Plant Architecture and Seeding Rate Responses to Markets, Resources, and Technologies

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Abstract

Corn and soybean seeding rates in the United States have moved in opposite directions over recent decades, with the former trending upward and the latter trending downward. Both seed markets have experienced similar market, technological and environmental shocks over that time. This paper aims to better understand how farmers make seeding rate choices and why corn and soybean seeding rates have trended in opposite directions. We develop a model of seeding rate choices by incorporating a resource budget trade-off between more seeds and fewer resources allocated to each seed. With a unique detailed U.S. farm-level market data, consisting of more than 600,000 plot-level choices over 1995-2016 for corn and 1996-2016 for soybean, we assess how farmers' seeding rate choices respond to markets, resources, and technologies. We find that the soybean seeding rate choice to be more price elastic than that for corn, i.e., seed companies are likely to have less power in the soybean seed market. Furthermore, most inputs that are endowed with the land, and so are shared across all seeds, increase both corn and soybean seeding rates; while inputs that come with the seed increase corn rates but decrease soybean rates. Representative farmers reveal some different ideas and they rely most heavily on their own experience when deciding on seeding rate choices. When joined with an earlier paper on ecological effects, our findings further suggest that targeted tax or price policies on seed or crop will mitigate neonicotinoid-related ecological impacts.

Keywords: Seeding rate, plant architecture, seed price elasticity, genetic technology

JEL Codes: Q11, Q12, Q15

Introduction

Seed rate choices have played a critical role in enhancing productivity and ensuring sufficient food supply for a rapidly growing population. Corn and soybean yields have significantly increased since the 1930s when hybrid varieties were commercialized. These increasing trends have been attributed to complex interactions among genetic improvement, advanced plant breeding, and improved agricultural management (Duvick 2005; Assefa et al. 2016; Assefa et al. 2018). However, no consensus has emerged on the exact yield contribution of seeding rates (i.e., seeds per acre). A literature in agronomy argues that, at least for corn, crop yield increases have been directly linked to increases in seeding rate over time (Stanger and Lauer 2006; Assefa et al. 2017; DeBruin et al. 2017; Assefa et al. 2018), while other agronomic literature indicates that higher seeding rates do not affect yields and can even reduce yields due to more competition among plants for the available soil nutrients (Hashemi, Herbert and Putnam 2005; Ciampitti et al. 2013; Assefa et al. 2016). Thus seeding rate may have positive, neutral, or negative effects on crop yield (Assefa et al. 2016). Despite the increasing trends in corn and soybean yields, seeding rate trends for these two crops have been very different. Therefore, understanding the factors that affect farmers' seeding rate choices and induce the different corn and soybean seeding rate patterns is of great importance to productivity gains.

Notwithstanding seeding rates' productivity-enhancing potential, seed input costs comprise a large proportion of production costs with technologies changing continuously. Soybean seed costs about $50 per acre while corn seed costs about $100 per acre[1], clearly large expenses for an enterprise. These seed markets are oligopolies (Ciliberto, Moschini and Perry

[1] Estimated seed costs are obtained from Estimated Costs of Crop Production in Iowa – 2021 at https://www.extension.iastate.edu/agdm/crops/html/a1-20.html.

2019) where supplier market power is further strengthened through possession of germplasm foundation lines and patents on seed traits. Seeding rates may also be affected by the choice of biotechnology trait. Seed varieties have changed quickly with a commercial life of about 4.6 years for corn (Perry, Hennessy and Moschini 2018) and about 3.5 years for soybean (Zhang and Bellaloui 2014). Technology trait endowed seeds are more costly, suggesting that growers will seek to economize on seeding rates when planting these seeds. Alternatively, the traits may promote healthier plants so that the ground can sustain a denser stand.

Seeding rate and variety choice decisions are made by farmers at the start of planting season when they face uncertainty. Corn seeding rates play a role in the magnitude of climate-change-induced risks (Aglasan 2020). Specifically, Aglasan (2020) finds that the magnitude of warming-related crop insurance losses becomes more severe at higher seeding rates due to the inter-plant competition for nutrients and moisture. These losses escalate under severe heat stress and higher seeding rates. However, the use of varieties that are potentially more resilient to warming can alleviate such loss increasing effects and so allow for high seeding rates (Aglasan 2020).

Seeding rate choices are also related to environmental concerns that are raised by the widely-used chemical coatings on seeds. The chemical coating can protect the seedling during germination and establishment but may have negative environmental implications (Perry and Moschini 2020). Higher seeding rates will impose a larger chemical load on the environment. For example, neonicotinoids are applied on more than 90% of corn acres (Perry and Moschini 2020) and more than 50% of soybean acres in the United States (Hurley and Mitchell 2017). Although neonicotinoids can reduce crop loss risks, residues from seed-applied neonicotinoid insecticides persist in the soil and water and pose a threat to many non-target plants. These chemicals can have negative effects on the abundance of birds (Li, Miao and Khanna 2020), bees (Rundlöf et al. 2015) and butterflies (Van Deynze 2020). Notwithstanding a literature on the environmental risks of neonicotinoid applications, little is known about the seeding rate choices that determine the amount of these chemicals that enter the environment. Therefore, a better understanding of farmers' seeding rate choices has significant implications for our capacity to appropriately manage farm profits and the environment.

In this paper, we investigate how seeding rate choices respond to market, resource, and technology factors and why corn and soybean seeding rates are different. We first develop a conceptual model of seeding rate choices by incorporating a resource budget trade-off between more seeds and fewer land-based resources allocated to each seed. The seeding rate input is a distinctive choice. While more seed on unlimited land resources should increase yield output, as with other inputs, an increase in the seeding rate rations fixed land and associated resources over more plants. Exogenous shocks have different effects on this trade-off depending on whether these shocks primarily affect plant profitability or resources available per acre. From the perspective of plant architecture, corn varieties have been bred to grow straight and tall rather than branch sideways; while soybeans are short and can readily branch laterally. In comparison with corn, the laterally growing soybean plant is better positioned to expand or contract when seeking to optimally gather sunlight and soil nutrients at varying seeding rates.

To conduct our empirical analysis, we draw on a large, unique farm-level dataset of more than 600,000 U.S. seeding rate choices. The data spans the period 1995-2016 for corn and 1996-2016 for soybean and contains information on the specific hybrid planted, seed price, and farmer-chosen seeding density. We control for unobserved confounders through both hybrid and farm-level fixed effects. We obtain two main findings based on farm-level market data. First, the soybean seeding rate choice is more price elastic than corn. Second, most land endowment inputs increase corn and soybean seeding rates; while seed endowment inputs increase corn seeding rates but decrease soybean seeding rates. In addition, we also collect survey data from representative farmers in three focus group meetings in Michigan and Ohio. These data reveal distinct viewpoints on seeding rate choices and also indicate that farmers rely most heavily on their own experiences when deciding on seeding rate choices. Finally, we develop a rough estimate of how ecological impacts are affected by price changes. We find that targeted tax or price policies will mitigate neonicotinoid-related ecological impacts. Taking grassland birds as an example, a 10% tax on corn (or soybean) seed or decrease in corn (or soybean) price will induce a 0.6% (or 3.6%) increase in the bird population.

Our paper contributes to the literature in the following ways. We are the first to develop a model that considers a resource budget trade-off between more seeds and few resources allocated to each seed. To our best knowledge, no existing work has explored why corn and soybean seeding rates respond so differently to different stimuli. Most previous work that has addressed seeding rate choices has typically done so with one kind of crop and from a purely agronomic viewpoint. Second, our findings also contribute to the literature on input choices and food production. Seed costs are very expensive and account for about 14% of total production costs for corn and about 10% for soybean.[2] Corn and soybean are the two most important field crops and key commodities for food production in the United States and, together with wheat and rice, are among the four most important globally. Our findings highlight features of the seeding rate choices that distinguish between corn and soybean. Third, our paper contributes to the literature

[2] Cost proportion calculations are based on Estimated Costs of Crop Production in Iowa – 2021 at https://www.extension.iastate.edu/agdm/crops/html/a1-20.html.

on agricultural production and environmental risks. Most seeds are treated by chemical coating such as neonicotinoids, so our paper provides a new perspective on mitigating environmental concerns through seeding rate adjustments. Fourth, we explain why seed own-price elasticity of demand for soybean is likely to be more negative than that for corn, our analysis adds to the work by Ciliberto, Moschini and Perry (2019), who estimate a larger absolute value of seed own-price elasticity for aggregate corn seed products than for aggregate soybean seed products and also find that the seed industry extracts more surplus from corn products than from soybean products.

In what follows we briefly summarize the agronomy and economics of corn and soybean seeding rate choices in the United States. Then we develop a model incorporating a trade-off between more seeds and fewer land-based resources allocated to each seed. Next we explain market data, survey data, and other external data that we analyze and we also explain the variables that we construct. We then examine plant bushiness, or plant elasticity, and plant rigidness by seed trials data and also study factors that determine commercial seeding rates. Moreover, we report and analyze the estimation results and further compare them with results from a focus group survey. Further, we conduct a rough estimate on the ecological effects of price changes through seeding rate adjustments. After reporting and analyzing the results, we conclude with a summary and some comments on policy implications.

Background on Seeding Rates

Corn seeding rates have increased dramatically (from about 26,000 seeds per acre in 1995 to about 32,000 seeds per acre in 2016), while soybean seeding rates have declined (from about 181,000 seeds per acre in 1996 to about 157,000 seeds per acre in 2016), which is shown in

Figure 1. These trends are also reflected in the cumulative distribution function (CDF) of seeding rates in some representative years in Figure 2.[3] The CDF lines of corn seeding rates shifted right from 1996 to 2016 while the lines of soybean seeding grates shifted towards the left. The temporal pattern in the national-wide level is also reflected at the state level even though different states have different seeding rates (Figure 3).

In addition to temporal differences, seed rates will differ geographically because higher latitude locations need short-season varieties, more arid locations need drought-tolerant varieties and varieties perform differently on different soils. Corn and soybean seeding rates are known to vary considerably, even in a locality. As depicted in Figure 4, which provides the seeding rates distribution by crop reporting district (CRD) in 2000 and 2016 for both corn and soybean, corn seeding rates were higher in 2016 when compared with 2000 in most districts. For a given year, corn seeding choices varied spatially in the United States, generally being highest in the Cornbelt and Great Lakes Region. By contrast, soybean seeding rates were lower in 2016 compared with 2000 in most districts and were greater in the Eastern Cornbelt and Northern Great Plains than in the Western Cornbelt.

