However, the crops driving neonicotinoid exposure are not the same ones that depend on bees for their services. Corn, soybean, and cotton are primarily considered self-pollinating [despite some recent evidence for yield benefits with bee visitation (43, 44)], and corn is wind-pollinated. Although bees are known to visit these crops for nectar and/or pollen, insect pollinators are not critical to their production. Row crops are cultivated over a large fraction of arable land in the United States [9.8% of the continental United States is dedicated to corn, soybean, and cotton (45)], and specialty crop fields in this region are often adjacent to at least one of these row crops; therefore, we may expect carryover effects of NSTs on specialty crop pollination. For example, NST-infused dust from corn planting moves hundreds of meters beyond the field border (10, 15, 46), resulting in honey bee mortality (summarized in ref. 47). Thus, the relatively smaller areas devoted to specialty crops may invariably experience extrafield exposure from nearby row crops. Similarly, specialty and row crops are common rotation partners, resulting in neonicotinoid soil residues that impact ground-nesting bees (48–50). These spatial and temporal avenues generate several possible exposure routes. A simulation model (46) using field-derived values predicted that NSTs from corn planting in late spring erode honey bee population size enough to reduce capacity for blueberry and cranberry pollination later that summer, resulting in the potential for economic losses to neighboring berry growers. A similar outcome was demonstrated when modeling almond pollination potential for honey bee colonies that reside in the corn-dominated Northern Great Plains for much of the year (51).

In the work described here, we empirically test the hypothesis that IPM implementation, consisting of pest thresholds and removal of NSTs, dramatically reduces insecticide use and improves pollinator function without sacrificing crop yields. To do so, we used a multiyear, multisite field study, conducted in a dual cropping system representative of agriculture in the midwestern United States, and other parts of the world, consisting of a smaller acreage specialty crop paired with (i.e., adjacent to and grown in rotation with) a larger acreage row crop. We compared the effects of IPM versus conventional insecticide practices across several key metrics: insect pest abundance and damage, pollination, and yield. This design is unique in integrating field measurements of all factors across years, locations, and cropping systems. We paired field corn and seedless watermelon—a functionally dioecious crop that requires bees to move pollen between plants for fruit production. The experiment was conducted over 4 y (2017 to 2020) across five sites in Indiana, a state that is typically ranked in the top five nationally for both corn and watermelon production (52). In the conventional management (CM) system, we applied industry-standard practices used by growers in the region, characterized by NSTs on corn and preventative, calendar-based insecticides on watermelon. In the IPM system, we used NST-free corn seed with watermelon inputs determined by population thresholds established for arthropod pests. We predicted that the IPM system would have both higher pest densities (while remaining below economic thresholds) and pollinator visitation rates, resulting in equivalent (corn) or higher (watermelon) crop yield and increased farm profitability. This field experiment provides a comprehensive reassessment of IPM principles for both modern row crop and specialty crop pest management in the highly productive and intensively managed agricultural region of the midwestern United States.

Results
IPM Systems Experienced Infrequent Pest Outbreaks, Requiring Few Insecticide Inputs. Neonicotinoid seed treatments target early-season pests; however, early-season corn damage was unaffected by NSTs with corn plant stand similar (P = 0.867) between IPM (11,040 ± 145 plants·ha⁻¹) and CM (11,052 ± 106 plants·ha⁻¹) fields (SI Appendix, Fig. S3; refer to SI Appendix, Table S6d for full statistical model for this and subsequent pest metrics). Similarly, during the first 3 y of the study, <1% of sampled plants showed any direct evidence of feeding by western corn rootworm Diabrotica virgifera virgifera LeConte—the primary insect pest of corn in this region—across both treatments (overall damage rating: 0.001 ± 0.000 nodes). In the fourth and final year (2020), damage was more prevalent, with 33% of IPM corn roots showing evidence of rootworm feeding. This pattern resulted in a significant treatment × year interaction (P = 0.006), with pairwise comparisons showing that IPM fields in 2020 had higher damage ratings than all other treatment × year combinations (SI Appendix, Fig. S4). Despite this statistical increase in pest pressure in the IPM treatment over time, the magnitude of the effect was low (2020 IPM damage rating (on a 0-to-3 scale): 0.17 ± 0.07 nodes).

