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A case for comprehensive analyses demonstrated by evaluating the yield benefits of neonicotinoid seed treatment in maize (*Zea mays* L.)

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ABSTRACT

With increased scrutiny of the neonicotinoid class of chemistry and its negative impact on the pollinator community, ecological cost/benefit analyses of agronomic crops that use these insecticides are increasingly important. This study initially sought to address the question of yield benefit due to neonicotinoid seed treatment in maize (*Zea mays* L.), using North Carolina yield contest data from 2002 to 2006, the time period from initial neonicotinoid seed treatment adoption to nearly ubiquitous adoption. However, we recognized that several agronomic practices, including planting date, hybrid selection, and fertilization, could affect the yield of this crop; moreover, they could be collinear with one another and the analysis could be skewed by early adopters of new technology. Hence, we used all available data to compare among traditional approaches and a data-mining approach for analyzing the impact of neonicotinoid seed treatment on maize yield. At-planting insecticide treatment was not an important predictor of maize yield. When analyzed using the traditional approach (T-test), yields were significantly higher for fields planted with neonicotinoid treated seed compared to seed without neonicotinoid; however, data-mining approach (Decision tree analysis) that took into account other factors contributing to yield did not identify seed treatments as important. The contrast in these results highlights the need for future carefully designed studies that target to minimize inter- and intra-site variation; and include measurements of additional factors that may influence yield, such as seeding rate, tillage, and herbicide applications, as input variables that are largely lacking in current approaches on the subject.

1. Introduction

Neonicotinoids, especially clothianidin, imidacloprid, and thiamethoxam, are commonly used as seed treatment in many crops, including maize, *Zea mays* L., soybean, *Glycine max* (L.) Merr. (Smith et al., 2004; Elbert et al., 2008), canola, *Brassica napus* L. and *Brassica rapa* L. (Tansey et al., 2008; Goulson, 2013), sunflowers, *Helianthus annuus* (Bredeson and Lundgren, 2015), and winter wheat, *Triticum aestivum* L. (Royer et al., 2005). Besides effectively controlling the seedling insect pest complex, neonicotinoid seed treatments can drastically reduce the use of the active ingredient of insecticide per area required to manage many insect pests. For example, 15-times more active ingredient (carbofuran in the carbamate class, applied using a granular formulation) is required in maize to control cutworms, *Agrotis* spp. (Notuidae: Lepidoptera), and rootworms, *Diabrotica* spp. (Coleoptera: Chrysomelidae), compared to the neonicotinoid seed treatment clothianidin (Altmann, 2003). Perhaps more importantly, the perceived correlation between positive crop yield response and the use of neonicotinoid seed treatments has led to their near complete adoption in maize and soybean across the U.S. (Andersch and Schwarz, 2003; Douglas and Tooker, 2015). Despite the ability of neonicotinoid seed treatment to increase yield in the presence of insect pests, peer-reviewed studies across the U.S. have not found consistent yield benefits of using neonicotinoid seed treatment under "typical" insect pest pressures in these crops (e.g., Pons and Albajes, 2002; Wilde et al., 2004; McMaizeack and Ragsdale, 2006; Johnson et al., 2008; Seagraves and Lundgren, 2012; Reisig et al., 2012; Douglas and Tooker, 2015; exceptions include: Andersch and Schwarz, 2003; Cox et al., 2007a, 2007b; Magalhaes et al., 2009; North et al., 2016).

Currently, small-plot experiments regarding the use of neonicotinoid seed treatment in several crops, including maize and soybean, use a linear regression approach to estimate their impact on yield per area (Andersch and Schwarz, 2003; Wilde et al., 2004; McMaizeack and Ragsdale, 2006; Cox et al., 2007a, 2007b; Johnson et al., 2008; Magalhaes et al., 2009; Reisig et al., 2012; North et al., 2016). However, with the recent rapid development of data mining, alternative

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estimation approaches analyzing multiple variables, such as decision trees and/or neural networks, have become more popular and easier to operate (Barlow and Neville, 2001; Tso and Yau, 2007); such analytical methods have applicability to both experimental and observational field data in the agricultural sciences.

