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Large-Scale Deployment of Seed Treatments Has Driven Rapid Increase in Use of Neonicotinoid Insecticides and Preemptive Pest Management in U.S. Field Crops

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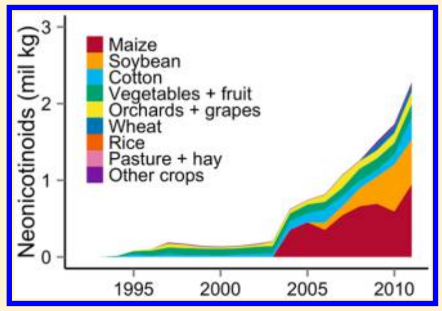
Ⓢ *Supporting Information*

ABSTRACT: Neonicotinoids are the most widely used class of insecticides worldwide, but patterns of their use in the U.S. are poorly documented, constraining attempts to understand their role in pest management and potential nontarget effects. We synthesized publicly available data to estimate and interpret trends in neonicotinoid use since their introduction in 1994, with a special focus on seed treatments, a major use not captured by the national pesticide-use survey. Neonicotinoid use increased rapidly between 2003 and 2011, as seed-applied products were introduced in field crops, marking an unprecedented shift toward large-scale, preemptive insecticide use: 34−44% of soybeans and 79−100% of maize hectares were treated in 2011. This finding contradicts recent analyses, which concluded that insecticides are used today on fewer maize hectares than a decade or two ago. If current trends continue, neonicotinoid use will increase further through application to more hectares of soybean and other crop species and escalation of per-seed rates. Alternatively, our results, and other recent analyses, suggest that carefully targeted efforts could considerably reduce neonicotinoid use in field crops without yield declines or economic harm to farmers, reducing the potential for pest resistance, nontarget pest outbreaks, environmental contamination, and harm to wildlife, including pollinator species.



INTRODUCTION

Since their introduction in the 1990s, neonicotinoids have become the most widely used class of insecticides in the world,[1] but patterns of their use in the United States (U.S.) remain largely undefined. It is unclear when, where, and how neonicotinoids are used in U.S. agriculture, because they are often applied as seed treatments,[2] a use that is not captured by the major national pesticide survey conducted by the National Agricultural Statistics Service (NASS).[3] Fortunately, seed-applied neonicotinoids are included in an independent data set that recently became available through the U.S. Geological Survey (USGS).[4] This data set shows that aggregate neonicotinoid use has increased dramatically over the past decade, but it does not report the percentage of cropland treated or the relative importance of different modes of application (e.g., seed treatments vs foliar sprays). Anecdotally, extension entomologists have noted that seed for some field crop species, such as maize (*Zea mays*), in the U.S. is now routinely treated before sale with neonicotinoids,[5,6] suggesting that neonicotinoid seed treatments (NSTs) are being used over a very large area.

Because seed-treatment use has not been captured in the national pesticide survey, recent analyses that relied on this survey to understand pest management trends in the U.S.[7,8] appear to have missed an important aspect of insecticide use, including how seed-applied insecticides relate to other pest-management approaches. In particular, it is unclear whether NSTs have displaced other insecticide applications, and how they relate to transgenic, insect-resistant crops. The void of information on seed treatments also challenges researchers and regulators seeking to assess environmental contamination and potential nontarget effects associated with neonicotinoids, areas of increasing concern.[6,9−13] The potential for lethal and sublethal effects of neonicotinoids on pollinators has attracted particular attention, prompting the European Union to suspend the use of neonicotinoids on bee-attractive crops,[14] and accelerating the review of neonicotinoids by the U.S. Environmental Protection Agency.[15] Characterizing the risk posed by neonicotinoids to nontarget species obviously requires understanding where and how these compounds are used. We therefore see an opportunity to synthesize the available information to estimate trends in neonicotinoid use in U.S. agriculture since their introduction 20 years ago.

Documenting patterns of neonicotinoid use is an important first step toward elucidating their role in U.S. pest management, but a full consideration also requires a broader context, including an understanding of their physical properties and importance of target pests in particular cropping systems. The physical properties of neonicotinoids have been well

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Table 1. Summary of the Major Data Sources We Relied Upon for Our U.S. Pesticide Use Estimates, 1992−2012

source	response variable (units)	region	crops	years
NASS[3,22]	non-seed treatment insecticides applied (mass a.i.)	major growing regions	maize	1992−2003, 2005, 2010
			cotton	1992−2001, 2003, 2005, 2007, 2010
			soybeans	1992−2002, 2004, 2006, 2012
			wheat	1992−1998, 2000, 2002, 2004, 2006, 2009, 2012
USGS[4]	total neonicotinoids applied (mass a.i.)	U.S.	maize	1992−2011
			cotton	1992−2011
			soybeans	1992−2011
			wheat	1992−2011
MNDA[30]	neonicotinoid sales (mass a.i.)	Minnesota	all crops	1996−2011
Pioneer[23]	area planted with insecticide-treated seed (%)	U.S.	maize	2004−2011
NDSU/NDDA[24−29]	area planted with pesticide-treated seed (%)	North Dakota	maize	1992, 1996, 2000, 2004, 2008, 2012
			soybeans	1992, 1996, 2000, 2004, 2008, 2012
			wheat	1992, 1996, 2000, 2004, 2008, 2012