Watermelon in the CM treatment received insecticide sprays on a predetermined schedule that did not depend on scouting. These calendar applications maintained populations of the primary insect pest—striped cucumber beetle (SCB) Acalymma vittatum (F.)—well below the published economic threshold of five beetles per plant (Fig. 1A; seasonal mean SCBs per plant = 0.11 ± 0.05). In IPM fields, SCBs also rarely reached their economic threshold (Fig. 1B; seasonal mean SCBs per plant = 1.18 ± 0.34). Over the 3-y experiment, only four total IPM insecticide sprays (2018: 1; 2019: 1; and 2020: 2) were required across all five sites combined (i.e., four applications in 15 site-year growing seasons). In contrast, 77 insecticide applications were made in the CM treatment over the same period across all sites. In the IPM treatment, a single spray per field was sufficient to keep populations below economic thresholds for the remainder of the season; however, in most site-years, even a single spray was unnecessary. Appearance of secondary pests—primarily aphids and spider mites—occurred under both management systems (CM = 6, IPM = 4), but, interestingly, these populations only warranted additional pesticide applications (n = 2) in the CM plots (SI Appendix, Table SS). All other observed secondary pests did not spread to neighboring plants and were likely controlled by abiotic factors (heavy rain) or natural enemies, which were confirmed by the presence of parasitized aphids or coccinellid larvae/adults on flagged plants known to be previously infested.

Pesticide Residues Were Higher in Conventionally Managed Systems. Neonicotinoids applied to both crops in the CM system were routinely found in sampled plant tissues and soil; 99% (n = 335) of all samples collected had residues of at least one neonicotinoid compared to only 65% (n = 221) of IPM samples. Neonicotinoids in the pollen of both crops were higher in the CM than IPM treatment. Watermelon pollen had consistently higher concentrations of imidacloprid in CM (median: 6.17 ng/g) compared to IPM (median: < limit of detection [LOD]) flowers (Table 1); however, residues in CM fields decreased over time, with highest values in early-blooming

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pollen, on the other hand, rarely contained imidacloprid residues (CM: 50%, IPM: 10%), but CM corn pollen contained higher levels of both clothianidin (93% detection, median: 1.91 ng/g) and thiamethoxam (100% detection, median: 2.01 ng/g) than IPM corn pollen, which only contained detectable amounts of clothianidin and thiamethoxam in 20% and 10% of all samples, respectively (Table 2). This low-level contamination is likely attributable to uptake of carryover NSTs from previous cropping seasons before the experiment began or from adjacent fields.

Neonicotinoid residues were also higher in soil and leaf samples within the CM management system, depending on sample date. Refer to SI Appendix, Tables S7–S9 for pesticide summary data across all sample types and years. Nonneonicotinoid pesticides applied to the system—fungicides and the pyrethroid lambda-cyhalothrin—were also detectable but at varying levels (SI Appendix, Table S10). In general, fungicide detection was roughly equivalent across CM and IPM fields, whereas lambda-cyhalothrin was more frequently detected in watermelon leaves and pollen in CM fields (but overall detection rates were relatively low; <20% of samples).

**IPM Enhanced Watermelon Pollination.** The pollinator community composition was broadly similar across treatments, with the most commonly observed taxa being honey bees, *Apis mellifera* (CM = 35%, IPM = 15%), *Melissodes* sp. (CM = 22%, IPM = 25%), and *Lasio Melissodes + Halictus* sp. (CM = 26%, IPM = 37%) (refer to SI Appendix, Fig. S5 and Table S11 for a complete description across taxa). Overall abundance of pollinators visiting flowers was 99% greater in IPM (0.64 ± 0.05 pollinators · min⁻¹) than CM (0.32 ± 0.02 pollinators · min⁻¹) fields (refer to SI Appendix, Table S6) for full statistical model for this and subsequent pollination metrics). Notably, this pattern was driven entirely by wild bees. When treatment effects were tested for managed and wild species as separate groups, there was no impact on honey bee visitation ($P = 0.202$), but wild bee visitation was lower ($P < 0.001$) in CM fields.

Number of flowers visited per minute was 129% greater in IPM (1.25 ± 0.11 visits · min⁻¹) than in CM (0.55 ± 0.05 visits · min⁻¹) fields (Fig. 2A). Also, transition visits (observed trips from male to female flower) were 305% higher in IPM (0.18 ± 0.02 transition visits · min⁻¹) than CM (0.05 ± 0.01 transition visits · min⁻¹) fields (Fig. 2B).