Many researchers have studied corn yield and seeding rate relationships and optimal seeding rate choices (Assefa et al. 2016; Assefa et al. 2018; Lindsey, Thomison and Nafziger 2018; Schwalbert et al. 2018). When considering technology only, corn optimal seeding rates should be determined by interaction effects between genotype (*G*), environment (*E*), and management (Assefa et al. 2016). Complementary management technologies such as insect resistant varieties (Ruffo et al. 2015), increased use of inorganic fertilizer (Ruffo et al. 2015;

[3] Detaied about cumulative distribution function of seeding rates can be found in the Appendix A.

Assefa et al. 2016), irrigation, and enhanced weed and pest control techniques (Assefa et al. 2016) have been found to be critical factors for successfully increasing both plant density and corn yield. However, Assefa et al. (2018) have shown that higher seeding rates do not improve corn yield when they are planted on poor land with inadequate nutrition and water. Similarly, in the more humid parts of the world, research trials show that yield per acre responds positively to plant density but this is not true in arid environments (Haarhoff and Swanepoel 2018).

Many studies have also been conducted on soybean seeding rate choices and yields (Thompson et al. 2015; Ferreira et al. 2016; Corassa et al. 2018). Similar to corn, soybean seed yield potential is also associated with genetic attributes, environmental conditions, and management practices, and their interactions (Corassa et al. 2018). However, soybean plants are more flexible with a wide range of seeding rates. For example, soybean plants can produce more branches and pods at low seeding rates while they can produce fewer branchers and pods at higher seeding rates. Due to this flexibility, soybean varieties can efficiently respond to their environment through branching (Singh 2021).

Genetically engineered (GE) crop varieties play an important role in seeding rate choices and yield potential. GE varieties, first introduced commercially in 1996, exploit the recombinant DNA tools of modern biotechnology (Moschini 2008). These tools are used to insert one or more foreign genes into the plant's genome to express desirable traits. Two sets of attributes, herbicide tolerance in corn and soybeans and insect resistance in corn only, have dominated commercial GE corn and soybean offerings.[4] Herbicide tolerant crops are mostly tolerant to glyphosate, and insect resistance crops embed one or more genes from the bacterium *Bacillus thuringiensis* (*Bt*), which emit proteins that are toxic to certain insects. GE crops were originally offered as single

[4] As of 2021, drought tolerance and other traits have not yet proven to be so popular.

trait varieties, but by 2010 corn seed with multiple GE traits had come to dominate the U.S. seed corn market. Figure 5 presents the diffusion pattern of GE varieties, which have accounted for the majority of U.S. corn and soybean in recent years.

Conceptual Model

We model profit-maximizing crop production, and our calculations will be for one land unit, which we will refer to as an acre. Let $s \in [0,\infty)$ represent seeding rate (i.e., seeds per acre). We consider two technology or resource related inputs: per acre land endowments τ divided across s seeds per acre, and per seed endowments θ. Examples of τ include better quality land and a new drainage technology, which improve resources per unit land area and not per seed. Examples of θ include seed coating or innovations in genetics, which improve resources per seed and not per unit land. Yield per seed is given generically as a function $y(s,\tau,\theta)$, which is decreasing in s and increasing in both τ and θ. With more seeds per acre, the available area and resources will decrease for each plant.[5] Given seeds per acre, endowment inputs will increase yield per seed. This yield function is assumed to be twice continuously differentiable where function derivatives are represented by appropriately subscripted variables. The function is also assumed to satisfy the boundedness constraint $\lim_{s\to\infty} y(s,\tau,\theta)s \to K$ with $K > 0$ for any τ and θ. For the sake of simplicity, germination rate is assumed to be 100%. Yield per acre is, therefore, seeding rate times yield per seed, $Y(s,\tau,\theta) = y(s,\tau,\theta)s$ so that the boundedness constraint merely requires finite limit on yield per acre as seeding rate increases to infinity.

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[5]At a later juncture well will impose the resource budget constraint by setting $y(s,\tau,\theta) \equiv F(\tau / s,\theta)$, but for now we consider only the generic specification.

Price Effects

With price per seed as *w* and output price as *p*, profit per plant is $py(s,\tau,\theta)-w$ and profit per acre (PPA) is

(1) $$\pi(s,\tau,\theta)=py(s,\tau,\theta)s-ws,$$

with first-order optimality condition

(2) $$\frac{d\pi(s,\tau,\theta)}{ds}=py(s,\tau,\theta)-w+py_s(s,\tau,\theta)s=0,$$

and solution s^*. The second derivative of the PPA function is

(3) $$\frac{d\pi^2(s,\tau,\theta)}{ds^2}=2py_s(s,\tau,\theta)+py_{ss}(s,\tau,\theta)s.$$

Notice that, $d\pi^2(s,\tau,\theta)/ds^2|_{s=s^*}=2py_s(s,\tau,\theta)|_{s=s^*}+py_{ss}(s,\tau,\theta)s|_{s=s^*}<0$ with the assumption that $2y_s(s,\tau,\theta)+sy_{ss}(s,\tau,\theta)<0$ for any *s*, τ and θ, so the PPA function is locally concave in seeding rate at any maximum or minimum point. Consequently, there can be only one interior solution s^* to (2) and it must maximize profit. However, profit needs not be globally concave on $s\in\mathbb{R}_+$. Considering (1) further, if $p\lim_{s\to\infty}y(s,\tau,\theta)<w$, then $\lim_{s\to\infty}\pi(s,\tau,\theta)\to-\infty$. Given that the yield function is bounded, it follows that $\lim_{s\to 0}\pi(s,\tau,\theta)\to 0$. If $\pi(s,\tau,\theta)\big|_{s=s^*}>0$, then continuity requires that $\pi(s,\tau,\theta)$ be convex somewhere on $s\in(0,s^*)$.

Returning to first-order condition (2), we have

(4) $$y(s,\tau,\theta)|_{s=s^*}\left[1+\frac{y_s(s,\tau,\theta)|_{s=s^*}\,s^*}{y(s,\tau,\theta)}|_{s=s^*}\right]=y(s^*,\tau,\theta)\left[1+\frac{d\ln[y(s,\tau,\theta)|_{s=s^*}]}{d\ln(s)}\right]=\frac{w}{p},$$

where $d\ln[y(s,\tau,\theta)|_{s=s^*}]/d\ln(s)<0$ as resources per plant decline. Alternatively, as area scales with s^{-1} or $a\sim s^{-1}$,

(5) $$y(s^*,\tau,\theta)\left[1-\frac{d\ln[y(s,\tau,\theta)|_{s=s^*}]}{d\ln(a)}\right]=\frac{w}{p}.$$

Were yield per plant invariant to area per plant then we would have $y(s^*,\tau,\theta)=w/p$. However, just as price per unit declines with an increase in quantity chosen in the monopoly problem we have seeding rate set at a quantity such that $y(s^*,\tau,\theta)=w/p$ whenever yield per plant is insensitive to area available. We take $B(s,\tau,\theta)=d\ln[y(s,\tau,\theta)]/d\ln(a)\in[0,1]$ to be a measure of 'plant elasticity' and $R(s,\tau,\theta)=1-B(s,\tau,\theta)\in[0,1]$ to be a measure of 'plant rigidity'. If $B(s,\tau,\theta)$ is close to 1, so that little yield is lost per acre by scaling back on seeds, then seed use will differ greatly from that defined by $y(s,\tau,\theta)|_{s=s^*}=w/p$. Figure 6 provides a characterization.

One interpretation of (5) is that there are two ways in which seeding rate changes the marginal value of seed. One is to change production per plant, through $y(s,\tau,\theta)$, and the other is to affect responsiveness to the area resource. A parameterization will illustrate. Notice that were $y(s,\tau,\theta)=s^{\varepsilon(\tau,\theta)}$ with $\varepsilon(\tau,\theta)\in(-1,0)$ then $B(s,\tau,\theta)=-\varepsilon(\tau,\theta)$ and $R(s,\tau,\theta)=1+\varepsilon(\tau,\theta)$ where each is independent of seeding rate for this technology. Therefore we can write $R(s,\tau,\theta)=\hat{R}(\tau,\theta)=1+\varepsilon(\tau,\theta)$ for this technology.

When $\varepsilon(\tau,\theta)\approx-1$ then yield per plant is more space elastic but $Y(s,\tau,\theta)=y(s,\tau,\theta)s$ is space inelastic. When $\varepsilon(\tau,\theta)\approx 0$ then yield per plant is insensitive to seeding rate and area available, i.e., the plant is rigid so that responsiveness to the area resource is constant (up to some external effect θ that might include genetics) and only the effect of seeding rate on production per plant matters.

For this technology,

(6) $$y(s,\tau,\theta)|_{s=s^*}\left[1+\frac{y_s(s,\tau,\theta)|_{s=s^*}\,s^*}{y(s,\tau,\theta)|_{s=s^*}}\right]=(s^*)^{\varepsilon(\tau,\theta)}[1+\varepsilon(\tau,\theta)]=\frac{w}{p},$$

and we have optimal seeding rate as

(7) $$s^* = \left(\frac{w}{p[1+\varepsilon(\tau,\theta)]} \right)^{1/\varepsilon(\tau,\theta)} = \left(\frac{w}{p\hat{R}(\tau,\theta)]} \right)^{1/\varepsilon(\tau,\theta)}.$$

Notice that plant rigidity separates the price ratio from the effective price ratio where the effective ratio is larger. When the plant becomes less rigid, or more elastic with respect to space, then the effective price ratio faced increases so that the absolute value of own-price elasticity will increase as the plant becomes more space elastic.

Figure 7 depicts responsiveness at the extreme when $\varepsilon(\tau,\theta) \approx 0$. We see this picture as representing the corn plant (Tian et al. 2011; Andorf et al. 2019) in which yield per acre is very elastic with respect to seeding rate when spare ground is available but inelastic when this ground has been filled. Thus when the input to output price ratio w/p is sufficiently low then the absolute value of own-price elasticity of demand for seed is very low.

Thus, we have our first hypothesis,

Hypothesis 1: H1) For given prices and seeding rate, the more elastic the plant, the more elastic the seed own-price demand curve.