documented; they generally have high acute toxicity to insects, low acute toxicity to mammals, and are systemic in plants, though the degree of these characteristics varies among neonicotinoid active ingredients.[2,16] Depending on the cropping system and target pest(s), they are applied using a variety of methods including foliar sprays, soil drenches, chemigation systems, trunk injection, and seed treatment. Seed-applied neonicotinoids are taken up into plant tissues, where they provide up to several weeks of protection against insect pests,[17,18] and persist at low concentrations for up to several months.[12] Their efficacy against target pests depends on the active ingredient being present when and where pests are feeding, an important consideration given their variable uptake into different crop tissues and declining concentrations as plant growth continues.[20] Finally, it is unclear how important many of the pest species being targeted by NSTs really are; there is a general dearth of information on prevalence and impact of most labeled pests, many of which are considered "secondary" in U.S. field crops because they occur sporadically in space and time.[21]

To contribute to a broader understanding of the role of neonicotinoids in U.S. agriculture since their introduction in 1994, in this paper we synthesize publicly available information and the entomological literature to address the following questions:

(1) Which uses, crops, and active ingredients accounted for the most neonicotinoid use?
(2) On major field crops (maize, soybean [*Glycine max*], wheat [*Triticum* spp.], cotton [*Gossypium* spp.]), what was the contribution of NSTs to total neonicotinoid use and total insecticide use?
(3) What proportion of the area of maize and soybeans was planted with neonicotinoid-treated seed?
(4) What role did neonicotinoids play in pest management in maize and soybean production?

To address questions one through three, we made simple calculations based on data from a variety of sources, primarily the USGS and U.S. Department of Agriculture (USDA), as well as state-level sources and pesticide label information. For question four, first we compared trends in neonicotinoid use to trends in use of other insecticides and transgenic insect-resistant crops, and then we integrated our findings with entomological literature on neonicotinoids in maize and soybeans. This last section of the results is necessarily interpretive given the nature of our question. We gave special attention to maize and soybeans because they are the largest area crops in the U.S.,[22] our results indicate that they account for the majority of neonicotinoid use, and they benefit from more research than many other crops.

EXPERIMENTAL METHODS

Pesticide Data Sources. We used five main sources for data on the use of insecticide active ingredients in the U.S. (Table 1). Our primary source of information on neonicotinoid use was the Pesticide National Synthesis Project of the U.S. Geological Survey (http://water.usgs.gov/nawqa/pnsp). These pesticide-use estimates were derived from proprietary farm surveys (conducted by GfK Kynetec, Inc.) within Crop Reporting Districts (CRDs).[4] For each crop-pesticide combination, from 1992 to 2011, the data set includes two estimates for pesticide use, which differ in how they treat missing values within surveyed CRDs. For the "EPest-low" estimate, researchers treated these values as zero, while for the "EPest-high" estimate, researchers treated these values as unsurveyed, and extrapolated pesticide-crop use rates from nearby CRDs.[4] We used both sets of estimates for many of our analyses, and when we did not, we relied on the EPest-high estimate but noted how using the EPest-low estimate would have influenced our results. Importantly, the proprietary data set used by USGS captures all agricultural pesticide use, including seed treatments. The data set we obtained from USGS (courtesy of Wes Stone) reported at the national level total mass applied for each neonicotinoid active ingredient by crop and year. This data set reports pesticide use on cropland, and so does not account for other uses of neonicotinoids such as homeowner or veterinary use.

The other major source of pesticide data we used was the Agricultural Chemical Use Survey, originally administered by USDA's National Agricultural Statistics Service (NASS) and now administered jointly by NASS and the USDA's Economic Research Service (ERS) as part of the Agricultural Resource Management Survey.[3] Importantly, this survey excludes pesticides applied as seed treatments, and so provides an estimate of non-seed treatment pesticide use.[3] The NASS survey focuses on major production states (called "Program

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States") for each crop, usually covering >80% of the national area. We estimated national, non-seed treatment neonicotinoid use for each crop and year by dividing the total mass of active ingredient applied in the program states by the proportion of area surveyed.

For maize, we found an additional document providing insight into use of neonicotinoid-treated seed, an environmental report accompanying a petition for nonregulated status of a genetically engineered maize variety submitted to USDA by Pioneer Hi-Bred International, Inc., one of the largest suppliers of maize seed in the U.S.[23] This report contains estimates of the percentage of maize seed treated with insecticides from 2004 to 2011, providing a comparison for our estimates of neonicotinoid use in maize. We assumed that neonicotinoids were the dominant class of insecticides used to treat maize seed (see Results for a detailed treatment of this issue).