**Table 1. Neonicotinoids were more frequently detected in watermelon pollen from fields under conventional management**

| Year | Conventional | IPM |
|------|--------------|-----|
|      | Percent detection (25) | Median (ng/g) | Range (ng/g) | Percent detection (25) | Median (ng/g) | Range (ng/g) |
| **Imidacloprid** | | | | | | |
| 2018 | 96% | 4.43 | < LOD-82.53 | 0% | < LOD | < LOD |
| 2019 | 100% | 6.28 | 1.38 to 55.86 | 44% | < LOD | < LOD-1.69 |
| 2020 | 100% | 4.84 | 1.54 to 22.94 | 4% | < LOD | < LOD-0.95 |
| **Clothianidin** | | | | | | |
| 2018 | 24% | < LOD | < LOD-2.12 | 0% | < LOD | < LOD |
| 2019 | 72% | 0.50 | < LOD-1.15 | 0% | < LOD | < LOD |
| 2020 | 52% | 0.14 | < LOD-0.79 | 0% | < LOD | < LOD |
| **Thiamethoxam** | | | | | | |
| 2018 | 24% | < LOD | < LOD-0.21 | 0% | < LOD | < LOD |
| 2019 | 16% | < LOD | < LOD-0.87 | 12% | < LOD | < LOD-0.16 |
| 2020 | 28% | < LOD | < LOD-0.25 | 8% | < LOD | < LOD-0.15 |

LC-MS/MS was used to quantify imidacloprid, clothianidin, and thiamethoxam from fields (n = 10). Watermelon represents pooled samples (3 g from 50 to 100 flowers) from each field across five consecutive weeks during peak bloom (n = 25 per year). LOD was 0.03, 0.01, and 0.025 ng/g for clothianidin, thiamethoxam, and imidacloprid, respectively.
NSTs Did Not Affect Corn Yield. There was no statistical difference ($P = 0.097$) in corn yields between management systems, but there was a trend for higher yield in IPM (10,602 ± 479 kg/ha) compared to CM (9,471 ± 694 kg/ha) fields (Fig. 3A; refer to Table $S6$ for full statistical model for this and subsequent yield metrics). Similarly, we conducted a more targeted small-plot trial in 2019 with higher replication and better control of local environmental factors. This follow-up experiment also showed no difference ($F_{1,51} = 0.47$, $P = 0.501$) between +NST (12,688 ± 269 kg/ha) and −NST (12,511 ± 311 kg/ha) corn yields ($SI Appendix$, Fig. S6).

IPM Watermelons Produced Higher Yields by Preserving Wild Bees. Watermelon yield was 25.7% higher in IPM (9.91 ± 0.84 kg/m$^2$) than in CM (7.88 ± 0.63 kg/m$^2$) fields (Fig. 3B). The significant difference in overall yield between treatments ($P = 0.002$) was driven by the reduced number of watermelons harvested in CM (59.07 ± 4.15) compared to IPM (72.13 ± 5.51) plots. Individual fruit weights were not statistically different ($P = 0.071$), but IPM melons (6.76 ± 0.18 kg) tended to be larger than those from CM (6.22 ± 0.23 kg) fields. Yield data only included fruit deemed marketable without any rind damage from insect feeding or other deformities. IPM watermelons experienced an increased number of damaged fruits (55 deemed unmarketable in IPM with only 1 in CM fields); this represented a <5% loss in potential yield.

There was no relationship between total pollinator visitation and crop yield, likely due to the high stocking of managed honey bee colonies in both pest management systems. To test this possibility, we separately analyzed honey bee visits apart from wild bee visits. This subset analysis confirmed that honey bee visitation could not predict watermelon yield (Fig. 4B; overall slope, $P = 0.097$), whereas higher rates of wild pollinator visitation, driven by lower insecticide use, resulted in correspondingly higher watermelon yield (Fig. 4B; overall slope, $P = 0.045$; CM slope, $P = 0.218$; IPM slope, $P = 0.728$).

IPM Was More Profitable than Conventional Management. The product cost (i.e., no application cost) of Cruiser 5FS on corn was $31.10 · ha$^{-1}$; however, using industry-provided data (53), the inflation-adjusted cost of an NST at the rate applied in this study was $57.79 · ha$^{-1}$. Using this cost calculation and the range of field sizes, the use of an NST in CM corn represented a cost of $330.93 ± 30.93 · field$^{-1}$. The cost relative yield (CRY; the minimum percentage in yield gain in which the insecticide cost is recuperated) was 3.3%, which was not reached in either the CM/IPM experiment or the within-site NST evaluation, indicating that the cost of NST was not recovered at any of the sites in this experiment.