This perspective then supports the idea that the corn seed market is vulnerable to high mark-ups. The infertility of highly productive hybrids curtail the option of saving seed from past harvests and, in addition, farmers cannot respond at the intensive margin to higher prices by spreading seed over larger areas.

External Shocks

We turn next to understanding the effects of an external shock, be it technology shock or change in natural resources available. Given the resource budget constraint $\tau = as$, yield per seed is

$y(s,\tau,\theta) = F(\tau / s,\theta)$, which is increasing in both arguments. We denote $F_1(\cdot) \equiv dF(\cdot)/d(\tau / s) > 0$ and $F_2(\cdot) \equiv dF(\cdot)/d\theta > 0$, while the function as a whole is assumed to be twice continuously differentiable and concave. PPA is $\pi(s,\tau,\theta) = pF(\tau / s,\theta)s - ws$

with optimality condition

$$(8) \qquad F\left(\frac{\tau}{s},\theta\right)|_{s=s^*} - \frac{\tau}{s^*}F_1\left(\frac{\tau}{s},\theta\right)|_{s=s^*} = \frac{w}{p},$$

and cross derivatives

$$(9) \quad \begin{array}{ll} (9a) & \dfrac{d^2\pi(\cdot)}{dsd\tau} = -\dfrac{\tau}{(s^*)^2}F_{1,1}\left(\dfrac{\tau}{s},\theta\right)|_{s=s^*} > 0; \\ (9b) & \dfrac{d^2\pi(\cdot)}{dsd\theta} = F_2\left(\dfrac{\tau}{s},\theta\right)|_{s=s^*} - \dfrac{\tau}{s^*}F_{1,2}\left(\dfrac{\tau}{s},\theta\right)|_{s=s^*} = F_2(\cdot)\left[1 - \dfrac{\tau}{s^*}\dfrac{F_{1,2}(\cdot)}{F_2(\cdot)}|_{s=s^*}\right] \overset{\text{sign}}{=} 1 - \dfrac{d\ln[F_2(\cdot)|_{s=s^*}]}{d\ln(\tau / s)}. \end{array}$$

Derivative (9*a*) asserts that an increase in per acre resources complements seed use and so optimal seed use should increase with an increase in this form of endowments, $ds^*/d\tau > 0$. Derivative (9*b*) cannot be so readily signed. If resources provided to each plant substitute for resources provided to each acre then optimal seed use should increase with an increase in endowment provided per plant, $ds^*/d\theta > 0$. This is because an increase in endowments per plant will then decrease the marginal value of endowments per acre where value can be restored by reducing resources per plant, i.e., increasing seeding rate. More generally, if the marginal value of resources per plant is inelastic with respect to resources per acre then an increase in resources per plant will increase seeding rate. An example where the two resources are likely to substitute is when resources per plant come in the form of genetics to protect against drought and the endowment per acre is soil moisture. Then the drought tolerance trait would provide confidence to the farmer that sharing water endowments over more seed will be beneficial. An example where two resources are likely to complement is when herbicide tolerant seed releases nutrients, sunlight and other land resources that would have been consumed by weeds for use by the plant.

Our second hypothesis is then

Hypothesis 2: H2*i*) The optimal seed rate will increase with an increase in per acre endowments for any plant architecture. **H2*ii*)** Whenever the marginal value of resources per plant is elastic (respectively, inelastic) with respect to resources per acre, then optimal seeding rate will decrease (respectively, increase) in response to an increase in resources per plant.

Both Hypothesis 1 and Hypothesis 2 provide avenues for empirical scrutiny, and it is to testing these hypotheses that we now turn.

Data Description

We first bring together data from several sources to construct a unique farm-year panel dataset, which includes information about seeding rate choices, spatial locations, prices, soil conditions, agricultural practices, and genetic technologies. We also collect seeding rate choice responses from corn and soybean growers and consultants through focus group meetings that occurred in 2018.

Market Data

The main econometric analysis that we perform relies on the TraitTrak® dataset, which contains a large sample of farm-level data for land sown to corn and soybean. The TraitTrak® dataset is constructed by a market research company Kynetec USA, Inc., which collected data from annual surveys from randomly sampled farmers in the United States. The sampled farmers were designed to be representative at the crop reporting district (CRD) level. CRD are USDA-designated groupings of counties with similar geography, climate, and cropping practices. Data collected are reviewed and verified by specially trained analysts to ensure accuracy, high completion levels, internal consistency, and compatibility with external information sources. The unit of observation is land tract level so that each surveyed farmer may report multiple corn and soybean plantings in a given year. Each surveyed farmer was asked to specify their seeding rate, seed trait, seed cost, and genetic technology choices during the previous growing season.

The original dataset reports 442,803 corn seed observations over 1995-2016 and 213,062 soybean seed observations over 1996-2016 across 235 CRDs in 31 states, where each observation is a unique combination of the year, farmer, and seed variety. We also include a tillage variable (i.e., the share of farms with conventional tillage at the CRD level) in some specifications. The tillage data is obtained from another dataset AgroTrak®, which is also constructed by Kynetec. Each plot is identified as using one of three following alternatives: "Conventional Tillage", "Conservation Tillage", or "No-Till". We treat conventional tillage as a distinct category and calculate the share of conventional tillage at the CRD level.[6]

At the time when farmers make seeding rate choice decisions, post-harvest-time market crop prices are not yet realized and each crop's futures prices are used to represent farmers' expectations of postharvest prices. To be specific, we incorporate monthly average pre-planting settlement price in February of each year's December Futures contract for corn (Chicago Board of Trade or CBOT) and November contract for soybean (CBOT).[7]

Location, Soil and Weather Data

Seeding rates differ geographically and so including location variables can capture climate-related effects and spatial variations. Latitude and Longitude coordinates are obtained from the

[6] Details about data screening are available at the Appendix B.
[7] Futures prices for commodities are downloaded from https://www.quandl.com/.

2018 Census U.S. Gazetteer files for counties.[8] Land capability classification (LCC) are from National Resource Inventory files. We use LCC to denote the fraction of land in a county that is best for crop production, namely land capability categories I or II among the eight categories available where only categories I through IV are suitable for cropping. The Palmer's Z (PZ) index measures soil moisture availability for crop growth (Heim 2002) by accounting for evapotranspiration, soil water storage capacity, and precipitation (Karl 1986). National Oceanic and Atmospheric Administration (NOAA) files[9] provide monthly PZ values for climate divisions in the conterminous United States. Each climate division contains multiple counties where some counties overlap with multiple climate divisions. To project these climate division data to the county-level of analysis, we calculate the intersection area between climate divisions and each county and then calculate area-weighted PZ values. Since PZ values have been normalized to zero on average in that location (Xu et al. 2013), we transform PZ values to capture moisture stress from dryness ($PZ \leq 0$, DRY) and wetness ($PZ \geq 0$, WET). Our wetness and dryness calculations are applied to March PZ values, the time when farmers begin to make seeding rate decisions.

Agricultural Practice and Seed Trial Data

Advances in crop management techniques such as increased irrigation area are critical factors for increase in both seeding rate and yield and available irrigation is correlated to water supply for crop growth (Assefa et al. 2016; Brown 1986). We calculate the ratio of irrigated harvested acres

[8] Latitude and longitude information are available at https://www.census.gov/geographies/reference-files/time-series/geo/gazetteer-files.2018.html.
[9] Detailed data are available at https://www1.ncdc.noaa.gov/pub/data/cirs/climdiv/, last accessed June 16, 2021.

to total harvested acres, which is denoted by IR. County-level irrigated harvested acres and total harvested acres are from the National Agricultural Statistics Service (NASS).

Agronomic optimal seeding rates vary with planting dates, and delayed planting would result in an increase in optimal seeding rates for certain varieties (Lindsey and Thomison 2016; Van Roekel and Coulter 2011). We obtain the median planting date (*MPD*) from NASS. We detrend *MPD* and include the deviation of detrended *MPD* from its mean value across all the study period as an explanatory variable.[10] In addition, trial data including information on crop yield, seed treatment, and seeding rate are obtained from seed trial reports or extension reports of land grant universities.[11]

The definitions of variables in the market estimation can be found in Table 1, in which we classify the variables into the following group: seeding rate choices, prices, land endowment factors, seed endowment factors, and other controls. Table 2 shows the corresponding variable descriptive statistics for corn and soybean. Table 3 reports the mean values of yield and area per plant by crop and region in the trial datasets.

Survey Data

We implemented three focus group meetings with corn and soybean growers and consultants in August 2018, during which participants were asked about seeding rate choice responses to precision agriculture technologies. We chose participants who varied in their farm size, soil types and were at various stages of incorporating precision agriculture technology into their farm

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[10] Details on median planting dates are included in the Appendix C.
[11] Detailed information about seed trial reports or extension reports can be found at https://agcrops.osu.edu/on-farm-research and https://webdoc.agsci.colostate.edu/csucrops/reports/corn/cornreport_2018.pdf.

operations. Three meetings were held on August 13 in East Lansing, Michigan, August 20 in Fulton, Ohio, and August 21 in Columbus, Ohio. The meetings were held at university offices and respondents generally resided within 30 miles of the meeting place. Each meeting lasted about 3.5 hours, and about 1.5 hours were required to complete the survey instruments which were available in paper format. A Michigan State University extension educator with a precision agriculture background led a presentation to help participants work through the instrument.

We received 14 responses from East Lansing attendees, 21 from Fulton attendees, and 14 from Columbus attendees. Of the 49 respondents who completed the questionnaire, 37 were operators and 12 were either crop consultants or suppliers. The average operated acres in our sample were about 1,100 acres in Wauseon, 1,800 acres in Columbus, and 3,200 acres in East Lansing, which were much higher than the average operated acres (441 acres) in the United States (USDA-NASS 2019). However, our sample farms were representative because they covered a large proportion of farmland. The 2017 Agricultural Census data reveals that the largest 8% of farms in the United States (1,000 or more acres) controlled 71% of all farmland (USDA-NASS 2019) while most farms in the United States are not commercially viable (Hoppe, MacDonald and Korb 2010). In Table 4 we compare the mean values for each surveyed grower response with average values for growers in the corresponding CRD. Although surveyed growers were younger and had operated farms for fewer years than those in the area, a greater share operated farms as their principal occupation.

The focus group survey provides information about how farmers adjust corn and soybean seeding rate choices when faced with changes in tillage type, planting date, soil moisture, soil quality, chemical treatment, and genetic technology. Moreover, the survey also explored how much impact different market or human influences had on seeding rate choices and what the most important factors were.