Decision trees are relatively simple and easy to understand, since they provide the user a decision-making process in a step-by-step fashion (Quinlan, 1986; de Ville, 2006). Decision trees are multivariate analyses that can predict, explain, describe, or classify an outcome (or target). They can be used for both continuous and categorical data (Rokach and Maimon, 2005; de Ville, 2006). Decision trees are produced by algorithms that identify various ways of partitioning a data set into subsets, until the subsets cannot be partitioned further (Quinlan, 1986; Rokach and Maimon, 2005; Barlow and Neville, 2001; de Ville, 2006). Algorithms that produce a decision tree analysis attempt to find a strong relationship between input and target values, where the inputs improve the ability to predict the targets; therefore, when this relationship is identified, then all these values are grouped into a bin that becomes a branch on the decision tree (de Ville, 2006). Much like a tree, the partitions are thought of as splits and the subsets as branches. The original data are set as the root node. Subsets emerge as nodes, from which branches sprout, which are the subsets created by partitioning a node; the unpartitioned subsets are leaves. One of the goals of generating a decision tree is to partition a heterogeneous group of objects/data, into smaller, homogeneous groups. By creating those groups, the analysis can predict with greater precision outcomes from data in each group. The final groups, represented by the leaves in a decision tree, are defined by a sequence or series of splitting/partitioning rules (Rokach and Maimon, 2005; Barlow and Neville, 2001; de Ville, 2006).

Maize is the most economically important crop in the U.S., with a farm gate value of over $50 billion (NCGA, 2016). Maize is also the most widely planted crop in the U.S., occupying 33% of the agricultural land, followed by soybean (31%) and wheat (21%) (Soystats, 2016). Maize production in the U.S. has also averaged around 330 million metric tons over the past three years (NCGA, 2016). There are numerous agronomic practices that can influence maize yield beyond external environmental constraints, including planting date, seeding depth and rate, and fertilization (Martin et al., 2006; Danforth, 2009; Krishna, 2013). Proper management of these practices is required to produce a uniform plant stand and optimal yield in commercial maize fields (Martin et al., 2006; Danforth, 2009).

Other biotic factors that can reduce maize yields include injury from soil-dwelling insect pests such as rootworms, *Diabrotica spp.* (Coleoptera: Chrysomellidae), white grubs, *Popillia japonica* Newman, *Cotinis nitida* L., and *Cyclocephala* spp. (Coleoptera: Scarabaeidae), wireworms, *Melanotus communis* Gyllenhal and *Conoderus* spp. (Coleoptera: Elateridae), and the southern maize billbug, *Sphenophorus callous* Oliver (Coleoptera: Curculionidae); these pests can negatively influence the stand uniformity of maize, and ultimately impact yield (Steffey et al., 1999). Before neonicotinoids were widely adopted as a management tool, farmers used in-furrow applications of liquid or granular organophosphate and pyrethroid insecticides targeting the rootworm complex and other soil-dwelling insect pests in maize, (Jeschke et al., 2011). Currently, neonicotinoids, an insecticide class that targets the nervous system of insects with a unique mode of action, are used to treat the seed of most of the maize and other crops planted in the U.S. (Elbert et al., 2008; Bredeson and Lundgren, 2015). Neonicotinoids first appeared on the market in 1991, having a broad spectrum action against many piercing-sucking and chewing pests in the insect orders Hemiptera, Coleoptera, Diptera, Hymenoptera, and Lepidoptera (Andersch and Schwarz, 2003; Jeschke and Nauen, 2008; Jeschke et al., 2011). Neonicotinoids are relatively long-lasting translaminar and systemic insecticides; therefore, they can be applied on root and seeds and the active ingredient is transported to stems and leaves of plants (Andersch and Schwarz, 2003; Elbert et al., 2008). Additionally, neonicotinoids have a lower mammalian toxicity compared to organophosphates and pyrethroids (Elbert et al., 2008).