Two state-level sources provided complementary pieces of information to understand neonicotinoid use and its role in pest management. First, North Dakota State University, in partnership with the North Dakota Department of Agriculture and NASS, has surveyed farmers on their use of pesticides six times since 1992.[24−29] These surveys estimate the percentage of field-crop area in North Dakota that was planted with pesticide-treated seed and how much of that seed was treated on-farm (vs by seed suppliers before sale). It is important to note that these estimates are not specific to neonicotinoids or even to insecticides; they include all kinds of pesticide seed treatments (e.g., fungicides). Nonetheless, they set an upper bound for the percentage of seed that was treated with insecticides, and by whom (i.e., seed suppliers or farmers). Second, to gain insight into the relative importance of different use sites for neonicotinoids (e.g., cropland, animal care, home gardens, buildings, etc.), we drew on pesticide sales data from Minnesota (reported in mass of active ingredient), generated by the Minnesota Department of Agriculture from information submitted by pesticide registrants.[30] We do not suggest that these state-level data sources are precise estimates of national trends, but they are the only data sources we know of that address these particular questions, and so they provide valuable insight.

Because many of our data sources were reported in imperial units, we converted all of our results to metric units for reporting here.

Seed Treatments As a Proportion of Neonicotinoid Use in Major U.S. Row Crops. To estimate the proportion of neonicotinoids that were applied as seed treatments, we took advantage of a key difference between the USGS and NASS data sets. Because USGS estimates all pesticide use, including seed treatments, while NASS estimates all non-seed treatment use, we estimated neonicotinoids applied as seed treatments by subtracting the NASS estimate from the USGS estimates for each crop. We could only make these estimates for those crop-year combinations for which both data sets were available (Table 1). Although the two data sets were generated independently, they both employed farmer surveys for data collection and used sampling designs to ensure their results represented U.S. agriculture as a whole.

Our analysis focused on the top four row crops by area: maize, soybeans, wheat, and cotton.[22] We focused on these crops for two reasons: i) they now account for a large proportion of neonicotinoids applied in the U.S. (Figure 1), and ii) crop-specific data were available for these crops in both the USGS and NASS data sets, while for many other crops the data were aggregated into larger groupings (e.g., "vegetables and fruit") that obscured crop-specific use.

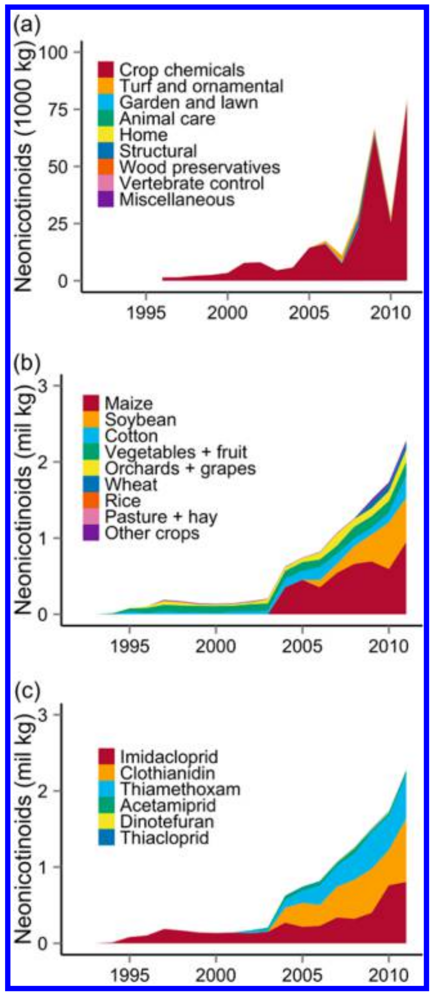

Figure 1. Neonicotinoid sales by product type (a), and use by crop (b) and active ingredient (c), from 1992 to 2011. Data on use (a) is based on sales data from Minnesota.[30] Data on crops and active ingredients are for the entire U.S., from USGS (EPest-High estimate).[4] *Y*-axes represent mass of neonicotinoid active ingredient in thousands or millions of kg.

Proportion of U.S. Maize and Soybean Area Planted with Neonicotinoid-Treated Seeds. Next, we conducted an additional analysis for maize and soybeans, the two dominant crops in U.S. agriculture.[22] We estimated possible ranges for the area of each crop planted with neonicotinoid-treated seed in each year, using the following equation:

$$\text{hectares}_{\text{ST}} = \frac{\text{kg applied}_{\text{ST}}}{\text{rate}\left(\frac{\text{kg}}{\text{ha}}\right)}$$

kg $\text{applied}_{\text{ST}}$ = the estimate for kg neonicotinoids applied as seed treatment (see above). Rate (kg/ha) = the neonicotinoid use rate, in kg per ha per year

Possible use rates were derived from pesticide labels for seed treatment products (Supporting Information (SI) Table S1). To translate these application rates (active ingredient (a.i.) per seed or per seed-kg) into per hectare rates (a.i. per ha), we needed to estimate seeding rates (seeds/ha or seed-kg/ha). For this we used a combination of USDA-ERS data on per hectare seed costs,[31] and USDA-NASS data on per unit seed costs,[32]

