Sowing Uncertainty: What We Do and Don't Know about the Planting of Pesticide-Treated Seed

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Farmers, regulators, and researchers rely on pesticide use data to assess the effects of pesticides on crop yield, farm economics, off-target organisms, and human health. The publicly available pesticide use data in the United States do not currently account for pesticides applied as seed treatments. We find that seed treatment use has increased in major field crops over the last several decades but that there is a high degree of uncertainty about the extent of acreage planted with treated seeds, the amount of regional variability, and the use of certain active ingredients. One reason for this uncertainty is that farmers are less likely to know what pesticides are on their seed than they are about what pesticides are applied conventionally to their crops. This lack of information affects the quality and availability of seed treatment data and also farmers' ability to tailor pesticide use to production and environmental goals.

Keywords: seed treatment, pesticide, agriculture, neonicotinoid

Technological advances in pesticide formulations and application methods have profoundly changed pesticide use in agriculture. Since the turn of the century, pesticides have been increasingly applied as a seed treatment, by coating the seed with one or more pesticides and a sticking agent. Over the 2012–2014 period, approximately 90% of corn, 76% of soybean, 62% of cotton, and 56% of winter wheat acres in the United States were planted with treated seed (Kynetec 2019). Despite the widespread use of seed treatments, recent government and industry data on pesticide use on farms has been focused on conventional, field-applied pesticides. The lack of publicly available data on seed treatments makes it more difficult for researchers, farmers, and regulators to balance the benefits and costs of pesticide use in agriculture when assessing farm economics, productivity, and adverse effects on off-target organisms.

For example, the lack of accurate publicly available data on seed treatments convolutes the evaluation of neonicotinoids, a class of insecticides that gained regulatory approval in the 1990s and early 2000s in the United States and that are frequently applied as seed treatments. Since their introduction, neonicotinoids have become the most widely used class of insecticide in the world (Jeschke et al. 2011). Although neonicotinoids are much less acutely toxic to mammals than older insecticide classes, such as carbamates and organophosphates (Jeschke and Nauen 2008), they are highly toxic to both pest and beneficial insects and persist in the environment (Bonmatin et al. 2015, DiBartolomeis et al. 2019, Douglas et al. 2020). Research is ongoing to understand the nature and extent of nontarget impacts of neonicotinoids, but it is apparent that, under some circumstances, they have significant negative effects on populations of beneficial insects and other taxa and the ecological services they provide (Krupke et al. 2012, Watanabe 2014, Botías et al. 2015, Douglas et al. 2015, Rundlöf et al. 2015, Stanley et al. 2015, Eng et al. 2019, Yamamuro et al. 2019). Characterizing the influence of neonicotinoids on nontarget organisms requires a solid understanding of spatiotemporal patterns in neonicotinoid use (Sponsler et al. 2019); this understanding is difficult to develop without accurate pesticide use data.

In response to findings on the harmful effects of neonicotinoids on bees and other beneficial insects, Germany, France, and Italy instituted partial bans of certain neonicotinoids starting in 2008. The bans were expanded in 2018, when the European Commission completely banned the outdoor use of neonicotinoids across European Union member states (EFSA 2018). In the United States, the Environmental Protection Agency (EPA) canceled the registrations of 12 out of 59 pesticide products containing the neonicotinoids clothianidin and thiamethoxam per a request from the manufacturers Syngenta, Valent, and Bayer in May 2019 (Federal Register 2019). The request came as part of a settlement in December 2018 (83 FR 63865) of a lawsuit related to the Endangered Species Act brought by a coalition of conservationists and beekeepers (Center for Food Safety 2019). The settlement also requires the EPA to analyze the impacts of the entire neonicotinoid pesticide class on endangered species under the Endangered Species Act, which could affect the reregistration of neonicotinoid-containing pesticides in 2022.

To determine the benefits and costs of neonicotinoid use in agriculture, accurate data collection on pesticides applied as seed treatments is essential. In fact, the Food Quality Protection Act (FQPA) of 1996 directs the US Department of Agriculture (USDA) to collect pesticide use data (§302, Public Law 104–170). Some ambiguity of this directive with respect to pesticide-treated seeds remains, since EPA regulations (53 FR 15977) amended the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) in 1988 to exempt pesticide-treated articles from FIFRA's registration and labeling requirements.

Despite the widespread use of treated seeds and the US congressional mandate to collect data on pesticide use, relatively little is known about when, where, and what kind of treated seeds are planted. There are three primary reasons for the lack of data on treated seed: Private data sources stopped collecting data on seed treatments use on farms in 2015, US government agencies did not begin collecting data on seed treatments until 2015, and collecting accurate seed treatment data from farmer surveys is a challenge because of difficulties farmers may have in accurately knowing or recalling the seed treatment products they used.

As we demonstrate below, farmers know less about the pesticides coated on their seeds than they know about traditional, field-applied pesticides. Difficulties in accurately recalling which pesticides are contained in seed treatments have led to lower response rates and higher proportions of response errors on survey questions related to seed treatments than on those related to traditional, field-applied pesticides.

In the present article, we present existing and new data on the use of seed treatments in crop production, document inconsistencies in the data that are available, and explore the extent of farmers' knowledge about the pesticides applied to their seeds. On the basis of how pesticide use information has been used by researchers and regulators, we show how uncertainty about the use of seed treatments could affect research, regulation, and agricultural practice. As seed treatment use becomes more prevalent, collecting and disseminating high-quality information about their use becomes increasingly important and has wide-ranging implications for both research and policymaking on topics as diverse as pest resistance and pollinator conservation.

Early history of seed treatment use

The practice of treating seeds to protect them from disease, pests, and decay has existed for centuries. As early as the 1600s, for example, wheat seeds were brined to help control wheat smut. In the early 1900s, experiments were conducted to determine whether coal tar, tobacco, and heavy metals could be used to control insect pests (Lange 1959). Most of these efforts were unsuccessful, although the use of mercury-based seed treatments continued for decades to control fungal pests. The development of organochlorides during World War II laid the groundwork for expanding the use of synthetic insecticidal seed treatments (Lilly 1956). Although insecticidal seed treatment use was relatively rare throughout the 1950s, adoption rates steadily rose, particularly in grains and vegetables (Lilly 1956, Lange 1959). Nonetheless, only 10% of corn acres were planted with insecticidal treated seeds in Iowa in 1954 (Lilly 1956), and 28% of seed-corn producers planted insecticidal treated seeds across ten states in 1956 (Lange 1959).