Watermelon insecticides in the CM system cost $44.05 · ha$^{-1}$ for the soil drench and $50.28 · ha$^{-1}$ for all foliar insecticide applications ($12.57 per application) for a total cost of $94.33 · ha$^{-1}$ on each field with additional applications required to control secondary pests in some fields, increasing this cost. While several insecticide sprays were applied to the IPM watermelons, this was a minority of fields, leading to an average cost for IPM insecticides at $3.35 ± 1.44 · ha$^{-1}$ compared to $100.98 ± 3.49 · ha$^{-1}$ across the CM watermelon fields. The insecticide program for CM watermelons had a CRY of 0.70%; however, all fields within the CM system failed to reach this threshold, and the insecticide applications were never cost-effective. The increased yield from wild pollinator enhancement in the IPM system would result in a financial gain of $4,512.69 · ha$^{-1}$ over the CM system, based on the previous 5-y regional sale price for seedless watermelon (52).

Discussion

IPM-based approaches, ones that prioritize treating only when insect pests are present at damaging levels, have become increasingly rare across a range of commodities. Instead, a suite of prophylactic approaches to pest management—including insecticidal seed treatments, soil drenches, and calendar sprays—now dominate most US cropping systems, including the corn and watermelon systems studied here. However, our comprehensive field experiment demonstrates that there is no clear rationale supporting this approach from multiple perspectives including insect pest damage and abundance, pollinator visitation and efficiency, environmental pesticide residues, or crop yield and profitability. These varied and integrative perspectives are vital for grower adoption but surprisingly rare in practice. Hundreds of studies, for example, have tested the negative effects of neonicotinoids and related insecticides on pollinator health in the laboratory and field. The potential threat from these products is incontrovertible. Yet pollination alone paints an incomplete picture without corresponding data on pest population dynamics and crop production. In previous studies that experimentally reduce insecticide use in crops to

| Year | Conventional | IPM |
|------|--------------|-----|
| 2018 | 10% | < LOD-0.11 |
| 2019 | 30% | < < LOD-0.73 |
| 2020 | 100% | 0.23 |

| Year | Conventional | IPM |
|------|--------------|-----|
| 2018 | 70% | < LOD-4.66 |
| 2019 | 100% | 1.94 |
| 2020 | 100% | 1.91 |

| Year | Conventional | IPM |
|------|--------------|-----|
| 2018 | 100% | < LOD-0.56 |
| 2019 | 100% | 3.49 |
| 2020 | 100% | 1.81 |

LC-MS/MS was used to quantify imidacloprid, clothianidin, and thiamethoxam from fields (n = 10). Corn pollen was taken during anthesis with two replicates per field. LOD was 0.03, 0.01, and 0.025 ng/g for clothianidin, thiamethoxam, and imidacloprid, respectively.
determine impact on pollinators, the implications for pests and crops are typically overlooked or omitted [e.g., canola (54), cucurbits (49, 55), apples (56), and sunflowers (57)]. Similarly, in studies in which landscape complexity is used as a predictor of pollination services (58, 59), wholesale changes in pest management practices are not explicitly measured or discussed. Farmers are unlikely to change their management practices—no matter how detrimental to bees—if foregoing insecticide treatments leads to excessive crop and economic damage. Conversely, studies on pest/yield relationships [with limited exceptions (60, 61)] involve self- or wind-pollinated crops (7, 11, 62). These experiments often fail to capture the additional losses to yield that nearby or adjacent crops could experience—even though, in some cases, the landowner/crop producer is the same individual.