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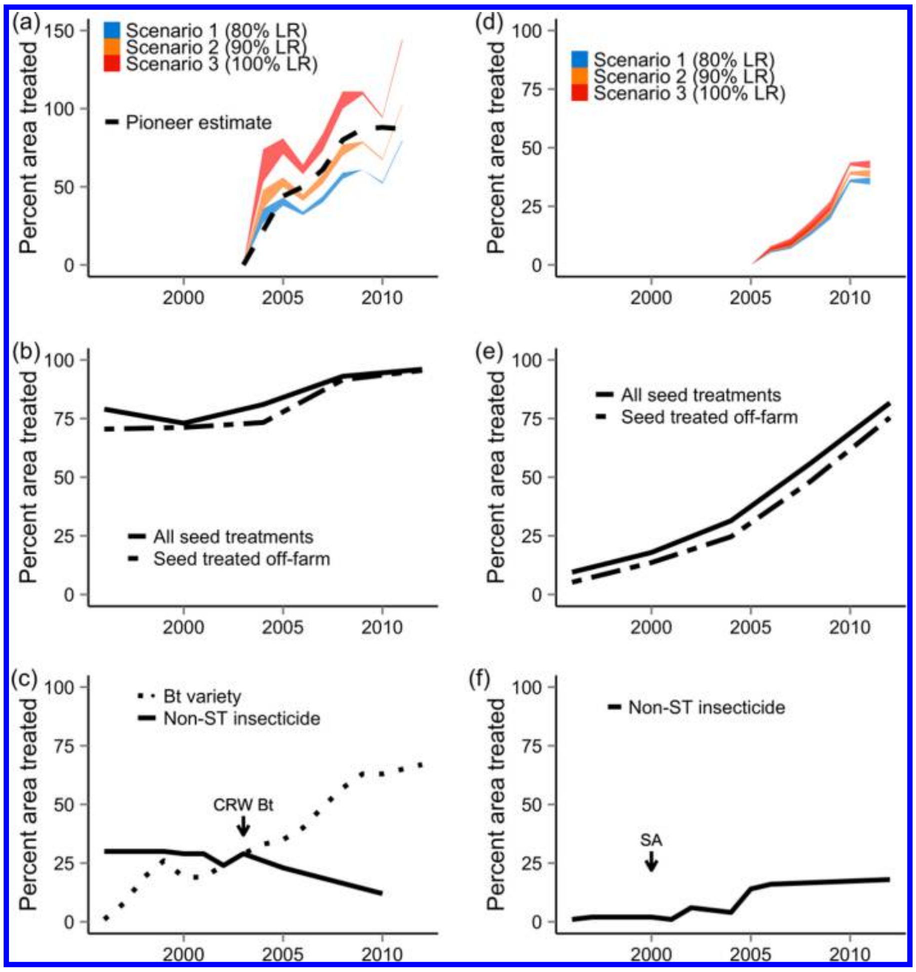

Figure 2. Estimated percent of U.S. maize (a−c) and soybean (d−f) hectares treated with neonicotinoid seed treatments (a,d), any pesticide seed treatment (b,e), and non-seed treatment (non-ST) insecticides (c,f) from 1996 to 2012. Estimates for national neonicotinoid seed treatment use (a,d) were based on the USGS data[4] and rates indicated on product labels (SI Table S1), for scenarios with varying amounts of low-rate (LR) versus high-rate treated seed (see text for details). Estimates for overall pesticide seed treatment use (b,e) are for North Dakota.[24−29] Estimates for national use of non-seed treatment insecticides (c,f) are from USDA-NASS.[7] CRW Bt = the introduction of *Bt* maize targeting the corn rootworm (*Diabrotica* spp.). SA = the first detection of soybean aphid (*Aphis glycines*) in North America.

based on previous work.[33] We checked these estimates against extension recommendations to ensure they were plausible.

Because most NST products can be applied at more than one rate, we also needed to make some assumptions about rates to calculate ranges for maize and soybean area planted with treated seed. We assumed that low rates were much more common than high rates based on marketing material from several major seed suppliers indicating that the low rate is "standard,"[34−36] agreeing with our own experience interacting with farmers and seed companies. We therefore calculated values based on the following scenarios: (i) 100% of hectare-treatments at the low rate, (ii) 90% of hectare-treatments at the low rate, 10% at the high rate, (iii) 80% of hectare-treatments at the low rate, 20% at the high rate. We fit each of these scenarios using the EPest-high and EPest-low estimates for neonicotinoid use, so that our calculated range of values incorporates uncertainty associated with both overall neonicotinoid use and application rates.

Once we obtained estimates for hectares planted with treated seed under each of our scenarios, we divided each value by total crop area[22] to estimate the proportion of planted area that was planted with treated seed for each crop.