Empirical Methods

Plant Architecture Estimation

Based on our measures of plant elasticity and rigidity in the conceptual model, we further explore whether corn and soybean present different plant architectures by examining crop yield responses to area per plant with seed trial data. Letting *y* denote yield per plant *a* denote area per plant, we apply a simple log-log ordinary least squares (OLS) regression model with year-fixed, county-fixed, and variety-fixed effects. The estimation equation is

$$(10) \qquad \ln(y^{l}_{c,t}) = \alpha_0 + \alpha_1 \ln(a^{l}_{c,t}) + \psi_t + b_c + d_v + \xi_{c,t},$$

where *c* denotes county, *t* denotes year, *l* denotes crop (i.e., corn or soybean) and *v* denotes variety. The term ψ_t represents year-fixed effects, which can capture the influence in the aggregate time trends; b_c represents county-fixed effects, which capture some unobserved factors, idiosyncratic to each county; d_v represents variety-fixed effects, which control for some specific factors within each variety; and $\xi_{c,t}$ represents error term.

Market Estimation

After examining the difference in plant architecture between corn and soybean, we turn to explore how crop seeding rate choices respond to price changes, land endowment and seed endowment inputs. The main estimation equation is

$$(11) \qquad \begin{aligned} s^{l}_{i,t} = {} & \beta_0 + \beta_1 PR^{l}_{i,t} + \beta_2 LE^{l}_{i,t} + \beta_3 SE^{l}_{i,t} + \beta_4 AG^{l}_{i,t} + \beta_5 t + \beta_6 LOC_{i,t} + \beta_7 t * LOC_{i,t} \\ & + \delta^{l}_{f} + h^{l}_{v} + \varepsilon^{l}_{i,t} t \end{aligned}$$

where each farm is denoted as i, each farmer who may own one or multiple farms is denoted as f, seed variety is denoted as v, and the time indicator is denoted as t. The dependent variable is $s_{i,t}^{l}$, the seeding rate (thousand seeds per acre) for farm i and crop l in time t. The main independent variables of interest are grouped into several vectors. *PR* is the ratio of observed seed purchase costs over the harvest-time crop contract futures price quoted at planting time. *LE* is the set of land endowment inputs including LCC, WET, DRY, and *TI* (the share of farms with conventional tillage in the total number of farms at CRD). *SE* is a set of seed endowment inputs, such as genetic technologies including *GT* and *Bt* for corn and only GT for soybean. *AG* is the set of agricultural inputs or practices as control variables, which contains the percent of irrigated acres on total harvested acres (IR), the deviation of detrended *MPD* from the average value of *MPD* (PD). *LOC* is the set of location variables including latitude (LAT), longitude (LON).

The remaining terms are farmer-specific effects denoted by δ_f^l, variety-fixed effects denoted by h_v^l, and the error term denoted by $\varepsilon_{i,t}^l$. The presence of farmer-specific fixed effects in the model is intended to control for unobserved factors, idiosyncratic to the farmers, and so account for any omitted variables such as education, age, and other personal characteristics, that are correlated with seeding rate choices. The presence of variety-specific fixed effects controls for the impact of excluded factors that could conceivably affect seeding rate choices but that may be presumed to be reasonably constant within a given variety.

Results and Analysis

In this section, we first present results for plant architecture estimations and compare the difference in plant elasticity and rigidity between corn and soybean. We then present results for market estimations on seeding rate responses to price changes, land endowment and seed endowment inputs. We then turn to comparing market results with farmers' responses from focus group meetings. We also discuss the social factors that affect seeding rate choices. Finally, we conduct a rough estimate of how price changes affect ecological outcomes through neonicotinoid-treated seeds.

Plant Architecture

Table 5 shows the eqn. (10) regression results of plant yield responses to area per plant for corn and soybean in some representative states. Comparing the coefficients of area per plant in log form, we find that soybean yield per plant is more elastic than corn with regard to the change in area per plant, i.e., the soybean plant is more elastic than corn. This finding is consistent with the intuition that soybeans are short and space elastic and can readily branch laterally, while corn is tall and rigid. Compared with corn, the soybean plant can more readily utilize the resources made available with more area, i.e., at a lower seeding rate. The difference in plant architecture among crops provides potential explanations for diverse seeding rate choices. We also test the hypothesis that coefficients of area per plant in the log form equal to one so that does not matter within a range. The null hypothesis is rejected for corn in OH and CO and for soybean in CO at 1% significance level and for soybean in OH at 10% significance level.

Price Effects on Seeding Rate Choices

Table 6 reports eqn. (11) market estimation results for four specifications, each differing by crop and the type of fixed effects included. For each crop we chose as our reference model the estimation with variety fixed effects. We find price ratio (i.e., ratio of seed costs over crop future prices) to be statistically significant with an expected negative coefficient value in all the specifications. Recall that sample average price ratio values are approximately 40.4 and 3.8 for corn and soybean, respectively. Hence, a 10% increase in seed prices or a 10% decrease in corn prices, given the estimated coefficient in column 2, would reduce corn seeding rates by less than 3% of the average seeding rate. By contrast, soybean seeding rates would decrease by 18% of the average seeding rate if there is a 10% increase in seed prices or a 10% decrease in soybean prices, given the estimated coefficient in column 4. This indicates that the demand for soybean seed is more price elastic than that for corn, which supports hypothesis H1 in our conceptual model. We also calculate the seed own-price elasticities by year (Table 7). Although price elasticities change over time, their absolute values are relatively larger in most recent years for both corn and soybean.

Land Endowment and Seed Endowment Effects

In addition to price effects, seeding rate choices are affected by a complex combination of land endowment and seed endowment and other control variables. Land endowment includes better quality land, suitable soil moisture, and beneficial agricultural practices which can improve resources per acre. Seed endowment includes genetically engineered seed varieties adoption (e.g., GT and *Bt*) which will improve resources per seed.

Table 6 also reports seeding rate responses to land endowment and seed endowment. For land endowment, we find that corn seeding rates will be higher on the lands with better qualities, but the effects of land quality on soybean seeding rate choices are not clear. The deviation from expected soil moisture can affect corn and soybean seeding rates. Specifically, severe wetness induces a seeding rate decline for both crops, since too much moisture or flooding can take away valuable plant-available nutrients and organic matters. At the same time, we observe dryness can increase corn seeding rates but it does not have much impact on soybean seeding rates.

Turning to tillage, conventional tillage usually incorporates most of crop residue into soil, and more resources per acre are released compared to conservation tillage or no-till. Estimation results show that a larger proportion of conventional tillage will increase seeding rates for both corn and soybean, which is consistent with our H2*i*. Although conventional grazing can release more resources to land, it could induce soil erosion and soil moisture loss in the long run. There has been a shift away from conventional tillage for soybean, so it is reasonable to see a decline in soybean seeding rate over time. For other agricultural practices such as irrigation and planting date, we do not know their exact roles on seeding rate choices and we include them as control variables.

As stated in the background section, genetically engineered seed varieties have been widely adopted in U.S. corn and soybean production. We find farmers choose lower soybean seeding rates with GT. For corn, we observe farmers increase seeding rates with GT or *Bt* treatment when only farmer-fixed effects are included. This increasing effect disappears after including variety-fixed effects since variety-fixed effects capture the GT and *Bt* impacts. Thus these findings are consistent with H2*ii* in the conceptual model. To be specific, GT corn increases resources per plant by better controlling resource consuming weeds, which will provide confidence to farmers that sharing resources over more seed will be beneficial. As corn is rigid the best way to use these resources is to increase the seeding rate. The soybean plant, however, can expand to consume these resources.

Table 8 compares farmers' seeding rate responses to land endowment and seed endowment across survey data and market data. Representative farmers in Ohio and Michigan differ in some regards with what market data convey. For land endowment, corn seeding rates increased when soil quality was better, soil moisture was higher, and soil varied smaller. Soybean seeding rates increased with higher soil moisture. These seeding rate responses are consistent with our H2*i*. However, soybean seeding rates did not respond to soil quality and variation as expected. We do not observe the increasing effects of more intensive tillage on seeding rates as revealed by market estimations. Turning to seed endowments, corn seeding rates would decrease if insect protection above and below ground trait was changed from yes to no, but seeding rates still increased when chemical treatment was changed from yes to no. For soybean, as expected seeding rates would increase when chemical treatment was changed from yes to no and would decrease when treatment was changed in the opposite direction.

Social Factors of Seeding Rate Choices

Figures 8 and 9 present the most important factors that affect corn and soybean seeding rate choices from the farmers' view, which are also discussed by Hennessy et al. (2021). Farmers rely most heavily on their own experience when making seeding rate choices. The second-order important factors are dealer, agronomy consultant, and university or extension recommendations. Peer farmer experience has little influence on seeding rate choices. Although price changes affect seeding rate choices, surveyed farmers claim that seed prices and crop expected prices are not major drivers in the decision process.

Ecological Effects Resulting from Farmers' Seeding Rate Responses to Price Changes

The use of chemical coating on seeds is known to improve germination (Sharma et al. 2015; Afzal et al. 2020) and also cause negative environmental damages (Rundlöf et al. 2015; Li, Miao and Khanna 2020; Van Deynze 2020). Given that the majority of corn and soybean seeds are coated with neonicotinoids (Hurley and Mitchell 2017), higher seeding rates will impose a larger chemical load on the environment. We develop rough conservative estimates of ecological effects resulting from farmers' seeding rate responses to price changes, by drawing upon values from the literature on neonicotinoid and biodiversity.

An increase in a seed tax or lower commodity price would also reduce acres allocated to that crop and so lower seed demand that way. To simplify the calculation, we assume crop acres will not change due to tax on seeds. In addition, we also assume that the potential tax does not differentiate among different types of seeds, and the tax is applied on general seeds rather than just chemical-coated seeds. Thus farmers' seed choices will not change toward seed without chemical coats.

To calculate how prices affect bird biodiversity through seeding rate and neonicotinoid, we rely on the semi-elasticities with respect to neonicotinoid use as reported by Li, Miao and Khanna (2020). They report the percentage impact of a 100kg increase (which represents a 12% increase on average) in neonicotinoid use on bird diversity measures. The three measures of bird biodiversity applied in their study are (1) bird population, measured by the number of birds observed; (2) species richness, measured by the number of bird species observed; and (3) species evenness, measured by the Shannon index, which takes the relative abundances of different species into account. Based on their semi-elasticities of bird biodiversity on neonicotinoid and our own price elasticity estimates of seed demand, we calculate how seed or crop price changes will affect bird biodiversity.