Little information is available on the extent of seed treatment use during the 1960s and 1970s. Major reviews of corn, soybean, and cotton pest management in the 1970s did not report estimates of seed treatment use (Turnipseed and Kogan 1976, Bottrell and Adkisson 1977, Chiang 1978). However, there is evidence that the types of pesticides used to treat seeds changed over this time period. Growing concerns about the environmental impact of organocholorine insecticides, which tend to be highly persistent, shifted overall pesticide use patterns toward organophosphates and carbamates. That trend also bore out in seed treatments. Despite a general decrease in organochlorines, at least one pesticide in this family, lindane, continued to be used as a seed treatment until the EPA issued final cancellation orders with an end of use date of 2009 (71 FR 74905).

Carbamates and organophosphates in seed treatments expanded in the 1970s as they replaced organochlorines, although it appears they were never widely used. According to Smith (1987), farmers planted seeds treated with carbamates and organophosphates on less than 5% of total corn, soybean, and cotton acres annually from 1978 to 1981. However, the methodology of the Smith (1987) study was not well documented.

Pesticide use surveys conducted by North Dakota State University (2014) provide valuable insights into regional trends in seed treatment use. Farmer surveys were conducted in 1989 and every 4 years from 1992 to 2012 and were used to estimate the percentage of planted seed that was treated with pesticides, including both on-farm seed treatment and seed treatment prior to sale. From 1989 to 2012, the vast majority of corn seed planted in North Dakota was treated, whereas under half of wheat seed was treated (figure 1). Soybean seed treatment was uncommon at the beginning of this period but increased after 1996. Wheat was predominantly treated on farm throughout the survey period (80%–90%), and corn seed was almost always treated before sale (90%–99%). In soybeans, the percentage of seed treated on farm declined from 48% in 1989 to 7.7% in 2012 as the overall percentage of pretreated seed increased.

Although the North Dakota data set covers a relatively long time period, it is limited in geographic scope and is unlikely to be representative of national seed treatment use because factors such as climate, pest pressure, and pest management

BioScience 70: 390–403. Published by Oxford University Press on behalf of American Institute of Biological Sciences 2020. This work is written by (a) US Government employee(s) and is in the public domain in the US.
doi:10.1093/biosci/biaa019
Advance Access publication 18 March 2020

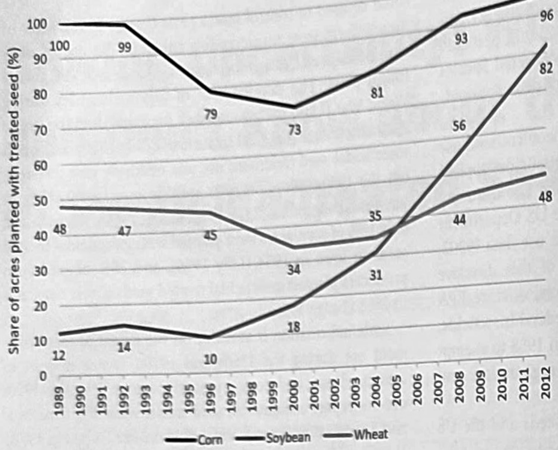

Figure 1. Share of acres of corn, soybean, and wheat planted with treated seed in North Dakota, in 1989 and every 4 years from 1992–2012. Source: Pesticide Use and Pest Management Practices in North Dakota (North Dakota State University 2014) for the years 1989, 1992, 1996, 2000, 2004, 2008, and 2012.

strategies differ from state to state. Furthermore, the types of seed treatments used (e.g., insecticides versus fungicides, particular active ingredients) are only reported for on-farm seed treatments, which are not common in corn or soybean production.

The increase in seed treatments, particularly over the 1990s and 2000s, is also documented in a review article (Munkvold 2009), which provides a detailed analysis of both insecticidal and fungicidal seed treatment use. Seed-applied insecticides are almost always used in conjunction with one or more seed-applied fungicides across a variety of crops, including corn, soybean, cotton, and cereal crops (Munkvold 2009). Several factors have driven this increase in seed treatment use, including intensification of agricultural production, an increased emphasis on quantifying the value of seed in corn and soybean production systems, and a shift toward earlier planting dates (Bradley 2008, Munkvold 2009, Sacks and Kucharik 2011). For example, planting dates for corn advanced by approximately 10 days from 1981 to 2005 and by approximately 12 days for soybeans (Sacks and Kucharik 2011). The trend toward earlier planting combined with the increased risk of early season soil-borne diseases as planting date advances helps explains the increased use in fungicidal seed treatments (Munkvold 2009), although these treatments do not consistently increase yield or economic return for soybeans (Mourtzinis et al. 2019).

Recent trends and use of seed treatments

Data sources. One of the most comprehensive data sets on pesticide use in the United States is collected by Kynetec, a third-party global marketing and research firm. Their annual chemical use survey, AgroTrak, is sent to farmers with the goal of quantifying "the use of seeds, herbicides, fungicides, insecticides, plant growth regulators and seed treatments at the end-user level." Kynetec added questions about seed treatments to AgroTrak in 2004 but removed them following the 2014 growing season citing farmer uncertainty and the difficulty of imputing the seed treatment applied from other information the farmer provided as reasons for discontinuing the data collection. Kynetec sells AgroTrak to public and private entities, including federal agencies, such as the US Geological Survey (USGS) and the EPA. Kynetec data are proprietary, and there are restrictions on what data can be shared with the public. The USGS purchased Agrotrak, making state- and county-level summary data on chemical use publicly available. However, because the USGS summary statistics on pesticide use are aggregated, it is not possible to disaggregate seed treatment use from other types of pesticide usage.

The USDA's National Agricultural Statistics Service and Economic Research Service conduct voluntary surveys of US farmers that grow major crops, including corn, soybeans, wheat, and cotton. This annual survey, the Agricultural Resource Management Survey (ARMS), is a multiphase survey with a stratified, probability-weighted design. It is used to collect information about field characteristics, nutrient applications, pesticide applications, field operations, acreage, capital expenditures, farm assets, farm debt, farm management, and household demographics. The second phase of ARMS, the Production Practices and Costs Report, is administered each year to a different set of commodity producers. For instance, cotton producers were surveyed in 2015, corn producers in 2016, wheat producers in 2017, and soybean producers in 2018. It has included questions on seed treatments since 2015 (a description of the seed treatment questions in ARMS can be found in the supplemental material). In contrast to the Kynetec data, ARMS data do not include sufficient seed product information to impute details about seed treatment usage for farmers who do not know which seed treatment product they used.