Neonicotinoid Seed Treatments in U.S. Maize and Soybean Pest Management. To understand the relationship of NSTs to other pest management approaches, for maize and soybeans we compared the temporal trend in percentage of hectares planted with neonicotinoid-treated seed to the percentage of hectares treated with non-seed treatment insecticides,[22] and the percentage of hectares planted with seed treated with any pesticide, as reported in North Dakota surveys.[24−29] For maize, we also looked at the temporal trend in the use of transgenic, insect-resistant crops expressing insecticidal toxins from the bacterium *Bacillus thiuringensis* (i.e., *Bt* crops[37]) because these crops have played a major role in maize pest management since their introduction in 1996.

RESULTS

Neonicotinoid Use in the U.S. by Product Type, Crop, And Active Ingredient. The first neonicotinoid (imidacloprid) was registered in the U.S. in 1994, and neonictoinoids now have over 500 registered uses (SI Table S2). Neonicotinoid use increased dramatically from 1994 to 2011, especially after 2003 (Figure 1). Insecticide sales data from Minnesota suggest that most neonicotinoids were applied to crops: from 1996 to 2011, 93% of neonicotinoid active

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ingredients were sold in crop-use products while the remainder were sold mainly in turf/ornamental (4%), structural (1.4%), and lawn/garden (1.2%) products (Figure 1a). Within crops, neonicotinoid use was fairly constant in fruits and vegetables, whereas use in field crops increased after 2003. By 2011, just three field crops (maize, cotton, and soybeans) accounted for the vast majority (∼80%) of neonicotinoid use (Figure 1b). The active ingredient imidacloprid was dominant for the first half of the study period (Figure 1c), but after 2003 the increase in neonicotinoid use coincided with the newer active ingredients clothianidin and thiamethoxam.

Using USGS EPest-low data did not change any of the conclusions about the relative importance of different crops or active ingredients as contributors to neonicotinoid use. The EPest-low and -high estimates generally came to resemble each other over time, with the greatest difference between estimates in 1994 (low estimate 28% lower than high estimate) and the smallest differences in 2010 and 2011 (low estimate 4% and 5% lower than high estimate, respectively).

Neonicotinoids Applied As Seed Treatments in Major U.S. Row Crops. From 2000 to 2012, virtually all neonicotinoids applied to maize, soybeans, and wheat were applied as seed treatments (SI Table S3). In cotton, seed treatments accounted for an estimated 7−72% of neonicotinoid use, with estimates less variable after 2004, ranging from 60 to 70% (SI Table S3). Per-seed application rates varied widely, with highest rates on maize and lowest rates on wheat, but per-hectare application rates were more comparable among crops (SI Table S1).

From 2000 to 2011, seed-applied neonicotinoids accounted for a growing proportion of the total mass of insecticide active ingredient applied to maize, soybeans, and wheat (SI Table S4). Neonicotinoid seed treatments accounted for roughly 43% of insecticide mass applied to maize by 2010, 21−23% of mass applied to soybean by 2011/2012, and 25−29% of mass applied to wheat by 2011/2012 (SI Table S4). Cotton was quite different; neonicotinoids accounted for less than 4% of insecticide mass applied from 2000 to 2011 (SI Table S4), reflecting the larger volume of other insecticides applied to this crop.

Hectares Planted with Neonicotinoid-Treated Seed in Major U.S. Row Crops. In maize, the percent of hectares planted with neonicotinoid-treated seed increased rapidly after 2003, and by 2011 had reached ≥79% under all three scenarios we simulated (Figure 2a). Data from Pioneer[23] most closely matched our 90% low-rate scenario and suggested that 87% of maize hectares were planted with insecticide-treated seed by 2011 (Figure 2a). Clearly our 100% low-rate scenario did not reflect reality, because by 2008 it estimated that over 100% of maize hectares were planted with treated seed (Figure 2a). The 90% low-rate scenario had also (barely) exceeded 100% of maize hectares by 2011, suggesting that neonicotinoid rates on maize seed were likely increasing toward the end of the study period.

In soybeans, the percent of hectares planted with neonicotinoid-treated seed increased steadily starting in 2006 (Figure 2d). By 2011, we estimate that NSTs were used on 34−44% of soybean hectares, depending on the prevalence of the low and high application rates and whether the EPest-low or EPest-high estimate was used. Our estimate is consistent with a recent analysis based on proprietary data by the U.S. Environmental Protection Agency,[38] which reported that NSTs were used on an average of 31% of soybean hectares from 2008 to 2012. There may be important regional variability in NST use in soybeans, as suggested by estimates from the Southern U.S. (ranging from 0% to 75% of hectares across seven states in 2011[39]) and the Corn Belt (73% of hectares in Iowa in 2009[40]).

With our data set we were unable to estimate the cotton area planted with NSTs, but some insight can be gleaned from a 2010−2013 survey that asked agricultural professionals working in cotton to estimate the prevalence of insecticidal seed treatments in their regions.[41] The results suggest that NSTs were used on 52−77% of national cotton area over those four years, with significant regional variability (in 2011 ranging from a low of 17% in Arizona, to a high of 96% in Tennessee).