We find that a tax on seed or a decrease in crop price would increase the population of four groups of birds (Table 9). For example, a 10% soybean seed tax or a 10% decrease in soybean price contributes to a 3.6% increase in the grassland bird population and a 3.0% increase in the non-grassland bird population. This tax or price change also increases the insectivorous bird population by 3.4% and the non-insectivorous bird population by 3.0%. In addition, this price change also leads to an increase in the species richness and evenness of four groups of birds. More specifically, a 10% tax on soybean seed or a 10% decrease in soybean price causes about 0.05% increase in grassland and non-grassland bird species richness (roughly 0.002 species) and a 0.09% increase in grassland bird species evenness (measured by Shannon index).[12] Compared with soybean, a 10% tax on corn seed or a 10% decrease in corn price can also improve bird biodiversity, but the magnitude of effects is smaller.

Conclusions and Discussions

Seed rate choice possesses a distinctive technological feature as reflected by the constraint that resources available to each plant decrease as seeding rate increases. This paper seeks to better understand how farmers make seeding rate decisions, as well as how and why corn and soybean seeding rates trend differently over time. We develop a theoretical model to understand the trade-off between within-plot extensive margin (more plants) and intensive margin (more resources to a given plant), in which we account for how elastic yield per plant is to greater area availability where corn and soybean are very different. With a large sample of farm-level market data and a survey dataset from focus group meetings, we examine how farmers' seeding rate choices respond to market, resource, and technology changes.

[12] The negative effects of neonicotinoid used on species evenness reflects heterogeneous impacts of neonicotinoids on different types of grassland species (Li, Miao and Khanna 2020).

We find that, first, soybean seeding rate choice is more price elastic for corn, i.e., seed companies are likely to have less power in the soybean seed market. Second, our market estimations provide evidence that better soil quality would increase corn seeding rates, and more conventional tillage would increase corn and soybean seeding rates. These findings support our H2*i* that the optimal seeding rate will increase with an increase in per acre endowments. However, the effects of soil moisture on seeding rates are not clear. Third, for seed endowments, we find GT and *Bt* traits will increase corn seeding rates without variety-fixed effects, while soybean seeding rates decrease with GT traits. This finding supports our H2*ii* that optimal seeding rate responses to an increase in resources per plant depend on the elasticity of the marginal value of resources per plant with respect to resources per acre.

Our seeding rate findings have implications in managing farm profits and environmental externalities beyond just documenting the different seeding rate patterns between corn and soybean. Our rough estimates reveal that a tax on seed or a decrease in crop prices has a positive effect on bird biodiversity through reducing seeding rates and mitigating neonicotinoids' adverse impacts, and this effect is more responsive for soybean than corn. Due to limited data availability, we cannot quantify the possible price effects on other neonicotinoid-influenced animals including butterflies, honey bees, wild bees, and mammals. However, adjusting seeding rates through targeted tax or price policies provides a new perspective on managing the ecological risks that neonicotinoids pose for biodiversity, with particularly negative effects directly coming from the consumption of coated crop seeds.

More efforts should be taken to conduct a comprehensive study of seeding rate choices in the future. One matter is that our analysis has not sought to quantify how seeding rate changes would affect social welfare, especially the effects of a tax on seed and economic welfare. Further analysis needs to obtain data on market values and also to conduct parameter calibrations.

A further matter is whether seeding rate choices are affected by behavioral factors since many researchers think that soybean seeding rates chosen by farmers might be excessive for profit maximization (Rees et al. 2019). Discrepancies between our market estimations and surveyed farmers' responses also suggest the farmers may not be fully rational. Some economic inquiries have found evidence that farmers misjudge their input choices, be it for crop insurance (Du, Feng and Hennessy 2017), pesticides (Perry, Hennessy and Moschini 2019), or nitrogen (Babcock 1992; Davidson et al 2011; Passeport et al 2013). These misjudges will lead to inefficiency (i.e. farmers lose some profits) and a better understanding of these behavioral factors will help improve policy designs and restore efficiency.

Externality is another important matter to consider. Some input applications will generate externalities and there will be a welfare loss if all farmers maximize their own profits. Taking nitrogen as an example, fertilizer use should consider the conflict between the need to use nitrogen and the need to protect groundwater quality (Huang and Lantin 1993). The decision will be more complicated when uncertainty about weather or soil nitrogen levels appears (Babcock 1992). Similarly, seeding rate choices also encounter the trade-off between farm profits and ecological risks as well as unpredictable climate and environmental changes. Seeding rates if excessive, especially chemical-coated seeds, have a negative externality. Possible behavioral drivers may provide an opportunity to adjust seeding rates and achieve social optimal.

Figures and Tables

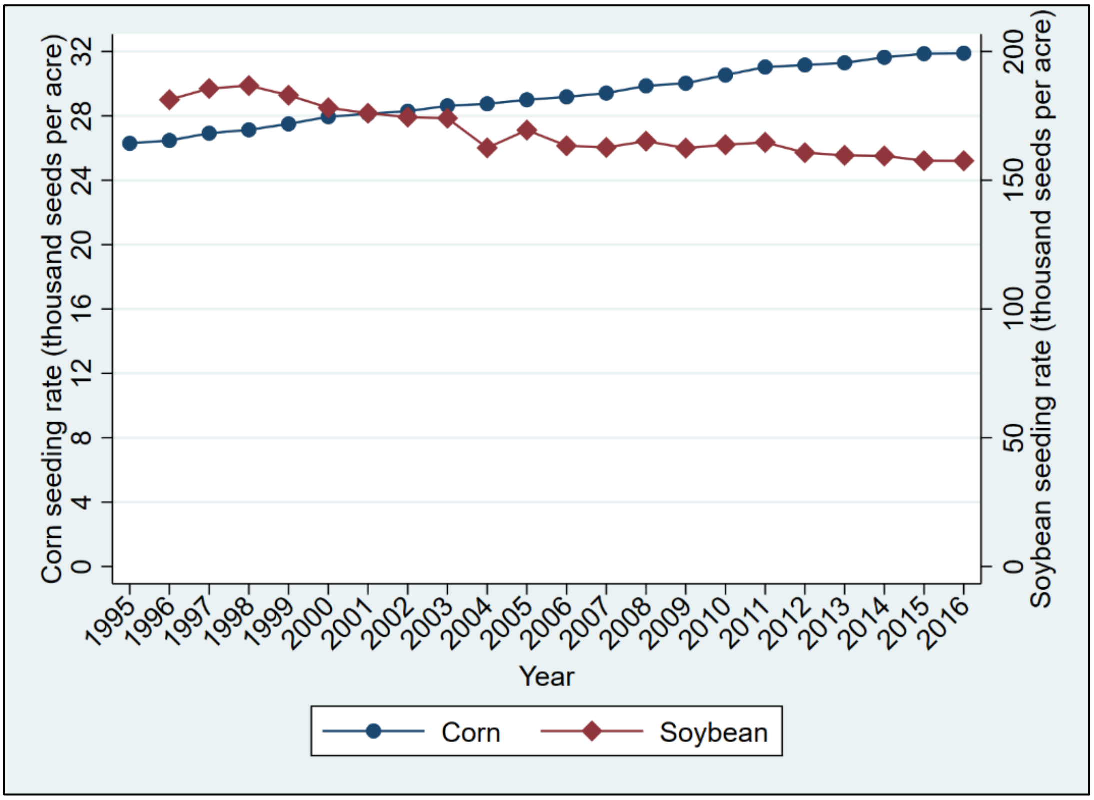
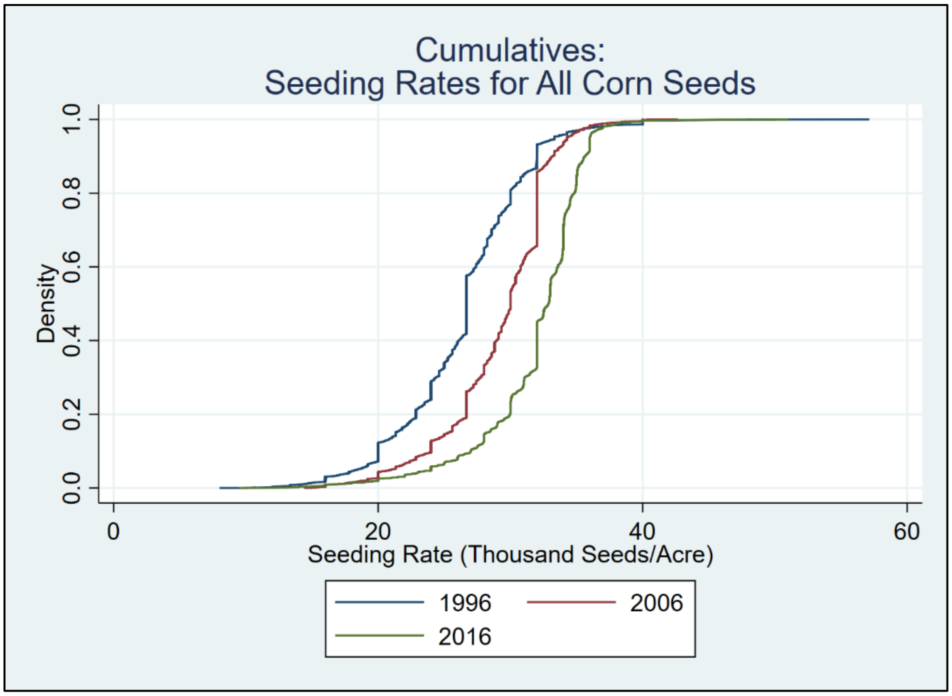
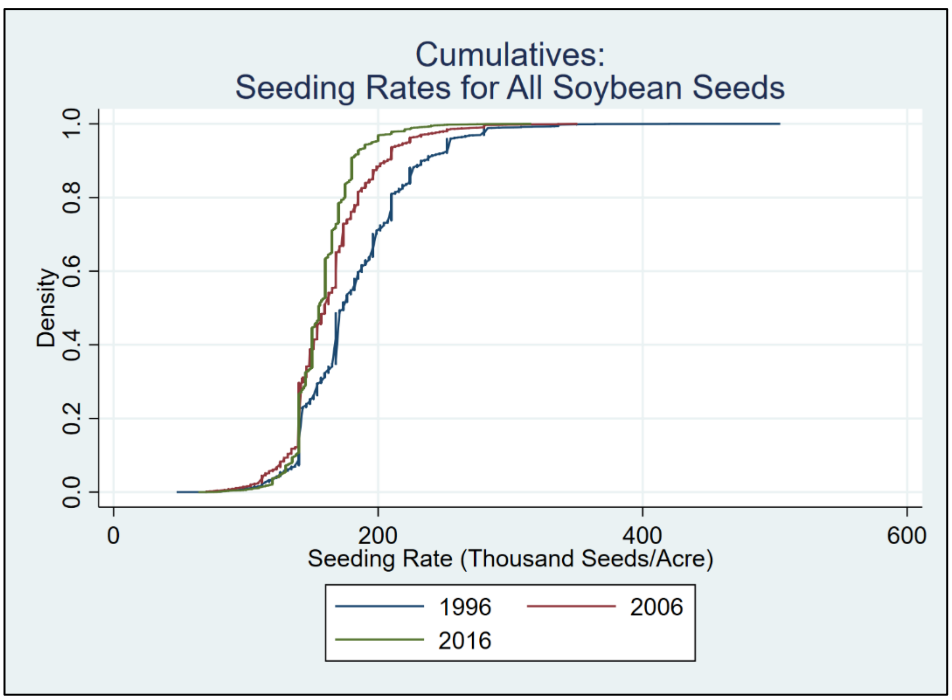