At the state level, the most comprehensive, publicly available information on pesticide use is gathered by the state of California, which requires all commercial applicators to report detailed information on their pesticide use. However, seed treatment use does not have to be reported, because treated seed does not meet the definition of a pesticide in California. Some states and land grant universities also collect data on common pesticides used for regionally important crops, although there is often not a clear breakdown of

pesticide use in terms of seed versus foliar treatments (see table S1 in the supplemental material).

Although we focus in the present article on seed treatment use and available data in the United States, we note that in Europe, data on treated seeds are also often not captured in government data sets. Eurostat, the statistical office of the European Union, provides data on the quantity of pesticides sold in EU member countries by pesticide type (e.g., herbicide, fungicide, insecticide; Eurostat 2019). Since 2016, Eurostat disaggregates these data by chemical class. However, detailed data by crop are not available, nor is specific information on seed treatments.

Some European countries provide more detailed information. For example, the United Kingdom reports seed treatment use for 13 crops, providing the share of acres planted with treated seeds, including a more detailed breakdown by active ingredient (Garthwaite et al. 2019). The federal government of Germany requires producers, distributors, and importers of pesticides to report the volume of pesticide products—and the active ingredients they contain—that were sold into the domestic and export markets (German Federal Office of Consumer Protection and Food Safety 2020). However, the volume sold of treated seeds does not need to be reported, and the data set on the volume of pesticides sold does not distinguish between pesticides applied to fields and pesticides applied as seed coatings. (In addition, a portion of the seed that is treated with pesticides in Germany—and for which the pesticide use would be captured as domestic use by the data set—is actually exported, which makes it more difficult to estimate pesticide use, let alone seed treatment use, within Germany.) In France, the Ministry of Agriculture and Food conducted farmer surveys of agricultural practices in 2011, 2014, and 2017. The resulting reports provide data on the share of farmland planted with treated seeds for 14 crops but do not provide information on the active ingredients or the type of pesticide (French Ministry of Agriculture and Food 2020). Therefore, overall, publicly available information on the extent of seed treatment use in Europe is sparse.

Data on seed treatment use in Europe is also collected by the Kleffmann Group, an agricultural market research company, which merged with Kynetec in 2019. However, the lack of farmer awareness about seed treatment limits their ability to collect accurate data for crops when the treatment is carried out on the seed before purchase (Kleffmann Group 2020). This is particularly the case for fungicidal and, to a lesser extent, insecticidal seed treatments in corn, sunflowers, oilseed rape, and soybeans. Farmer awareness about seed treatment is very high for cereal crops, because farmers can save their own seed and play a more active role in selecting the treatments to be applied to their seed. This is also true for potatoes when the treatment is carried out during planting. Therefore, the Kleffmann Group has data on seed treatment use for cereal crops in Bulgaria, the Czech Republic, Germany, Hungary, Poland, Romania, and the Slovak Republic since about 2014. More information on the crop, year, and country combinations, for which seed treatment data from the Kleffmann Group are available in their global database, is presented in table S2 in the supplemental material.

Increased use of seed treatments since the turn of the century. During the late twentieth century, seed and chemical companies became increasingly integrated. This market development enabled input suppliers to bundle pest management technologies with genetically engineered pest management seed traits, such as herbicide tolerance and insect resistance (Macdonald 2017, Macdonald 2019). This bundling increased the likelihood of seed treatment use because the addition of seed treatments comes at relatively low cost compared with the overall cost of buying seed, and untreated versions of seeds with popular genetically engineered traits were often not available (Shi et al. 2010). With the emergence of integrated seed-chemical companies in the late twentieth century and the introduction of a novel class of insecticides (neonicotinoids), the market for insecticidal seed treatments grew more than fivefold, from roughly $200 million in 1990 to over $1 billion in 2008 (Jeschke et al. 2011).

Our analysis of proprietary data from Kynetec (figure 2; Kynetec 2019) demonstrates that the use of seed treatments in the United States grew over the past decade, particularly in corn and soybean production. The data from Kynetec include annual estimates of the share of acres planted with treated seed for corn, soybeans, cotton, and spring and winter wheat from 2004 to 2014. We computed a 3-year moving average to protect proprietary data. To the best of our knowledge, these data include all seed-applied pesticides (e.g., insecticides, fungicides), regardless of whether the farmer, seed company, or supplier applied the treatments. However, data on fungicidal seed treatments on corn are not included in any year. On average, from 2012 to 2014, 90% of corn acres, 76% of soybean acres, 62% of cotton acres, 57% of winter wheat acres, and 46% of spring wheat acres were grown with treated seeds.

The 2017 AgPro Retailer survey has a lower estimate of soybean acreage with treated seeds (65% in 2014) than the Kynetec estimate, but their wheat estimate (50% in 2014) is similar to the Kynetec estimates (Nordwald 2018). The national trends in seed treatment use reported by Kynetec are broadly similar to trends for the overlapping time periods in North Dakota. The Kynetec data suggest that approximately 30% of national corn acres were planted with treated seeds in 2006. The North Dakota data suggest that 70%–100% of corn acres were treated throughout the 2000s. This difference is likely because of the inclusion of fungicide seed treatments in the North Dakota data set and the almost universal use of them in corn.

Regional variation is manifest in pesticidal treatments of cotton seed, reported by Allen and colleagues (2018) on the basis of data from Williams (2011, 2012, 2013, 2014, 2015, 2016). About 20% of cotton seed planted in the West was treated, compared with close to 100% of cotton seed planted