Summing the area planted with neonicotinoid-treated seed for maize, soybean, and cotton, we conservatively estimate that at least 42 million hectares of cropland (57% of the total area) were planted with NSTs by 2011 in these three crops alone, an area roughly the size of California.

Neonicotinoid Seed Treatments and Pest Management Trends in U.S. Maize and Soybeans. Two trends coincided with rapidly increasing use of NSTs in maize after 2003: (i) increased planting of transgenic *Bt* hybrids, from 29% of hectares in 2003 to 80% of hectares in 2014, and (ii) decreased application of non-seed treatment insecticides, from 29% of hectares in 2003 to 12% of hectares in 2010 (Figure 2c). Importantly, the introduction of NSTs closely followed introduction of *Bt* hybrids targeting corn rootworms (*Diabrotica* spp.), a pest complex that has historically driven insecticide use in U.S. maize.[42] In the 1990s, chemical control for the rootworm complex was dominated by soil-applied insecticides (mainly organophosphates and pyrethroids[22,42]), which may have also protected against some secondary soil pests (e.g., wireworms, grubs, maggots). Because *Bt* hybrids do not control most secondary pests, and because low- and midrates of NSTs do not control the rootworm complex,[43] the two technologies are potentially complementary. Importantly, however, NSTs are now used on almost triple the area historically treated with non-seed treatment insecticides (Figure 2a,c); therefore, NSTs (together with *Bt* hybrids) have more than displaced non-seed treatment insecticide use on an area basis. This finding supports the apparent shift toward an "insurance" paradigm of pest management in maize,[5] in which transgenic crops and NSTs are deployed even when target pest densities are expected to be low. This notion is also supported by a recent survey, in which 39% of maize growers using NSTs were not targeting any particular pest.[44]

In soybeans, use of both seed-applied and other insecticides have intensified over the past several decades (Figure 2d,f), a development that can be partly, but not entirely, explained by changing pest pressure. Prior to introduction of soybean aphid (*Aphis glycines*) into North America around 2000, soybeans in the Midwestern U.S. were only sporadically challenged by insect pest populations,[42,45] explaining the historically low insecticide use in this crop (<1% of area treated, Figure 2f). Soybean aphid changed this situation, and is now the most economically important soybean insect pest, often controlled in outbreak years with foliar sprays.[46,47] Seed-applied neonicotinoids rarely displace foliar sprays against soybean aphid, because in most regions the period of insecticidal activity wanes prior to aphid attack,[17,18,48] though there are exceptions.[49] In contrast, NSTs can sometimes displace other insecticide applications against the overwintered generation of bean leaf beetle (BLB, *Cerotoma trifurcata*).[50] Populations of BLB in the

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Midwest increased dramatically in the late 1990s and early 2000s,[51,52] and NSTs were first used on soybeans in Iowa and Wisconsin under an emergency exemption for BLB concerns.[53] BLB populations in the Midwest have returned to more typical lower levels,[54] and only 12% of U.S. farmers reported "actively managing" beetles (including BLB) in soybeans.[55] Nevertheless, use of NSTs on soybeans continues to rise. This trend may reflect that an "insurance" approach to managing insects is also prevalent in soybeans; indeed, 47−65% of farmers using NSTs on soybeans reported they are not targeting any particular pest.[38,44]

An important question is whether NSTs have displaced older seed-applied insecticides, or whether they represent a truly new trend. In North Dakota soybeans, pesticide seed treatments appear to have been uncommon into the early 2000s (Figure 2e). In maize, seed-applied insecticides have a longer history, but available evidence suggests that they were not very prevalent prior to neonicotinoid introduction. Dieldrin and lindane (organochlorines) were used to treat seed on significant maize area as early as the 1950s,[56,57] but dieldrin was discontinued in 1974 because of environmental and human health concerns.[58] Lindane was used as a seed treatment as late as the 2000s (SI Table S5), but was used on only ∼6% of maize area in 2002.[59] Similarly, some organophosphates and carbamates were available as seed treatments in maize (SI Table S5), but were used on only ∼5% of the combined area of maize, soybean, and cotton in the early 1980s.[60] A few pyrethroid-based seed treatments were introduced in the 1990s (SI Table S5), but were replaced with neonicotinoids because the latter are easier to handle and have systemic activity.[61] Finally, North Dakota data suggest that supplier-applied seed treatments were already widespread in maize before neonicotinoids were introduced (Figure 2b), but most of these applications likely involved only fungicides, because most of the older insecticidial seed treatments were applied exclusively on-farm (SI Table S5). Based on the evidence available, we conclude that seed-applied insecticides were uncommon in maize and soybeans before the advent of NSTs.