**Insecticide Use, Pest Outbreaks, and Crop Yield.** One expected corollary of reducing insecticide inputs over years of the experiment was an increase in pest densities over time. Surprisingly, the only evidence of increasing pest pressure on untreated corn was higher damage from rootworm larval feeding in year 4. To isolate the effect of NSTs with minimal confounding factors, corn in our experiment was grown somewhat atypically: without any Bt traits or crop rotation. Therefore, IPM corn was cultivated under a “worst-case scenario” with no protection for the duration of the study. Despite being entirely defenseless for four consecutive years, only three of the five fields experienced increased root feeding and only in the final year. These locations were at the northernmost sites, which is the region of the state, where rootworm pressure is historically highest (63). This outcome demonstrates that corn rootworm populations in major production areas should not be left unchecked and can increase in a relatively short time but that the industry standard of Bt corn with soybean rotation likely maintains rootworm at sufficiently low levels. It is also important to note that, while we focus on rootworm as the primary corn pest, and one for which we observed some evidence of feeding damage, NSTs are largely marketed as targeting secondary pests (e.g., wireworm and seedcorn maggot). These taxa were not present at appreciable densities in any of our experimental fields. Although these cryptic belowground insects are hard to directly sample, indirect evidence of their presence and impact (e.g., poor plant stand in early-season corn) was never observed.

Despite the rise in rootworm damage over time in NST-free corn, yields were not significantly different across the two systems, reinforcing other published studies that show no yield benefit from NSTs (8, 11, 14). Interestingly, the only factor impacting corn yield had nothing to do with insecticide use. We observed gradual but consistent reductions over time with year 4 yields 28% lower than year 1 yields. This effect was apparent across both IPM/CM treatments. The outcome is not surprising, as numerous studies have documented that single-species cultivation has negative feedbacks on crop productivity, including corn (64). These data strongly point to crop rotation as a factor in maintaining high corn yields and likely far more critical in mitigating rootworm damage than NST use (12). For the purposes of this study, we more narrowly defined IPM in the context of insecticide use, but a “true” IPM system would employ crop rotation rather than continuous cropping.

Unlike corn, the key insect pest in IPM watermelon colonized in the initial year and was present at moderate densities throughout the entire experimental period, but, similar to the corn system, these elevated densities did not translate to yield reductions, even using the fairly liberal threshold of five beetles per plant. These data suggest that watermelon should be routinely scouted to protect against the rare site or year in which pests, like cucumber beetles, exceed their threshold but can mostly be cultivated without insecticide use (65–68). Notably,
we only observed outbreaks of secondary pests—aphids and mites—in the CM system, in which we repeatedly treated the crop with insecticides. Cucurbit growers in our region frequently mention these as pests of concern; however, many of these same producers also use repeated applications of pyrethroids and neonicotinoids (69), compounds that are highly disruptive to beneficial insect communities that suppress aphid and mite populations (70). Altogether, these observations imply that overly aggressive treatment with broad-spectrum insecticides trigger secondary pest outbreaks in watermelon and that adopting a scouting-based IPM program with fewer inputs prevents the problem.

A major challenge to scouting adoption is that the CRY for watermelon is <1%, reflecting the reality that insecticides such as pyrethroids are inexpensive relative to other farm inputs (e.g., labor). Moreover, our CRY calculations do not account for the additional cost of scouting in IPM systems, which can be challenging to estimate (69). Some growers scout their own fields for pests, while others hire crop consultants. Similarly, scouting a subset of fields or sporadically observing a few edge plants (versus walking transects with a specified sample number and location) will undoubtedly reduce costs but also accuracy. In our experiment, insecticide costs were ca. $101 · ha⁻¹ in CM compared with $3 · ha⁻¹ in IPM. Thus, scouting would need to add at least $98 · ha⁻¹ to offset the difference. Other factors that affect the reliability of this estimate include the additional cost (e.g., fuel, equipment, and labor) of repeated insecticide applications in CM fields and variation in insecticide price or efficacy. Despite these complexities, Ternest et al. (69) found that the cost of seasonal pest scouting ranges from $29 to $120 for a field, well within our estimated price point for a commercial watermelon grower to see a positive return from scouting.

The economics of scouting and IPM as a whole also vary widely across cropping systems. We primarily consider watermelon for which crop value is relatively high, fields are relatively small, and the pests are mostly aboveground and can be controlled with insecticide sprays. In large acreage row crops such as corn with belowground pests that are both hard to sample and lacking immediate rescue-treatment options, the cost/benefit ratio of scouting may be less favorable. Even among specialty crops, we expect the net value of IPM to be highly variable. Watermelon exhibits a few features that could tip the balance in favor of IPM. Compared with other cucurbits, for example, watermelon has a much higher pest threshold due to its natural resistance to the SCB-transmitted bacterial wilt (Erwinia tracheiphila) that kills infected plants (71). Also, seedless watermelon has among the highest reliance on bee pollination (72) and, consequently, the risk of insecticide overuse disrupting fruit production is correspondingly greater in this system. Specialty crops with lower pest tolerances and pollination requirements or those produced in regions with higher pest pressures will experience vastly different trade-offs. These relationships are also dynamic and need to be reevaluated regularly over time. In our region and many other parts of the world, insect invasions [e.g., brown marmorated stink bug (73), spotted winged drosophila (74), and spotted lanternfly (75)] result in a constantly changing landscape of pests and the economics underlying their management.