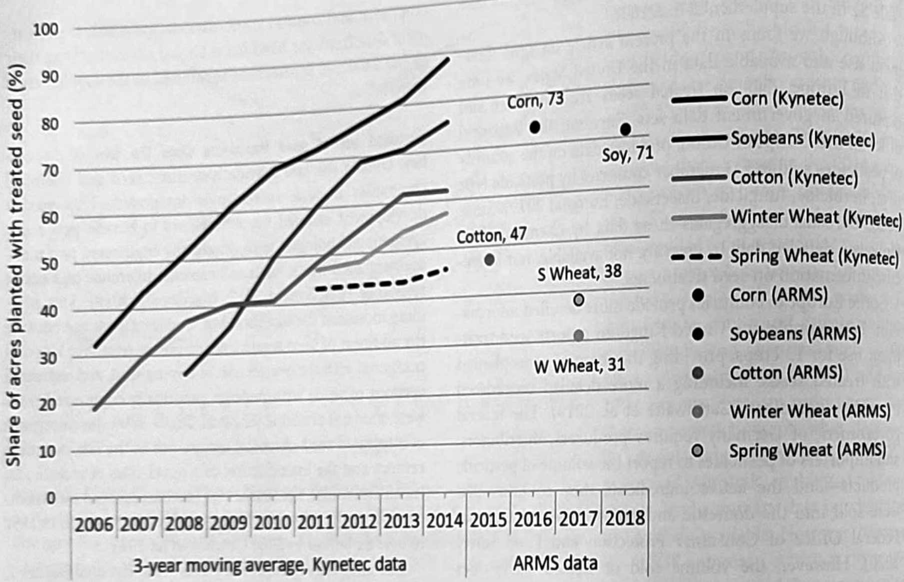

Figure 2. Trends in the share of acres with seed treatments, by crop, using two different data sources, 2006–2018. For the Kynetec estimates, we computed the 3-year moving average for each year to protect proprietary data. To the best of our knowledge, seed treatment data in Kynetec include all pesticides regardless of whether the farmer, seed company, or supplier applied the treatments. However, data on fungicidal seed treatments on corn are not included in any year. Source: Kynetec data for 2004–2014. USDA, National Agricultural Statistics Service and USDA, Economic Research Service, Agricultural and Resource Management Survey (ARMS) for cotton (2015), corn (2016), winter and spring wheat (2017), and soybeans (2018).

in the Mid-South. The average seed treatment use on cotton across the entire United States increased from about 56% in 2010 to 77% in 2015. These estimates are slightly higher than estimates using Kynetec data but show a similar trend.

Estimates of seed treatment use in the United States calculated using ARMS data (figure 2) tend to be lower than estimates using Kynetec data. For example, the responses to ARMS suggested that 73% of corn acreage was planted with treated seed in 2016, although the responses to Kynetec suggest that 90% of corn acres was planted with treated seed, on average, from 2012 to 2014. This discrepancy might stem from farmers' lack of knowledge about the pesticides that are applied to their seeds.

Although estimates of seed treatment use have varied depending on the source, all available data suggest that seed treatment use is more prevalent on corn, soybean, and cotton seeds now than it was two decades ago and that a majority of corn, soybean, and cotton acres are currently being treated. Analyses of the survey data suggest that seed treatment use is most common in corn and soybeans and least common in spring and winter wheat.

In Europe, we see a similar picture, with data on seed treatment use in the United Kingdom and France showing that seed treatments are a common practice (table 1). As early as 1998, over 90% of acres in wheat, barley, rye, triticale, oilseed rape, linseed, peas, and sugar beets in the United Kingdom were planted with treated seed. Although the use of seed treatments in corn for grain and silage in France is high (86% and 92%, respectively, in 2017), only about 10% of soybean acres were planted with treated seeds. An explanation for the low use of seed treatments in soybean in France is that soybean makes up only 0.5% of cultivated land in France (French Ministry of Agriculture and Food 2020), so that pest pressure and pathogen density are relatively low.

Regulatory context. Since 1990, the USDA has surveyed farmers to collect information on the pesticide active ingredients applied to agricultural fields in its Agricultural Chemical Use Program. The 1996 FQPA formalized this data collection effort and directed the USDA to collect data on pesticide use (Sec. 302, Public Law 104–170). The FQPA also amended the FIFRA, which provides statutory authority for the federal regulation of pesticide distribution, sale, and use (7 USC §136 et seq.). An EPA regulation (53 FR 15977) in 1988 exempted pesticide-treated articles, such as treated railway ties, from FIFRA's definition of a pesticide

Table 1. Share of hectares (percentage) planted with treated seed in the United Kingdom and France for select years, by crop.

	United Kingdom											France		
Crop	1998	2000	2002	2004	2006	2008	2010	2012	2014	2016	2018	2011	2014	2017
Wheat	99	97	96	94	92	96	95	98	97	96	96	94	95	94
Barley (winter)	98	91	97	92	97	97	98	97	98	95	97	96	93	92
Barley (spring)	98	92	83	87	86	89	89	91	87	90	89			
Oats	85	79	85	80	75	68	69	85	76	76	82	nd	nd	nd
Rye	99	61	89	95	95	100	67	100	100	63	95	nd	nd	nd
Triticale	92	44	52	25	17	3	22	84	70	41	88	84	80	76
Oilseed rape	95	88	86	91	84	92	96	98	96	88	89	86	88	80
Linseed (fiber)	92	62	91	94	84	97	96	99	71	39	49	nd	nd	93
Linseed (oil)												nd	nd	64
Potatoes (ware)	77	70	86	72	73	90	88	96	84	83	89	85	78	76
Potatoes (seed)	75	73	100	97	84	100	90	96	98	84	99			
Peas	92	81	94	89	90	96	93	94	93	80	76	91	82	81
Beans	13	9	10	3	8	8	7	39	4	6	7	nd	nd	49
Sugar beet	99	100	100	100	100	100	100	100	100	99	100	99	99	97
Sunflower	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	93	91	85
Corn (silage)	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	92	92	92
Corn (grain)	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	93	90	86
Soybean	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	10

Abbreviation: nd, no data available. *Sources:* Garthwaite and colleagues (2019), French Ministry of Agriculture and Food (2020).

and therefore also from pesticide registration and labeling requirements under FIFRA. Section 152.25(a) of title 40 of the Code of Federal Regulations defines treated articles or substances as follows: "An article or substance treated with, or containing, a pesticide to protect the article or substance itself (for example, paint treated with a pesticide to protect the paint coating, or wood products treated to protect the wood against insect or fungus infestation), if the pesticide is registered for such use."

A citizen petition submitted to the EPA in April 2017 by the Center for Food Safety argues that the EPA "improperly [relies] on the Treated Article Exemption 40 C.F.R. §152.25(a)" when it "exempts the coated seeds from FIFRA's registration and labeling requirements" (EPA 2018). The petitioners made the argument that "because the coated crop seeds are not treated primarily to protect the seed itself, but rather to protect the growing plant, ... they cannot be properly exempted as 'treated articles'" (EPA 2018). The EPA sought public comments on the petition in December 2018. If pesticide-treated seeds were determined to be pesticides by the EPA, the USDA may be required to collect data on their use through the Agricultural Chemical Use Program.

Although the USDA may not currently be required to collect data on the planting of treated seed under FQPA, the agency can do so, as was demonstrated by the recent addition of questions about seed treatment use to ARMS in 2015. Unlike questions about field-applied pesticides in ARMS that are part of the Agricultural Chemical Use Program, which makes the data available to the public (USDA-NASS 2020), ARMS questions about seed treatments are considered research questions, and the associated data are not made public. Access can be requested by researchers at accredited domestic academic institutions and government agencies (Wechsler and Smith 2018's appendix C), and we present, in this article, estimates from our analysis of these ARMS questions on seed treatments.