■ DISCUSSION

Neonicotinoid use in the U.S. increased dramatically after 2003 and was driven by seed treatments on field crops such as maize, soybean, wheat, and cotton. The significant (>20%) contribution of neonicotionids to mass of insecticide active ingredient applied on maize, soybeans, and wheat is all the more striking because these insecticides are used at relatively low rates due to their high insect toxicity (e.g., in corn: 18−90 g ai/ha for clothianidin versus 84−185 g ai/ha for tefluthrin (Force 3G) and 526−1052 g ai/ha for chlopyrifos [Lorsban Advanced]). If current trends continue, neonicotinoid use could increase considerably further through use of seed treatments on additional crop area (e.g., on soybeans or wheat), or through higher per-seed application rates. In 2013, mid- or high-rate products were apparently widely used[55] and this year at least one seed company has announced that its "standard" treatment for maize seed will now include the highest labeled rate of NST (1.25 mg ai/seed, five times the low rate).[62]

Our results lead to very different conclusions than analyses that did not consider insecticidal seed treatments. For instance, a recent summary of U.S. pesticide-use trends based solely on USDA-NASS data estimated that neonicotinoids accounted for a maximum of 6% of insecticide hectare-treatments and 1% or less of insecticide quantity in 2005 and 2010.[8] In contrast, our estimates suggest that neonicotinoids accounted for >10% of insecticide quantity and probably far more than 6% of hectare treatments over this period, given their widespread use in large-area crops. Furthermore, analyses based on USDA-NASS data suggested that insecticide use on maize has been declining, with only 12% of maize hectares treated with insecticides in 2010, a trend attributed mainly to *Bt* hybrids.[7,8,63] Our results are critically different; we too found that quantities of insecticides (i.e., mass of active ingredients) applied to maize declined during the period when *Bt* hybrids became prevalent, but at the same time the extent of insecticide use almost tripled, to >75% of maize hectares treated with NSTs by 2011. Our findings are consistent with previous research based on U.S. agricultural census data, which found that insecticide use in maize increased in extent between 2002 and 2007, despite widespread use of *Bt* hybrids.[64] Several analyses on the influence of *Bt* crops on pesticide-use patterns do not seem to have considered seed treatments,[65,66] and so may have overstated reductions in insecticide use (especially "area treated") associated with this technology. Clearly, seed treatments should be considered in future assessments of pest management trends.

It would be easier to account for seed-applied pesticides if these products were included in major pesticide use surveys. It is remarkable that almost the entire area of the most widely grown crop in the U.S. (i.e., maize) is now treated with an insecticide, yet we have no public survey data reflecting this trend (USGS data are based on proprietary surveys and do not report the key metric of percent area treated). We made the most accurate estimates we could with publicly available data, but it is clear that significant uncertainty remains in some of our estimates, and additional uncertainty may have been introduced by differences in methodology in our two major data sources. Given the rising prevalence of pesticide seed treatments, not only insecticides but also fungicides and nematicides, it would be valuable for USDA-NASS to update its survey methodology to include seed treatment use. Survey questions could be modified to quantify the percent of crop area planted with treated seed, and the active ingredients and rates applied. If this is impossible due to resource constraints, at a minimum the agency could make it clearer in its data products that seed treatment use is excluded from pesticide use estimates, to ensure that users are aware of limitations of the data.

The rapid rise of NSTs in the U.S. is ultimately a social phenomenon, and several factors may have facilitated this trend. Seed suppliers rather than farmers typically apply neonicotinoids, meaning that both groups have a role in "adopting" this technology, though their relative contributions are unclear. According to the seed-chemical industry, the unique properties of neonicotinoids shifted the perspective of seed suppliers away from seeing seed treatments as a cost of production and toward seeing them as a profit center,[67] creating incentives to strongly market these products to farmers. At the same time, during the recent ethanol boom (2004−2011), U.S. maize and soybean prices more than doubled,[22] and seed costs rose dramatically with increasing use of transgenic seed,[31] contributing to a perception of NSTs as relatively cheap insurance for expensive seed. This perception may have been bolstered by arrival of soybean aphid, and transient outbreaks of BLB in soybean and Stewart's wilt, vectored by flea beetles, in maize, which led the U.S. EPA to issue emergency exemptions, bringing these products to the maize and soybean seed markets.[53,68] Neonicotinoid seed treatments may also have "tagged along" with other

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technologies that were attractive to farmers. They are usually one component of larger packages, that, for instance in maize, can include germplasm (i.e., crop variety), up to eight transgenes, and up to six or more different seed treatments (fungicides, nematicides, and insecticides). While many U.S. maize and soybean farmers appear to value NSTs, a significant minority (21% for maize, 15% for soybean) would reduce or eliminate their use of these products if the same seed were available without them.[55]