**Fig. 3.** Corn yield was unaffected by CM system (A), but watermelon yield was significantly higher when grown under an IPM system (B). Each point within a cluster (n = 5) represents the yield from a site during that field season. Whiskers within the plot show the mean ± SEM of all sites within each cluster. Corn and watermelon icons from BioRender.

**Fig. 4.** Honey bees (A) did not predict watermelon yield, but increased wild pollinator visitation (B) in the IPM fields resulted in higher watermelon yield. All plots were stocked with two honey bee colonies at opposite corners of the field. Each point is the total number of observed pollinator visits per field (n = 5 sites with 225 observation minutes) and the corresponding site’s average watermelon yield. Best-fit trend line shows relationship using regression model with $P < 0.05$. Bee icons from BioRender.
Not require multiple years of insecticide reduction or installation of pollinator habitat. There is a perception that farmland in its current state is devoid of natural life, but these data show that reduced inputs alone, independent of habitat or land use changes, can have demonstrably positive effects in the near-term.

Conclusion
One of the central challenges of global food security in the 21st century is ensuring adequate food supply for a growing population while conserving natural resources. These are often viewed as contradictory endeavors (i.e., a trade-off between agricultural productivity and “protecting the world” as a common rationale for excessive pesticide use and insurance-based pest management approaches in crop protection. Yet, increasingly, studies find that substantially lower pesticide inputs result in equivalent yields (85), suggesting that high productivity can be maintained—or even increased, as shown in our study—with less intensive management. This finding dovetails the recent call for ecological intensification of agriculture, for which IPM adoption is a central theme (86–88).

Overall, our study demonstrates that the current, prophylactic approaches offer no consistent benefits to offset the demonstrably negative impacts to both pollinators/pollination and crop yields. The convenience of NST and calendar sprays to manage pests is clearly attractive to some producers. However, this argument rests on the twin assumptions that 1) populations of target pests can be expected to be at economically damaging populations each year, and 2) monitoring-based IPM alternatives expose producers to higher risks and/or upfront costs. Our data do not offer support for these claims in either cropping system and, in fact, show that embracing the use of IPM may offer readily available “win-win” scenarios for crop production and pollinator health across diverse crops.

It is important to note that conducting pest surveys with economic thresholds is not a new phenomenon; thus, our approach was not revolutionary and did not reinvent the wheel. The tools, in principle, have been established for decades, even if they have fallen out of practice. A key step forward is better understanding the thought process underlying when and why farmers decide to use insecticides. There is a myth that farmers only care about profit and refuse to monitor pests because it is too much effort or too time-consuming. Neither of these seem to be universally true.

In a recent grower survey of reasons for implementing action thresholds, saving money on insecticide sprays was not among the top three responses and ranked beneath “less harmful to the environment” (89). Similarly, “reducing scouting” and “convenience” were among the bottom several reasons when soybean farmers were surveyed about their pest management decisions in the context of seed treatments, whereas “protecting water quality” and “public safety” were among the top factors (90). These trends are validated by the success of previous extension-based programs in helping growers adopt IPM tactics (89). However, IPM adoption has a long and rocky history that extends far beyond grower education efforts (91–95). This circumstance is particularly complicated for seed treatments in which growers may not be making explicit decisions to use neonicotinoids, since they are typically the default option offered by seed suppliers (16). In this case, an “extended peer community” that engages farmers, consumers, industry, government, and conservation programs will be vital (96) while ensuring that choice is maintained in crop seed sales and that growers are provided with clear guidelines for how to implement scouting using scientifically backed pest thresholds.

Materials and Methods
Site and Experimental Design. The experiment was conducted over 4 y (2017 to 2020) on five research farms at the Purdue Agricultural Centers (PACs)
located in Indiana (SI Appendix, Fig. S1): Northeast (NEPAC, Columbia City, IN), Pinney (PPAC, Wanatah, IN), Throckmorton (TPAC, Lafayette, IN), Southeast (SEPAC, Butlerville, IN), and Southwest (SWPAC, Vincennes, IN). These sites are positioned along a latitudinal gradient across the state with at least 100 km separating one another, ensuring that sites represent a diversity of climatic conditions, soil types, and local pest pressures.