Figure 1 Average seeding rates for corn (1995-2016) and soybean (1996-2016) in the United States (Kynetec data)

Note: In the TraitTrak® dataset, prior to 2010, soybean units are reported in the unit of 50 lb bags, while all soybean units are converted to 140,000 seed bags since 2010. Thus, we convert soybean planting rates prior to 2010 by multiplying 2,800 seed/lb to uniform the measurement scale over 2001-2016.



(a) Corn



(b) Soybean

Figure 2 Cumulative distribution for corn and soybean seeding rates in representative years[13]

[13] Details on cumulative distribution can be found in the Appendix A.

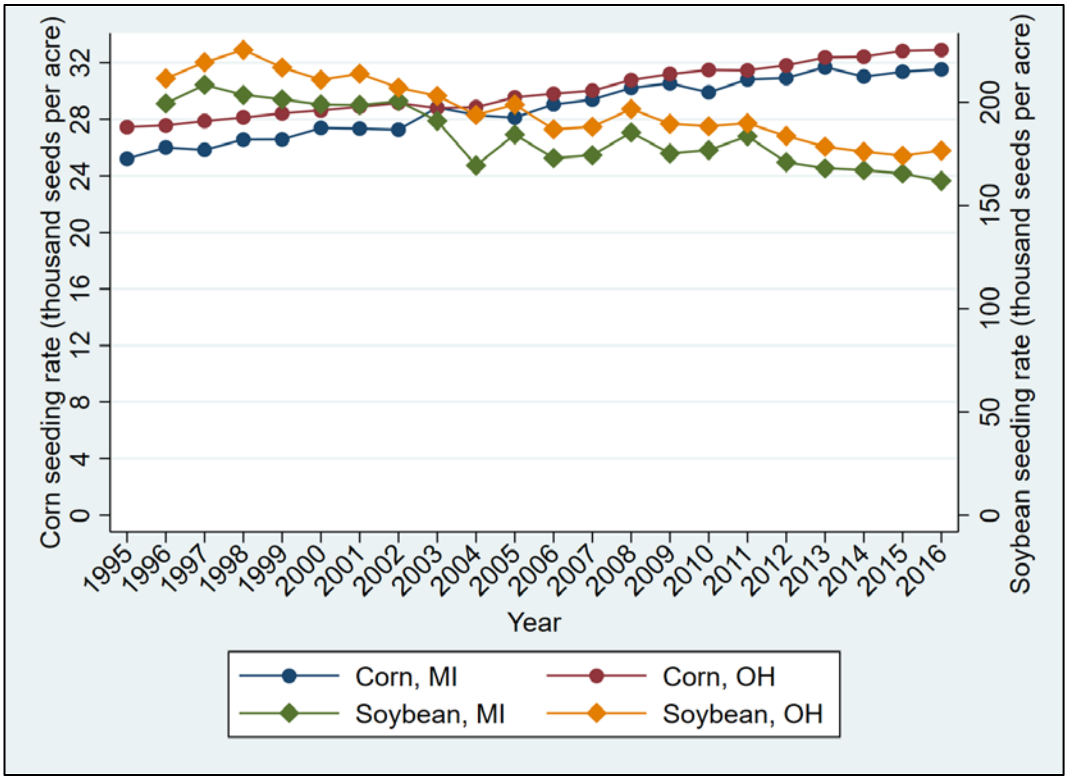
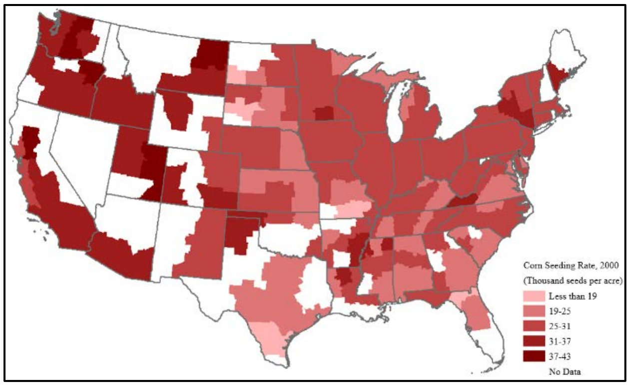
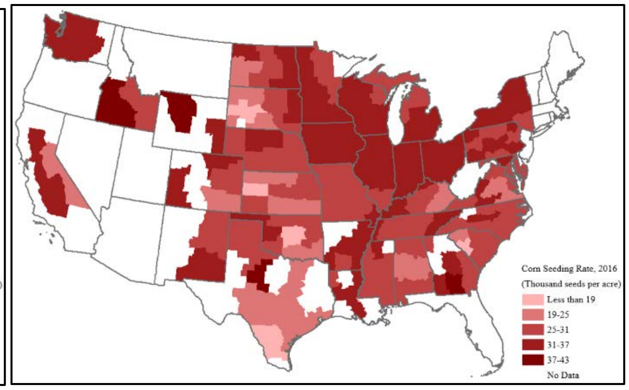


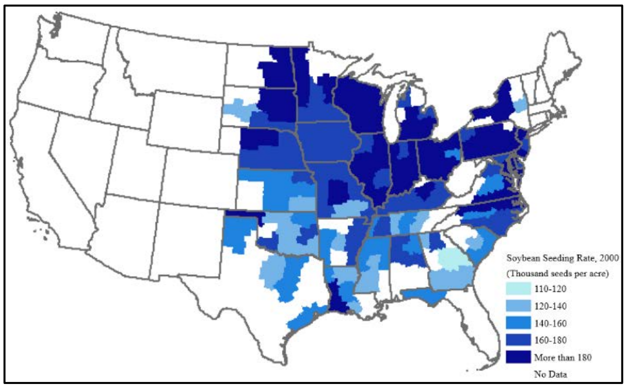
Figure 3 Average seeding rates for corn (1995-2016) and soybean (1996-2016) in Michigan and Ohio (Kynetec data)



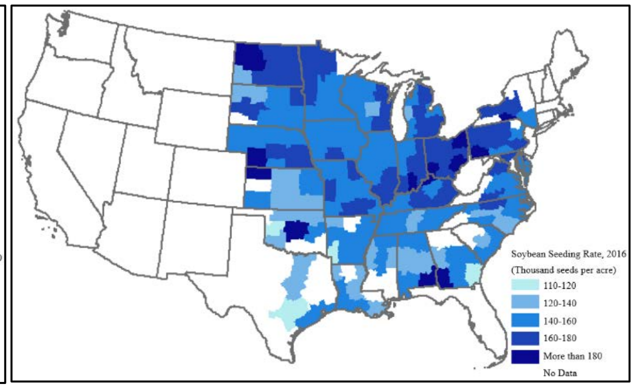
(a) Corn, 2000



(b) Corn, 2016



(c) Soybean, 2000



(d) Soybean, 2016

Figure 4 Seeding rates (thousand seeds/Acre) for corn and soybean by crop reporting district (CRD) in 2000 and 2016 (Kynetec data)

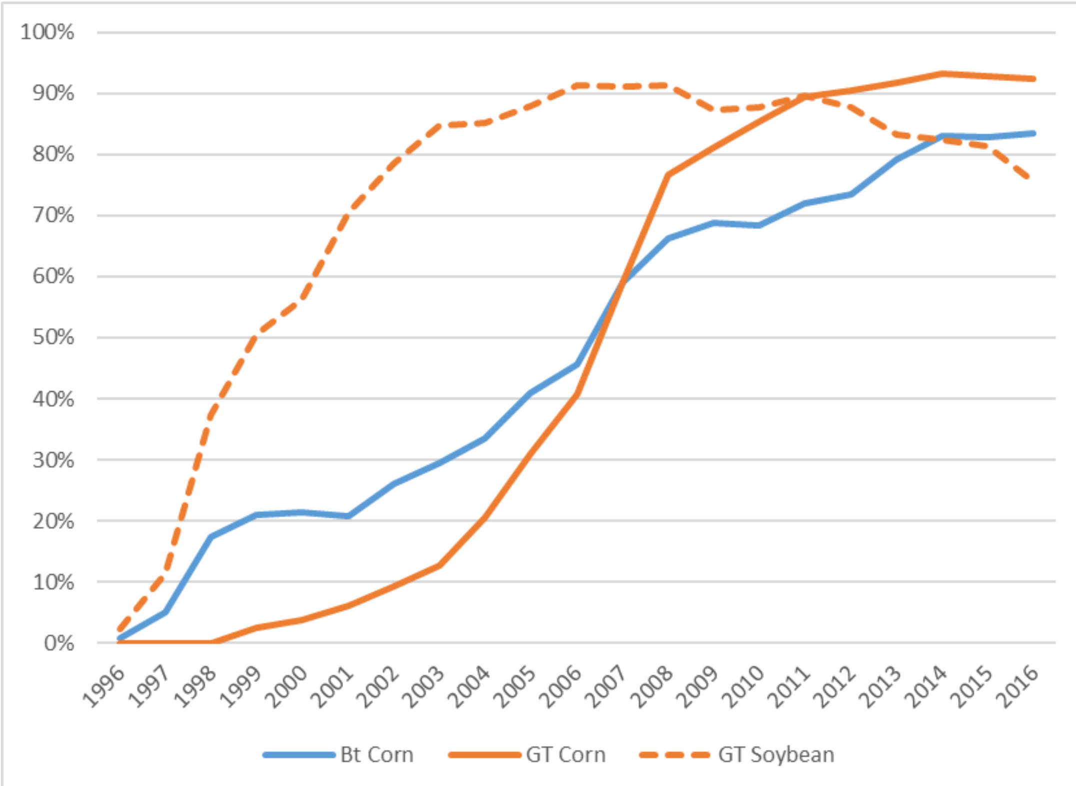


Figure 5 Area percentage of GE corn and soybean in the United States, 1996-2016
Note: Acre percentage is calculated based on Kynetec data. "*Bt* Corn" refers to corn varieties with *Bt* trait alone or in combination with other traits, "GT Corn" refers to corn varieties with GT trait alone or in combination with other traits, and "GT Soybean" refers to soybean varieties with GT trait.