A form of the treated article exemption can also be found in the European Union. EU regulation (EC) no. 1107/2009 concerns the placing on the market of plant protection products (i.e., pesticides) and lists treated seeds as a special case. Although the treatment of seeds with pesticides is considered a use of plant protection products, the sowing of treated seeds is not considered such a use (European Commission 2015). Treated seeds are freely tradable throughout the European Union (article 49, regulation (EC) no. 1107/2009). Therefore, it is permissible to plant treated seeds that were imported from other EU countries, even if an active ingredient contained in the treatment is not registered (permitted) for use in the country where the seed is planted. Treated seeds must be labeled with the product name of the treatment and the active ingredients contained in the product and must include standard phrases for safety precautions and risk mitigation measures (article 49, regulation (EC) no. 1107/2009).

Active ingredients in seed treatments. Pesticide formulations are combinations of active and inert ingredients. Active ingredients are chemicals (such as thiamethoxam or imidacloprid) that kill or otherwise mitigate weeds, insects, fungi, or nematodes. Inert ingredients serve any number of different purposes: They can help active ingredients adhere to plant surfaces, prevent vaporization, or prolong a pesticide's effectiveness. Pesticides are often referred to by their product, or trade name (e.g., Cruiser or Gaucho) or by the names of their active ingredients.

A wide variety of fungicidal, insecticidal, nematicidal, and growth-regulating active ingredients are currently applied as seed treatments. Often several active ingredients are combined into a single seed treatment product. For instance, the product Avicta Complete Beans 500 (Syngenta) contains abamectin for nematode control, thiamethoxam for insect control, and the fungicides mefenoxam and fludioxonil. Seed treatments have various combinations of active ingredients, and the composition of these products evolves rapidly. Since 2011, the efforts to examine the different combinations of seed treatments have been summarized in an annual extension-style poster that is freely available (Smith and Proost 2019).

Insecticidal seed treatments underwent an important change in the late twentieth century with the commercialization of neonicotinoid insecticides (Jeschke and Nauen 2008). Neonicotinoids in the nitroguanidine group are water soluble, persistent, systemic, and highly toxic to a wide range of insect species. These traits make them good candidates for seed application. Research has shown that a small percentage (less than 2%) of the chemicals put on the seed are incorporated by the plant as it grows (Alford and Krupke 2017). Nonetheless, seed treatments can provide plant protection, especially early in the growing season. By 2008, neonicotinoids accounted for roughly 80% of the total market for insecticide seed treatments (Jeschke et al. 2011).

The majority of fungicidal seed treatment products were developed and released in the early 1990s (Munkvold 2009). These products contain a variety of active ingredients, including azoxystrobin, pyraclostrobin, and trifloxystrobin (quinone outside inhibitors), difenoconazole, prothioconazle, and triticonazole (demethylation inhibitors), fludioxonil (phenylpyrroles), and mefenoxam (phenylamides). In general, fungicide seed treatments target two pathogen groups, the oomycetes and true fungi such as *Fusarium* spp. and *Rhizoctonia solani* (Munkvold 2009).

In an effort to disseminate information about seed treatments available, Esker and Proost (2011) developed an extension guide that matched active ingredients with product trade names for a variety of field crops. This document has been updated annually since 2011 (Smith and Proost 2019). Currently, the guide contains approximately 24 active ingredients and some biological compounds. The increase in available products and use by farmers is also documented in preliminary analyses of the USGS Pesticide National Synthesis Project (using Kynetec data): From 2006 to 2014, for five active ingredients (metalaxyl, mefenoxam, thiram, captan, and fludioxonil) commonly used in soybean production, the researchers estimated a 700% increase in total fungicide use in grams per hectare across 28 states in the United States (Bandara et al. unpublished).

Because the annual pesticide use estimates released by the USGS Pesticide National Synthesis Project (USGS 2018) no longer contain seed treatment information after 2014 (and never included fungicide seed treatments in corn), the estimates before and after this change provide a window into the extent to which seed treatments make up overall use for particular active ingredients. We present trends in use of select insecticides, fungicides, and nematicides in figure 3. These active ingredients were chosen because extension materials from the University of Wisconsin (Smith and Proost 2019) and Mississippi State University (Catchot et al. 2017) suggest that they are among the most commonly applied components of seed treatments in major crops. Our comparison of trends up to and after 2014 suggests that there is significant lost data for most of these compounds. For instance, clothianidin use dropped from more than 1.5 million kilograms per year in 2014 to less than a tenth of a million kilograms per year in 2015 (figure 3). A similar trend in potential lost data can be seen in other insecticides and fungicides that are commonly used in seed treatments (figure 3).

Douglas and Tooker (2015) compared pesticide use from USDA's Agricultural Chemical Use Program, which historically excluded seed-applied insecticides, and the USGS (Kynetec), which included them between 2004 and 2014. They concluded that, as of 2010–2012, neonicotinoid seed treatments accounted for significant percentages of total insecticide weight applied in corn (43%), soybeans (21%–23%), and wheat (25%–29%) but not cotton (approximately 3%). These proportions are relatively large, given that seed treatments are typically applied at very low per-acre rates. The likely explanation is that seed-applied insecticides are now used on many more acres than were historically treated with insecticides (see also Meehan and Gratton 2016, Douglas et al. 2020).

Farmer knowledge of pesticides applied as part of treated seeds

Until the late twentieth century, farmers tended to purchase and apply pesticides themselves or in close cooperation with applicators. This involvement meant that farmers had a practical understanding of the pesticide products used on their farms. As purchases of treated seeds became more common, farmers became less knowledgeable about some of the pesticides that they were using. We find that farmers are less knowledgeable about seed treatments (which tend to be applied by others) than they are about pesticides they choose to have applied directly to the field, either by themselves, by hired labor, or by custom applicators.

The lack of awareness means that farmers are often unable to answer questions on seed treatments accurately. When necessary, Kynetec corrected farmers' responses or imputed nonresponses on the basis of the seed product information supplied by the farmer and product information supplied by seed manufacturer. In 2015, Kynetec stopped gathering information on seed treatments because of the time and effort required for this imputation (personal communication, Melissa Sims, Real Time Trackers, Kynetec, Washington, DC, 25 October 2017). In the documentation for its Pesticide National Synthesis Project, the USGS reported that Kynetec discontinued making estimates for seed treatment application of pesticides "because of complexity and uncertainty" (USGS 2018).