Each site contained a pair of agricultural fields that were randomly assigned to either a CM or IPM program. These treatments were designated in year 1 of the study (2017) and remained within this management system for the duration of the experiment. CM systems were considered the “industry standard” and were designed to mimic the pest management regime typically found in both row crops and vegetable production, including the routine use of prophylactic insecticides. The IPM system was an experimental treatment that relied on pest scouting to determine the use of insecticides. We only applied insecticides as needed based on published action thresholds as specified in SI Appendix, Supplemental Methods. Within a site, paired fields were separated by an average of 5.6 km (range: 4.63 to 6.63 km), which resulted in similar abiotic conditions (e.g., temperature and precipitation) while providing sufficient buffer for biological independence of CM/IPM treatments, as insect pollinators are unlikely to fly >5 km (97).

Cropping Systems. Fields (area mean: 5.74 ha, range: 4.82 to 7.73 ha) were planted continuously with corn in all 4 yr of the study. While corn-soybean rotation is common in the midwestern United States (72.3% of all corn acreage is in key corn producing states—lowa, Illinois, and Indiana—from 2015 to 2019), continuous corn is the next most prevalent system, constituting 24.7% of acres (52). Starting in year 2 of the study (2018) and continuing for three growing seasons, we planted a 0.2-ha watermelon plot embedded centrally within the corn matrix (SI Appendix, Fig. S2). Corn is the dominant crop grown in Indiana, constituting much of the Midwest’s corn (11.7 million ha; lowa, Illinois, and Indiana). Thus, this design is a microcosm of midwestern US agriculture, in which pollinator-dependent crops such as watermelon are bordered, and often completely surrounded, by corn. The goal of this design was to document the effects of large field crop plantings upon other, adjacent cropping systems. Corn was planted 1 y in advance of watermelon because neonicotinoid exposure can occur both in season through a variety of exposure vectors (e.g., leaching from the previous year’s inputs). This aspect of the experimental design reflects that the vast majority of watermelon acreage on Indiana farms (77%) is in rotation with either corn or soybean (52). Management practices (e.g., tillage, irrigation, fertilizer, herbicides, and fungicides) were standardized across sites such that the only factors differentiating CM/IPM field pairs were insecticide inputs (refer to SI Appendix, Supplemental Methods for management details and field histories).

All corn seed (Spectrum 6334) across both treatments received a fungicide seed treatment (Maxim Quattro: azoxystrobin 2.5 g/kg, fluoxonil 6.5 g/kg, mefenoxam 5 g/kg, thiabenazole 50 g/kg active ingredient [a.i.]). However, corn seed was also treated with the neonicotinoid thiamethoxam applied at the maximum rate, marketed for control of corn rootworms and a suite of insects including wireworms and seedcorn maggots (100, 101). At corn anthesis, which typically either rent honey bee hives from beekeepers or purchase bumble bee hives. Increasingly, growers in our region stock with both honey bees and bumble bees in the same field due to their foraging at different times and weather conditions. In each field, two honey bee colonies were placed on opposite corners at the edge of watermelon plots in an arrangement that avoided interference with pesticide application. This stock rate (1 hive per 0.1 ha) falls within the recommended range for commercial production used by regional growers (99). Additionally, one Quad pollination hive (Koppert Biological Systems) containing four bumble bee (Bombus impatiens) colonies was placed in each field at 4 to 5 wk posttransplant to synchronize activity with the watermelon bloom period.

Insect Pest Abundance and Damage. Corn plants were evaluated for both early- and late-season pest damage to assess the efficacy of insecticidal seed treatments. Because foliar insect pests were rarely observed, sampling focused on the more economically damaging guild of soil-dwelling root pests. First, corn stand was evaluated at the V3 to V4 stage, along six 5.3-m transects down a row, in which the number of emerged plants was counted. Transect counts were averaged and extrapolated to estimate plant population and compare with known planting densities. Poor corn stand, relative to initial planting rates, is often an indication of belowground seedling damage by insects including wireworms and seedcorn maggots (100, 101). At corn anthesis, root damage was quantified to determine potential for lodging due to corn rootworm feeding. In each field, 10 random plants were excavated along each of four transects that were >20 rows from the field edge with >10 m separating sampled plants within a transect. The root mass was then rinsed and scored for percentage of damaged roots (102), the established approach for assessing rootworm feeding.