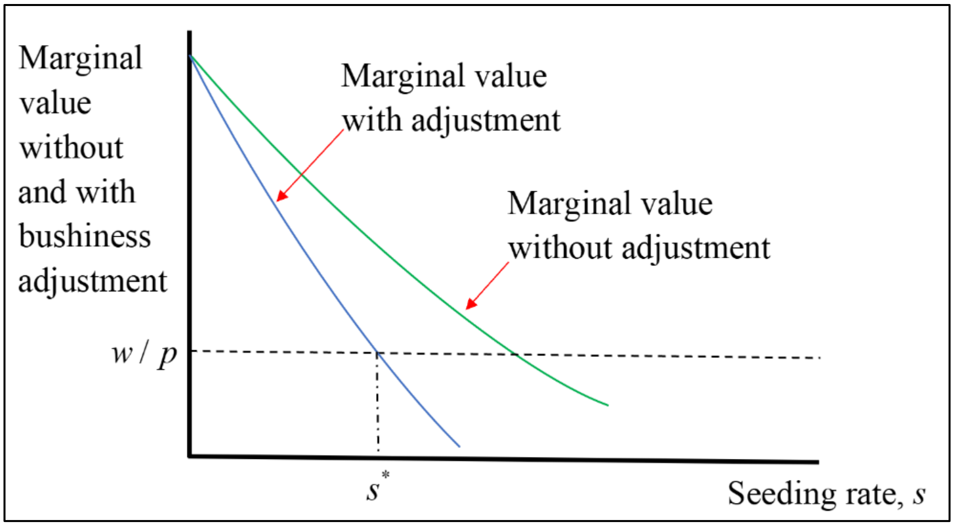


Figure 6 Optimal seeding choice and plant architecture

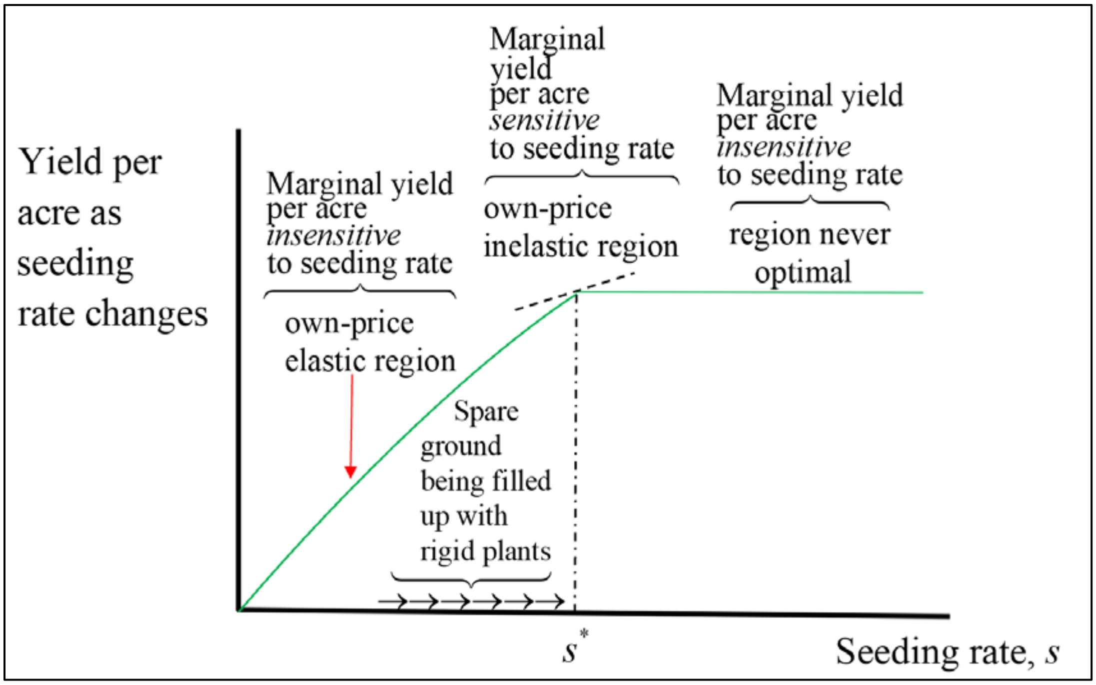


Figure 7 Yield as a function of seed under rigid plant architecture

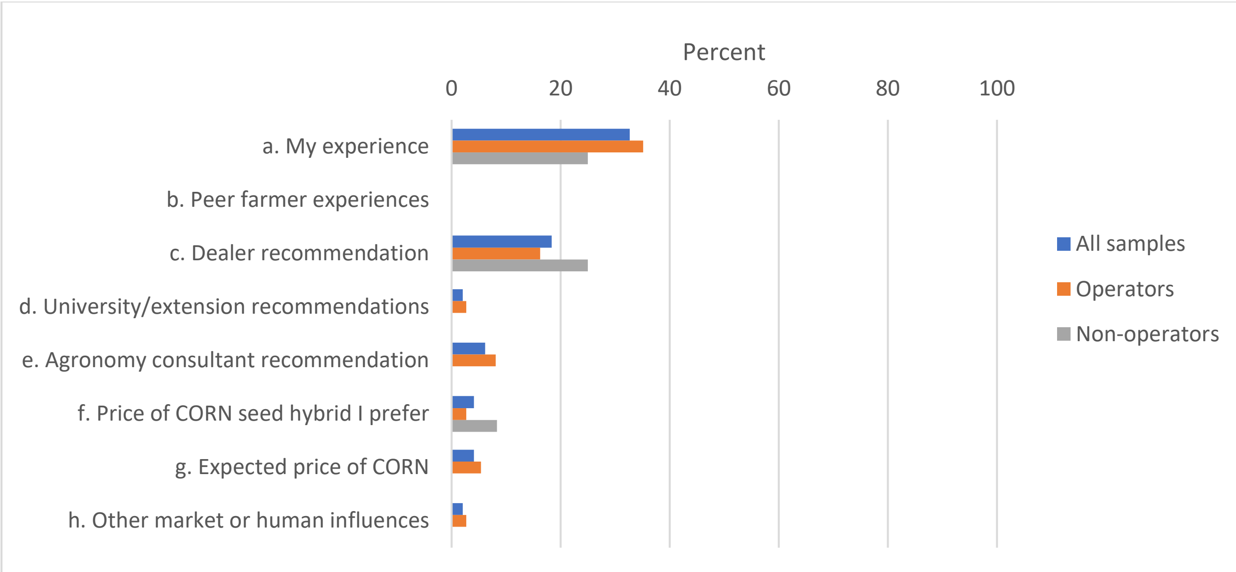


Figure 8 The most important factor that affects corn seeding rate choices from the farmers' view (Survey data)
Note: Fifteen participants did not answer this survey question.

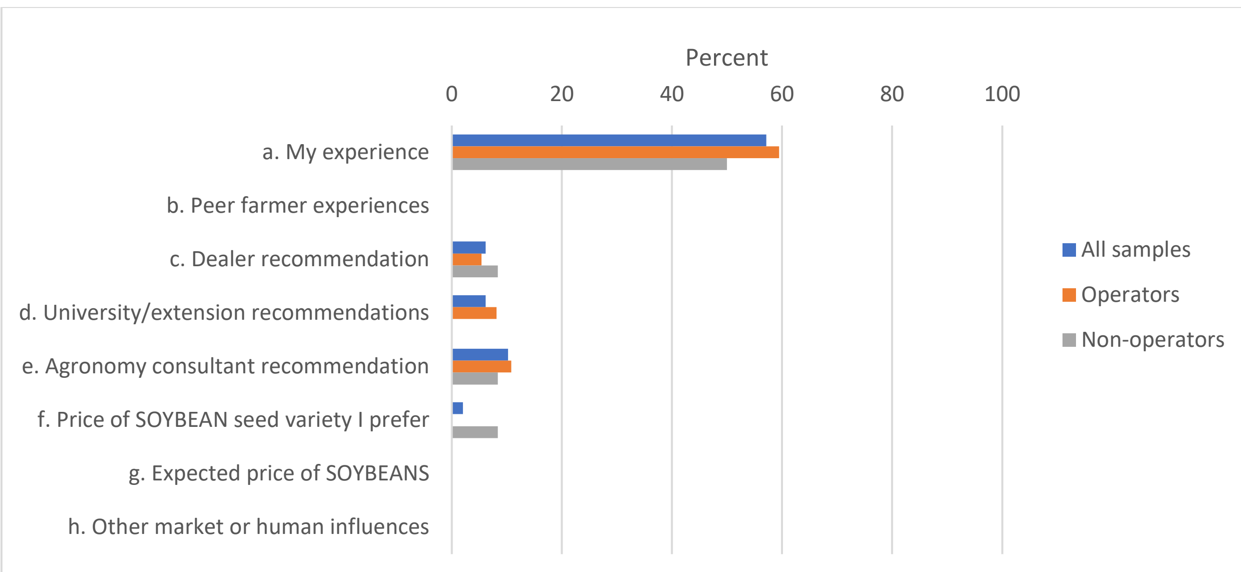


Figure 9 The most important factor that affects soybean seeding rate choices from the farmers' view (Survey data)
Note: Ten participants did not answer this survey question.