From 2004 to 2014, statisticians at Kynetec gleaned insights about farmers who planted treated seeds (personal communication Melissa Sims, Real Time Trackers, Kynetec, Washington, DC, 24 January 2018). For instance, they found that farmers planting seeds that had been coated with a high dose of pesticides had better information about seed treatments than other farmers, perhaps because farmers pay a premium for seed treatments that deliver higher doses. When and where the coating is applied also appears to affect the probability of farmers responding correctly to seed treatment questions. If the treatment was applied by the retailer, farmers were more likely to respond to questions about seed treatments than if the treatment was applied farther upstream by a seed company.

We analyzed farmer responses to commodity-specific versions of ARMS for cotton in 2015, corn in 2016, wheat in 2017, and soybeans in 2018 to test the hypothesis that farmers would know more about pesticides applied in the field than pesticides applied to their seeds. Although the soybean survey included a response option for "seed treatment is not known," the lack of a response to a question on the cotton, corn, or wheat survey could imply either a lack of knowledge or a refusal to respond. For the cotton, corn, and wheat survey, we analyzed all instances of no response to the seed treatment product question for fields that had indicated that they were using a seed treatment. The survey is enumerated, meaning that an enumerator goes through the survey in person with the farmer. Analyzing the enumerator notes on the survey forms, we were able to identify cases in which the lack of response was due to the farmer not knowing what type of seed treatment was applied to their seed. The

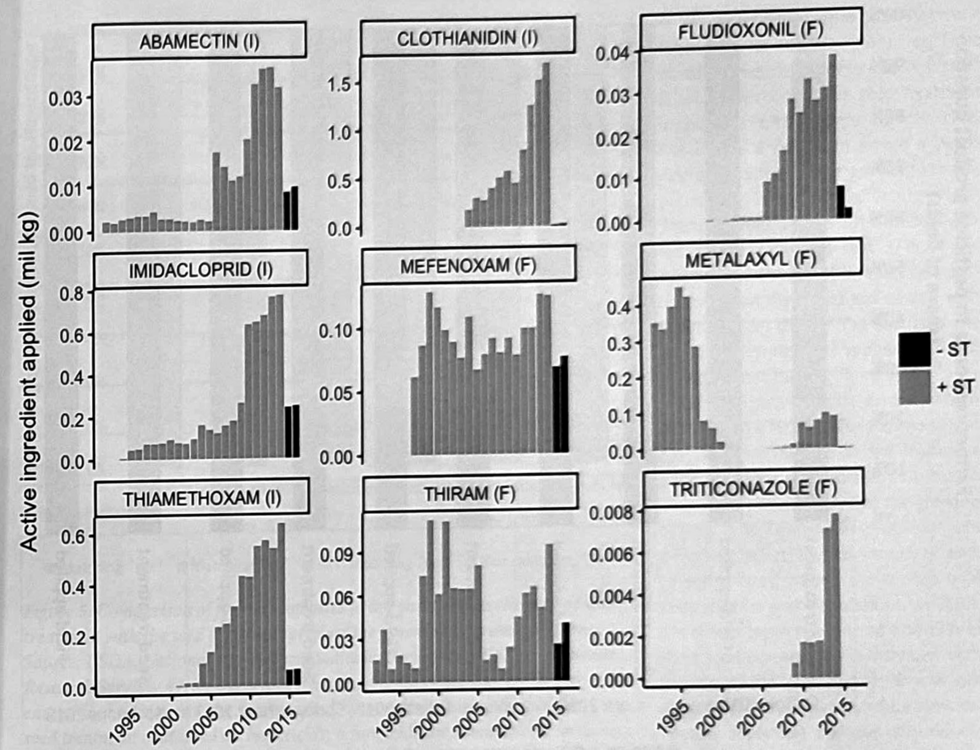

Figure 3. Trends in use of select active ingredients for both field and seed applied pesticides for 1992–2014 and field applied only for 2015–2016. Through 2014, amounts applied include both nonseed treatment uses and seed treatment uses (+ST), after which the survey excluded seed treatments (−ST). Abbreviations: F, fungicide; I, insecticide; N, nematicide. Source: USGS Pesticide National Synthesis Project from 1992–2016 using Kynetec data.

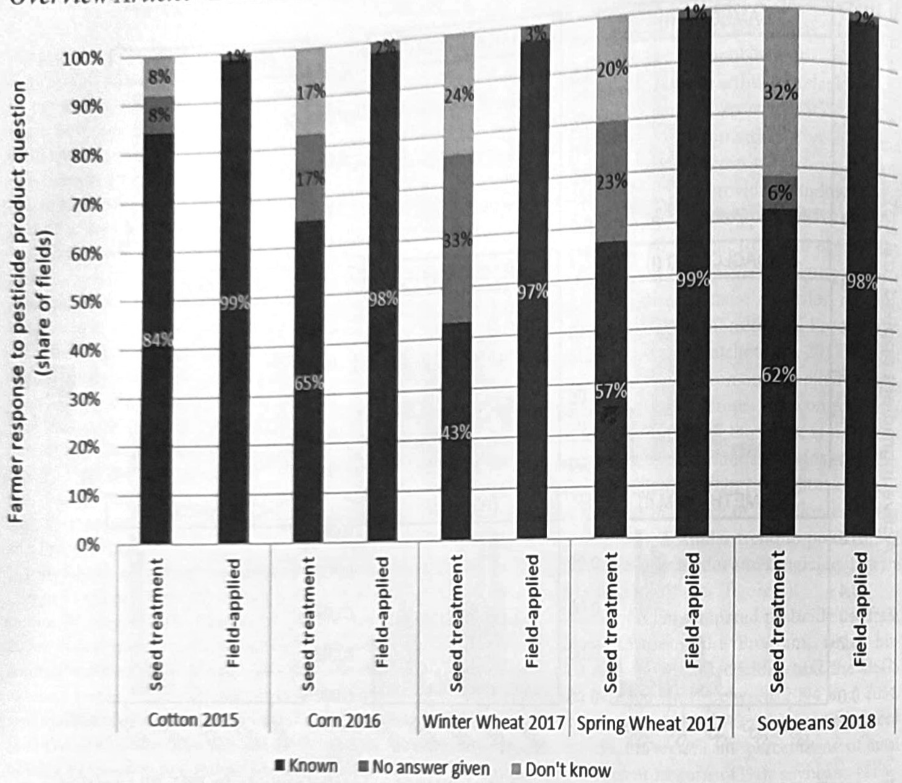

Figure 4. Farmer knowledge or response to pesticide product, if indicating product used, as share of fields. Source: USDA, National Agricultural Statistics Service and USDA, Economic Research Service, Agricultural and Resource Management Survey. The seed treatments include fungicides, insecticides, and nematicides that are applied either by the farmer or the seed company or supplier. The field-applied pesticides include all types of pesticides that are applied by the farmer or another operator to the field.

farmer responds to the practices used on one of their fields, chosen at random, so the results below are given in terms of the share of fields, although we interpret them as roughly representing the share of farmers.