The extensive use of NSTs raises the question of how these products relate to Integrated Pest Management (IPM), the guiding framework for U.S. pest management policy since the 1970s.[69−71] In an IPM framework, insecticide applications are reserved for situations where monitoring reveals that pest populations have reached levels of economic concern.[71] Preemptive use of insecticides (as with seed treatments) can be justified within IPM rarely, when two conditions are satisfied. The first is that rescue treatments cannot keep pests under the economic injury level. This does not apply to most foliar pests targeted by NSTs (e.g., bean leaf beetle on soybean), for which scouting protocols and economic thresholds are well developed.[72] Detection, however, is challenging for many secondary soil pests targeted by NSTs because their belowground activity is difficult to observe before economic damage occurs, though preplant scouting procedures do exist for some soil pests (e.g., wireworms).[73] The second condition for preemptive insecticide use is that target pests have a high probability of causing economic damage. The prevalence of secondary soil pests is poorly documented in most of the U.S., but "secondary pests" are not consistently troublesome. The sporadic nature of these pests may explain why peer-reviewed studies from across the U.S. have not found consistent yield benefits of NSTs under "typical" pest pressure in maize,[74−78] or soybeans.[18,48,49,79−84] These findings, together with the patterns of neonicotinoid use we documented, suggest that NSTs are being used on many hectares where they do not deliver an economic return and cannot be considered part of an IPM approach.[38] This phenomenon is also apparently common in European maize systems.[85] Note that this conclusion should not be extrapolated to other cropping systems, where neonicotinoid use can be more consistent with IPM and where these compounds may more often displace insecticides that are acutely hazardous to human health (e.g., for managing insect vectors in cucurbit production[86]).

The possible unintended consequences of overusing insecticides were summarized in the classic contribution of Stern et al.:[87] (i) evolution of insecticide-resistance in target pests, (ii) outbreaks of nontarget pests, (iii) resurgence of target pests, and (iv) negative effects on human health or wildlife. For neonicotinoids, some, but not all, of these unintended consequences are possible or already occurring. History and common sense dictate that the use of NSTs in many fields year after year will select for resistant pest populations. Indeed, resistance to imidacloprid and/or thiamethoxam was recently detected in populations of tobacco thrips (*Frankliniella fusca*) in the Southern U.S.[88] Neonicotinoid seed treatments can also exacerbate some nontarget pests (spider mites and slugs[89−91]), suggesting that they are not always "cost-free" insurance. On the other hand, pest resurgence does not appear to have been documented with NSTs, and one of the important, attractive features of neonicotinoids is their low acute mammalian toxicity (e.g., high LD_{50}) relative to older insecticide classes such as organophosphates.[16] Neonicotinoids do have potent activity against many invertebrates, including pollinators[6,92,93] and natural enemies of crop pests.[83,86,93] The risk of neonicotinoids to wild and managed pollinator species is a topic of current debate, and could be modeled in the U.S. by combining our estimates on the extent of neonicotinoid use in various crops with data on bee visitation to specific crop species and the concentrations bees would likely encounter through planting dust and/or floral products. The influence of neonicotinoids on wildlife is not well investigated in the U.S., but in the Netherlands neonicotinoid concentrations in surface water have been correlated to declines in aquatic invertebrates and insectivorous birds.[9,95] These findings are concerning in light of recent detections of neonicotinoid residues in 76% of samples taken from streams in the U.S. Corn Belt, a substantial increase over insecticide detections in the region in the 1990s,[10] consistent with our finding that insecticide use in field crops has expanded dramatically with NSTs.

In conclusion, NSTs are a recently developed insect-pest-management tactic that has become very widespread in U.S. agriculture since the mid-2000s. This development remained anecdotal because it was partially obscured by the lack of information on pesticide seed treatments in the nation's major pesticide-use survey. Our synthesis of publicly available information indicates that NSTs are being used over a very large area (>40 million hectares), and that in major crops (maize and soybeans) these products are often used as part of an insurance-based approach to pest management that may be reinforced in the seed market by limited availability of neonicotinoid-free seed. This pattern of use may have unintended consequences, namely resistance in target pests, outbreaks of nontarget pests, and pollution with detrimental effects cascading to wildlife. As noted above, some of these effects have already emerged. Rather than seeing neonicotinoids as an "either-or" issue, we believe there is an opportunity to judiciously decrease use of these powerful products, and their attendant risks, using the well-established framework of integrated pest management (IPM). At a minimum, such an approach would include identifying which pests are present, monitoring those pests for their potential to cause injury, and keeping records to identify fields where problems are likely or unlikely in the future. A further step would be to weigh short-term yield benefits of insecticide application against documented risks to nontarget organisms and the long-term health of the agroecosystem. Entomologists can support such efforts by better characterizing risk factors for early season pests targeted by NSTs and developing crop- and region-specific, decision-support tools for neonicotinoid use,[96] which are surprisingly scarce. Seed companies could help by increasing availability of neonicotinoid-free seeds. Nonetheless, recent history suggests that IPM will not be widely adopted in U.S. field crops given current incentives and disincentives (as detailed above) for farmers and seed suppliers, which appear to strongly favor an insurance-based approach.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Available as an online supplement are additional tables (as noted in the text), including a summary of neonicotinoid use rates of some common seed-treatment products, a summary of neonicotinoids and their major agricultural uses, estimates of amounts of neonicotinoids applied, and insecticidal seed treatments that have been available on maize. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

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