One of the first reports addressing the relationship between crop yield and neonicotinoid seed treatment used experimental small plots and found that clothianidin-treated maize seed had higher yields compared with plots with untreated seed (Andersch and Schwarz, 2003); this was attributed to protection provided by the neonicotinoid to seeds through the germination process and while the seedlings were most susceptible to early or secondary pests, such as wireworms and rootworms. Other small plot studies (Cox et al., 2007a, 2007b) also confirmed a positive yield response from using neonicotinoid seed treatment in maize under high infestation of early season insect pests. However, there is also conflicting information from small plot studies that, although early season insect pests can be successfully controlled with neonicotinoid seed treatments, maize yield will remain unaffected (Pons and Albajes, 2002; Wilde et al., 2004). Likely, extrinsic factors, such as timing and intensity of pest pressure, growing conditions throughout the season, hybrids used in the study, fertilization regime, etc., have an influence on the results of these studies.

In contrast to maize, yield benefits from neonicotinoid seed treatments in soybean are perceived as less common, although they are effective at controlling many of the seedling insect pests encountered in this crop. For example, neonicotinoid seed treatment can protect soybean against injury from the soybean aphid, *Aphis glycines* Matsumura (Hemiptera: Aphididae), but yield is not consistently influenced by this protection (McMaizeack and Ragsdale, 2006; Johnson et al., 2008). Similarly, yield, oil, or protein content in soybean is not influenced by neonicotinoid seed treatment (Seagraves and Lundgren, 2012). Neonicotinoid seed treatment can also reduce thrips populations of the most abundant species, *Frankliniella fusca* (Hinds) and *Neohydatothrips variabilis* (Beach) (Thysanoptera: Thripidae), in soybean early in the season; but there is no positive yield response from neonicotinoid seed treatments from these pests alone (Reisig et al., 2012). Conversely, other studies have shown a correlation between higher soybean yields and neonicotinoid seed treatment. For example, there was a significant yield reduction due to aphid feeding in soybean fields planted with no insecticide treated seed, compared with fields planted with a neonicotinoid seed treatment (Magalhaes et al., 2009). Additionally, a recent study pooled 170 small plot experiments comparing the effect of neonicotinoid seed treatment against plots with fungicide-only treated seed, over the course of 10 years in Arkansas, Louisiana, Mississippi, and Tennessee and found higher yields with neonicotinoid seed treatments (North et al., 2016). Moreover, the yield difference resulted in economic profits in four out of the 10 years and in two out of the four states in the study.

In the present study our first objective was to analyze if neonicotinoid seed treatment had an impact on maize yield from the highest yielding fields, using historical data from the North Carolina state maize yield contest from 2002 to 2006. The contest summarizes the agronomic practices related to the highest maize yield across the state and provides farmers prize incentives and recognition for entries (Heiniger and Boerema, 2015). These data represented a time period when neonicotinoid seed treatment adoption ranged from 13%, during 2002, to nearly 75% of the entries by 2006. Hence, yield results could be compared from fields with and without neonicotinoid seed treatment, as well as fields where other in-furrow insecticides might have been used. The impact of neonicotinoid seed treatment on maize yield was investigated using two traditional approaches, including a T-test, and a stepwise selection of regression effects using a general linear model. Furthermore, we recognized the potential of having collinearity between some variables in the selected data set, for instance, seeding rate and row spacing; therefore, a third analysis was included using a data-mining approach such as the decision tree analysis. Therefore, our second objective was to test if use of the decision tree could cope with collinearity and identify which agronomic practices, including neonicotinoid seed treatment, influence the yield of maize. A third objective