We found that the farmers had better knowledge about the pesticides applied to fields than they did about seed treatments (figure 4). About 97%–99% of the farmers provided the names of the field-applied pesticides used on their cotton, corn, wheat, or soybean crops. By contrast, only 84% of the cotton growers, 65% of the corn growers, 62% of the soybean growers, 57% of the winter wheat growers, and 43% of the spring wheat growers provided the name of the seed treatment product on their crops. The farmers that did not provide the name of the seed treatment either refused to answer the question or indicated that they did not know the name of the product (as captured in the enumerator notes). The responses to the 2018 ARMS for soybeans, which included a "seed treatment not known" response option, suggest that 32% of the soybean farmers did not know what seed treatment product had been applied to their seeds.

The soybean survey asked the farmers whether the seed treatment was applied prior to or after purchase. Of the 64% of soybean farmers using seed treatments, approximately 88% purchased pretreated seeds; the remaining 12% applied a treatment after purchase. The farmers' knowledge of the seed treatment product was greater among those who treated their seeds after purchase (22% "did not know") than among those who purchased pretreated seed (35% "did not know"). Therefore, the farmers who played a more active role in treating their seeds knew more about the seed treatment products than those who purchased a seed that was pretreated.

Farmers may have difficulty accurately recalling information about their seed treatment for a variety of reasons. For example, they could have indicated that they used the product Cruiser when, in fact, they may have used a product

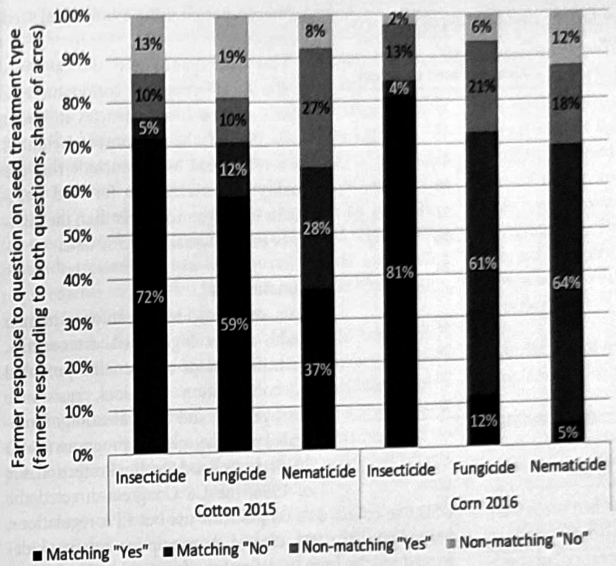

Figure 5. Comparison of farmer responses to the questions on the type of seed treatment with the seed treatment product they provided, as share of acres. Source: USDA, National Agricultural Statistics Service and USDA, Economic Research Service, Agricultural and Resource Management Survey. In the case of seed treatments, the survey asked farmers to indicate whether the seed treatment contained an insecticide, a fungicide, or a nematicide in three separate questions with the option to answer yes or no. The farmers were then asked to select the product name from a list of products. This chart compares the farmers' answers to these two sets of questions on the basis of known information about the types of pesticides contained in various seed treatment products. Mismatches could reflect the farmer being mistaken about the types of pesticides contained in a product or the name of the product applied.

with a similar sounding name, such as Cruiser Extreme 1250 or Cruiser Force. Cruiser contains the insecticide thiamethoxam, whereas Cruiser Extreme 1250 contains thiamethoxam and three fungicidal active ingredients. It is unclear how to interpret the responses when the product name reported by the farmer does not match the types of pesticides contained in the product.

The cotton and corn surveys from 2015 and 2016 asked the farmers for the seed treatment product name, as well as whether they had planted seeds treated with insecticides, fungicides, or nematicides. We assessed whether the farmers' responses to these two sets of questions were contradictory (figure 5). For cotton and corn, the product names and pesticide types reported did not match in approximately 15%–35% of the cases. The farmers were best informed about insecticidal seed treatments and less informed about fungicidal and nematicidal seed treatments. The responses from about 30% of the corn farmers in 2016 and 35% of the cotton farmers in 2015 reflected a mismatch between product name and the presence or absence of a nematicide.

We consider two types of recall errors: false positives and false negatives. False positives, which occur when a farmer falsely believes that the seed treatment includes a certain type of pesticide, can induce a farmer to forego a pesticide application in the growing season, potentially negatively affecting yield. The responses to the 2015 ARMS cotton survey suggested that 27% of the respondents (weighted by share of acres) believed that their seed was coated with a nematicide, despite the fact that the product they reported applying did not include a nematicide (figure 5).

False negative recall errors, which occur when a farmer falsely assumes that the seed treatment does not include a particular type of pesticide, can induce overuse of pesticides during the growing season. The overuse of pesticides can adversely affect the environment and, in some cases, hasten the evolution of resistance in pest populations. In 2015, the cotton growers reported that 13% of their total acreage was not treated with an insecticide and that 19% was not treated with a fungicide, while simultaneously reporting the use of products containing those types of pesticides on that acreage.

If false negatives are less likely for pesticides that are important to farmers, then the rate of false negatives is inversely related to farmer demand. For example, farmers may demand insecticidal seed treatments but only be able to purchase these seed treatments by buying a treatment that contains a fungicide (because of bundling). If so, the rate of false negatives for the fungicide would likely be higher than the rate of false negatives for the insecticide.

Some pesticidal seed treatments may be purchased by farmers only because a restricted set of bundled treatments is available. These seed treatments are more likely to be overapplied. There is evidence supporting this hypothesis. In a survey sponsored by pesticide manufacturers, 21% of corn growers and 15% of soybean growers reported that they would reduce or eliminate their use of insecticidal seed treatments if the same seed variety were available without these products (Hurley and Mitchell 2014).

Furthermore, evidence of a lack of farmer awareness about seed treatments is available from data collected as part of the United Kingdom's Pesticide Usage Survey (Garthwaite et al. 2019). The survey asked farmers to indicate whether their seeds were treated and to name the

Table 2. Percentage of area for which the farmer could not specify the seed treatment product in the United Kingdom, 2018.