Beginning the week following transplant, watermelon plants were surveyed for pests weekly for a 10-wk period extending to harvest. Each survey consisted of five randomly positioned transects, with plants sampled at 10, 20, and 30 m from the plot edge (n = 15 plants per plot per week). For each plant, all aboveground tissue was inspected, and the identity and number of insect pests found on the plant or the soil directly below were recorded. If the density of the primary pest, SCB A. vittatum (F.), exceeded the economic threshold of five adult beetles/plant, then the plot was treated with a foliar spray of lambda-cyhalothrin within 2 d of the observation (103). Refer to SI Appendix, Supplemental Methods for additional details on pest scouting protocol.

Watermelon Pollinators. To assess pest management impacts on pollinators, we conducted visual observations of watermelon flowers to quantify pollinator visits and community composition. Flowering cobs consisted of at least five male and one female flower, were observed for a 3-min period, during which pollinator type, number of flowers visited, and transition of pollen from a male to female flower (i.e., a pollination event) were recorded. Behavioral observations were conducted on the same date at both fields at each site. First observation began 5 to 6 wk postplanting and continued for 5 consecutive weeks to encompass most of the blooming period that contributes to harvested yield. Refer to SI Appendix, Supplemental Methods for more detail on sampling design.

Crop Yield. Corn maturity was monitored, and the crop was harvested during each of the 4 y to assess the impact of NSTs on yield. All yield reports were
adjusted to account for variation in moisture at harvest, and data were stan-
dardized to a 15.5% moisture content.

Because corn yields were strongly affected by local factors (e.g., soil type,
ph, and drainage) determined by random field assignment, we conducted a
separate companion study in 2019 using the same two corn seed treatments.
This higher-resolution study focused exclusively on yield in smaller, more
highly replicated plots with both treatments (neonicotinoid-treated versus
untreated) included in the same field to control for site variation. The trial
was repeated at six sites; four of the five original PACs used in the experiment
(all but SEAPAC and two additional locations (Davis PAC in Farmland, IN,
and the Agronomy Center in West Lafayette, IN). At each site, we planted four
to nine replicates of two adjacent 5.3-m-length rows of each corn treatment in a
randomized complete block design with the same planting date across all rep-
licates at each site (n = 33 total plot replicates for both treated and untreated
seed). At harvest, the weight and moisture adjusted yield for each replicate
was extrapolated to a per-hectare yield.

Beginning at fruit maturity (approximately 80 d), five randomly positioned
subplots (5 × 2 m area) of each watermelon field were hand-harvested and
used to estimate yield. Mature fruits from each subplot were counted,
weighed, and inspected for marketability using US Department of Agriculture (USDA)
grading standards (104) for lack of physical deformities or disease.
Subplots were harvested weekly for four consecutive weeks, after which data
were summed over time to calculate a total yield per unit area.

Pest Management Profitability. Cost of insecticides applied were either calcu-
lated from direct expenditures from purchased product or sourced from exter-
nal guides (105). The cost of the product (Cruiser 5FS) applied as an NST could
be quantified but the cost of additional costs of seed treatment prac-
tices that include labor, infrastructure, specialized equipment, and transporta-
tion. A proxy for this calculation can be used based on industry-provided costs
for the other commonly used neonicotinoid in corn pest management, clo-
thianidin (53). We also calculated the CRY, which is interpreted as the mini-
imum percentage in yield gain required to cover the cost associated with an
insecticide treatment and reach a break-even point at which the treatment
cost is recuperated (6, 106, 107). CRY was calculated by dividing the insecticide
treatment cost by the crop price × crop yield. For both watermelon and corn,
price and yield were based on the previous 5-y average (2016 to 2020) from the
state of Indiana (52).

Pesticide Residues. Samples of soil, watermelon leaf tissue, and corn and
watermelon pollen were collected during each of the 4 y and analyzed to
detect residues of insecticides and fungicides applied to both corn and water-
melon crops using the QuEChERS procedure, followed by liquid chromatogra-
phy–tandem mass spectrometry (LC-MS/MS) for pesticide identification and
quantification. Refer to SI Appendix, Supplemental Methods for sample num-
ber, preparation, and analytical details.

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IPM reduces insecticide applications by 95% while maintaining or enhancing crop yields through wild pollinator conservation

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