Crop	Area grown	Area with seed treatment
Wheat	13	12
Winter barley	15	14
Spring barley	20	22
Oats	24	29
Rye	32	35
Triticale	25	29
Oilseed rape	22	24
Linseed	27	56
Potatoes	30	32
Peas	18	24
Beans	6	88
Sugar beet	0	0

Source: Garthwaite and colleagues (2019).

treatment product. When the farmers knew their seeds were treated but were unable to name the treatment product, the affected acres were captured in the category "unspecified seed treatment" (table 2). According to the survey administrators, this occurred because seed treatment data are not as readily available as foliar pesticide applications and because seed treatment information is often not stored in the same place as foliar applications. The farmers were unable to specify the seed treatment product for 12% of the wheat acres and 32% of the potato acres that were planted with treated seed.

Impacts on data collection and accuracy. The questions in ARMS have evolved to deal with farmers' knowledge of the treatments applied to their seeds. Since farmers were first asked about their use of seed treatments in the cotton grower survey of 2015, the ARMS survey team have altered the way the questions on seed treatments are asked, based in part on the farmers' difficulties in ascertaining what kind of treatments were applied to their seed. In 2015, the farmers had to identify whether their seeds were treated with insecticides, fungicides, or nematicides and then name the product. By 2017, the farmers were no longer asked to distinguish between the types of seed treatments (insecticides versus fungicides versus nematicides), and in 2018, a specific response code for not knowing the seed treatment product was added.

Discrepancies between agricultural extension documents, anecdotal evidence, and analyses of the Kynetec and ARMS data suggest that surveys can fail to capture comprehensive data on seed treatment use. One example of such a discrepancy concerns fungicidal seed treatments in corn. Fungicides applied as seed treatments appear to be used almost universally in corn (Munkvold 2009) but are absent in the Kynetec data. The ARMS survey did collect these data in its 2016 survey of cornfields but only 28% of the farmers reported using a fungicidal seed treatment.

This discrepancy and our analysis of the ARMS corn and cotton surveys, which showed inconsistencies in about 15%–35% of the responses, weighted by acreage, lead us to conclude that the quality of pesticide data for seed treatments is likely much lower than the quality of conventional pesticide data.

Conclusions

Data on pesticide use inform human health and ecological risk assessments, quantification of the benefits provided by conservation practices, resistance management, and the evaluation of integrated pest management programs (GAO 2010). In its Food Quality Protection Act of 1996, the US Congress directed the USDA to collect data on pesticide use but EPA regulations, promulgated in 1988, created an exemption for pesticide-treated articles from its definition of pesticides. The USDA's Agricultural Chemical Use Program provides publicly available pesticide use estimates only for field-applied pesticides. In 2015, the USDA began collecting data on pesticides applied as seed treatments as part of a series of research questions outside of the framework of the Agricultural Chemical Use Program and its regular data publications. Therefore, although seed treatments have become an increasingly common pest management strategy, they are not fully captured by publicly available federal data.

In private industry, Kynetec provided the most extensive data on seed treatments from 2004 to 2014. The company stopped collecting data on seed treatments after 2014, because of the need to correct and impute survey responses, because farmers had difficulty accurately recalling the pesticides in their seed treatments. The questions on seed treatment that were added to the USDA survey of farmers starting in 2015 are subject to similar limitations regarding farmer recall. Similarly, in European countries, seed treatments are often not captured in pesticide use surveys, and when they are, lack of farmer awareness of the treatment pesticide product limits the availability of detailed information in government and private industry data sets.

The result is a lack of reliable data on pesticides applied as seed treatments in agriculture, even though the majority of corn, soybean, wheat, and cotton acres in the United States are planted with pesticide-treated seeds. The lack of public data limits research into farm productivity and economics, pest resistance, and environmental effects. It also makes the evaluation of pesticide-related policies and mitigation efforts more difficult.

A changing regulatory landscape is likely to increase the importance of complete and accurate data on seed

treatments. In January 2020, the EPA took a step in the registration review of neonicotinoids by releasing proposed interim decisions for all five neonicotinoids registered for use in the United States. The EPA is expected to complete this process in 2021. As a result of a lawsuit settlement, the EPA must now complete Endangered Species Act effect determination for neonicotinoids, many of which are applied as seed treatments. In addition, a citizen petition to the EPA filed in 2017 seeks to eliminate an exemption for seed treated with systemic pesticides and require some pesticide-treated seed to follow the registration and labeling requirements as provided by FIFRA. However, this petition has no direct impact on regulations.

Improved data collection and labeling could help farmers make more informed decisions. As seed manufacturers have increasingly bundled seed characteristics, including genetically engineered traits and multiple pesticide active ingredients, into standardized seed packages, farmers may end up purchasing a seed that has more pesticide active ingredients than they want. Farmers may also not know exactly what assortment of pesticide active ingredients is on their seed. The lack of alternative seeds and the lack of knowledge of what the seed coatings contain could lead to overuse of pesticides. We find some evidence for the overuse of pesticides in farmers' inability to accurately recall the types of pesticides applied to their seeds, because the ability to recall is, in theory, related to the importance of the pesticide to the farmer for production. For example, 19% of cotton growers in 2015 mistakenly assumed their seed did not contain a fungicide when it likely did. The result is that farmers may be unwittingly paying for a fungicide they do not want or need, which may also entail consequences for the environment. The overuse of pesticides and farmers' lack of knowledge about the pesticides coated on their seeds can therefore negatively affect worker safety during seed handling and planting, the environment, pest resistance management, and farm economics.

Opportunities for providing more information about pesticidal seed treatments to farmers include improved labeling of pesticide-treated seeds and posting information about the active ingredients contained in treated seed products on public websites. In addition to surveying farmers, alternative methods to obtain data on pesticidal seed use rates could include collecting sales data from seed retailers and companies. These companies would be able to provide more accurate data on what kinds of seed are purchased but would not show where exactly these seeds are planted, which is the advantage of surveying farmers. Information about the planting location of treated seeds is important to assessing pest resistance and the local effects of pesticides on the environment. Ultimately, there are tools available to improve data collection of pesticidal seed treatments. Reliable pesticide use data are used by farmers, researchers, and regulators to increase agricultural production and profitability and to protect the environment from the adverse effects of pesticides.

Acknowledgments

We thank three anonymous reviewers for their insightful comments. This work was supported by the National Socio-Environmental Synthesis Center under funding received from the National Science Foundation (grant no. DBI-1639145). Partial support for Paul Esker was under the USDA National Institute of Food and Agriculture Federal Appropriations Project (grant no. PEN04660 and accession no. 1016474). This research was supported in part by the US Department of Agriculture. The findings and conclusions in this publication are those of the authors and should not be construed to represent any official USDA or US government determination or policy.

Supplemental material

Supplemental data are available at *BIOSCI* online.

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