Table 1 Definition of variables

Category	Variable	Description	Data Source
Seeding choices	*s*	Seeding rate (thousand seeds per acre)	TraitTrak®
Prices	PR	The ratio of seed costs over crop futures prices	TraitTrak®, Quandl
Land endowment	LCC	The fraction of land in a county that is in land capability categories I or II	NRI
	WET	The maximum among 0 and the Palmer Z in March	NOAA
	DRY	Negative value of the minimum among 0 and the Palmer Z in March	NOAA
	TI	Fraction of farms with conventional tillage by CRD	AgroTrak®
Seed endowment	GT	An indicator function for corn and soybean seeds where GT=1 whenever seed trait is glyphosate tolerance	TraitTrak®
	BT	An indicator function for corn seed where BT=1 whenever seed trait is either rootworm resistant or cornborer resistant or both	TraitTrak®
Controls	IR	The ratio of irrigated harvested acres to total harvested acres by CRD	NASS
	PD	The deviation of detrended median planting date (MPD) from the mean value of MPD during all the study years	NASS
	t	Time trend variable centered at the year 2007	
	LAT	The latitude of a county's internal point, the greater the north towards	Gazetteer files
	LON	Absolute value of longitude of a county's internal point, the greater the west towards	Gazetteer files

Table 2 Variable descriptive statistics

Crop	Variable	Obs	Mean	Std. Dev.	Min	Max
Corn	*s*	403,262	29.532	4.509	8.000	57.143
	PR	403,262	40.405	14.909	0.000	114.490
	LCC	402,807	0.490	0.229	0.000	0.935
	WET	403,262	0.539	0.998	0.000	9.240
	DRY	403,262	0.842	0.960	0.000	5.890
	TI	360,529	0.406	0.187	0.000	1.000
	GT	403,262	0.499	0.500	0	1
	BT	403,262	0.503	0.500	0	1
	IR	401,949	0.121	0.212	0.001	1.430
	PD	383,073	0.097	1.263	-3.053	6.674
	t	403,262	-0.577	6.237	-12	9
	LAT	403,262	41.422	2.699	26.083	48.831
	LON	403,262	91.235	6.365	68.722	124.148
Soybean	*s*	187,776	168.761	34.446	14.000	504.000
	PR	187,776	3.818	1.381	-0.938	9.566
	LCC	187,721	0.506	0.221	0.000	0.935
	WET	187,776	0.521	1.030	0.000	9.240
	DRY	187,776	0.857	0.950	0.000	5.290
	TI	172,829	0.360	0.178	0.000	1.000
	GT	187,776	0.744	0.436	0	1
	IR	187,059	0.070	0.145	0.000	0.822
	PD	181,043	-2.635	1.091	-5.164	1.065
	t	187,776	-0.712	6.110	-11	9
	LAT	187,776	40.879	3.185	28.288	48.828
	LON	187,776	90.864	5.274	73.656	106.352

Table 3 The mean of yield and area per plant by crop and region

Variable	Corn OH	Corn CO	Soybean OH	Soybean MI
Yield per Plant (×1,000)	6.510	6.435	0.455	0.551
Area per Plant (×1,000)	0.033	0.041	0.008	0.009
Seeding rate range (×1,000)	[22, 47]	[8, 37]	[50, 300]	[80, 160]
Obs	113	193	191	516

Table 4 Grower characteristics by location

	East Lansing, MI	CRD 80, MI	Wauseon, OH	CRD 10, OH	Columbus, OH	CRD 50, OH
Mean years as grower	19	25	22	26	26	24
Mean age	46	57	45	57	45	57
Share who farm as principal occupation	0.75	0.41	0.60	0.38	0.50	0.39

Note: In "mean years as grower", we record 15 years for one operator in East Lansing who reported "15+" years, and 12.5 years for another in Wauseon who reported "10-15" years. Area comparisons are from the 2017 Agricultural Census.

Table 5 Regression of yield per plant on area per plant with fixed effects

	Corn OH	Corn CO	Soybean OH	Soybean MI
Variable	Log (Yield per Plant)			
Log (Area per Plant)	0.896***	0.335**	0.970***	0.943***
	(0.0198)	(0.131)	(0.0153)	(0.0108)
Year FE	Yes	No	Yes	Yes
County FE	Yes	Yes	Yes	Yes
Variety FE	Yes	Yes	Yes	Yes
Constant	3.814***	-2.126*	3.471***	3.286***
	(0.210)	(1.203)	(0.187)	(0.127)
Observations	113	193	191	513
R-squared	0.981	0.921	0.985	0.964
	H_0: coefficients of log (Area per Plant) equal to 1			
F statistics	27.89	25.69	3.86	27.61
Prob>F	0.000	0.000	0.051	0.000

Note: Standard errors in parentheses, *** p<0.01, **p<0.05, * p<0.1

Table 6 Regression results with fixed effects for corn and soybean (Kynetec data)

	Corn		Soybean	
	(1)	(2)	(3)	(4)
Variable		*s* (thousand seeds per acre)		
PR	-0.000962**	-0.00203***	-1.106***	-0.758***
	(0.000387)	(0.000470)	(0.0590)	(0.0714)
LCC	1.643***	1.383***	-2.414	0.214
	(0.216)	(0.224)	(3.527)	(3.751)
WET	-0.0148***	-0.0118**	-0.506***	-0.456***
	(0.00535)	(0.00569)	(0.0719)	(0.0779)
DRY	0.0386***	0.0218***	0.0123	0.0659
	(0.00556)	(0.00606)	(0.0826)	(0.0897)
TI	0.0386***	0.0218***	6.564***	3.373***
	(0.00556)	(0.00606)	(0.807)	(0.866)
GT	0.208***	0.312	-3.742***	-4.941***
	(0.0146)	(0.293)	(0.190)	(1.431)
BT	0.156***	0.329		
	(0.0101)	(0.218)		
PD	0.0162***	0.000469	0.356***	0.557***
	(0.00388)	(0.00428)	(0.0694)	(0.0756)
IR	-0.832***	-0.999***	-5.843	-1.431
	(0.266)	(0.284)	(3.999)	(4.483)
t	0.647***	0.313***	-6.605***	-7.145***
	(0.0261)	(0.0338)	(0.351)	(0.519)
LAT	0.0274	0.0744**	0.776	0.319
	(0.0332)	(0.0346)	(0.525)	(0.571)
LON	-0.0858***	-0.102***	-1.407***	-1.015***
	(0.0157)	(0.0171)	(0.289)	(0.312)
*t**LAT	0.00478***	0.0142***	-0.138***	-0.100***
	(0.000529)	(0.000712)	(0.00700)	(0.0109)
*t**LON	-0.00665***	-0.00751***	0.121***	0.110***
	(0.000244)	(0.000279)	(0.00397)	(0.00471)
Farmer FE	Yes	Yes	Yes	Yes
Variety FE	No	Yes	No	Yes
Constant	35.34***	35.02***	272.0***	254.4***
	(1.573)	(1.703)	(29.02)	(31.94)
Observations	342,794	333,237	163,316	157,225
R-squared	0.775	0.796	0.636	0.678

Note: Standard errors in parentheses, *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 7 How seeding rate changes with a 10% increase in seed price or a 10% decrease in crop price

Year	Corn	Soybean
1998	-2.15%	-9.74%
1999	-2.53%	-13.76%
2000	-2.41%	-14.09%
2001	-2.50%	-17.14%
2002	-2.69%	-18.99%
2003	-2.66%	-16.87%
2004	-2.40%	-16.01%
2005	-2.98%	-21.20%
2006	-2.92%	-20.41%
2007	-1.98%	-15.86%
2008	-1.93%	-10.47%
2009	-3.19%	-20.72%
2010	-3.41%	-21.12%
2011	-2.28%	-14.51%
2012	-2.65%	-17.42%
2013	-2.87%	-18.31%
2014	-3.62%	-21.46%
2015	-3.97%	-25.90%
2016	-4.20%	-28.00%

Table 8 How seeding rates choices are affected by different environmental changes or agricultural practices based on regression and survey results

	Environmental changes or agricultural practices	Corn		Soybean	
		Regression	Survey	Regression	Survey
Land endowment	Soil quality was better.	R[a]	R[a]	L	L[a]
	Soil moisture was higher.	L[a]	R[b]	L[a]	R[b]
	Soil moisture was lower.	R[a]	L[b]	L[a]	R[c]
	Soil varied greater.		L[a]		R[a]
	Tillage choice would be changed to be more intensive.	R[a]	L	R[a]	L[a]
	Tillage choice would be changed to be less intensive.	L[a]	R[b]	L[a]	R[a]
Seed endowment	Chemical treatment was changed from Yes to No.		R[c]		R[a]
	Chemical treatment was changed from No to Yes.				L[b]
	Insect protection above ground trait choice was changed from Yes to No.		L[c]		
	Insect protection above ground trait choice was changed from No to Yes.		E		
	Insect protection below ground trait choice was changed from Yes to No.		L		
	Insect protection below ground trait choice was changed from No to Yes.		R		
	GT was adopted.	R[a]		L[a]	
	Bt was adopted.	R[a]			
Other agricultural practices	Planting date was earlier.	R	R[a]	L	L
	Planting date was later.	L	L[a]	R	R[a]
	The share of irrigated acres in harvested acres was greater.	L[a]		L	
	Tile drained was changed from Yes to No.		L		R
	Tile drained was changed from No to Yes.		R[b]		L[b]

Note: L denotes farmers would like to lower seeding rates; R means farmers would like to raise seeding rate; E means farmers would not change seeding rates. Red color means the responses are consistent with our hypothesis. Standard errors are at the significance levels: [a] $p<0.01$, [b] $p<0.05$, [c] $p<0.1$.

Table 9 Price effects on bird biodiversity through neonicotinoid use and seeding rate choice

% change in bird diversity	Grassland bird	Non-grassland bird	Insectivorous bird	Non-insectivorous bird
Due to 10% tax on corn seed or 10% decrease in corn price				
Population	0.6%	0.5%	0.6%	0.5%
Species richness	<0.01%	<0.01%	<0.01%	0.02%
Shannon index	0.02%	<0.01%	<0.01%	<0.01%
Due to 10% tax on soybean seed or 10% decrease in soybean price				
Population	3.6%	3.0%	3.4%	3.0%
Species richness	0.05%	0.05%	0.05%	0.09%
Shannon index	0.09%	<0.02%	<0.02%	<0.02%

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Appendices

APPENDIX A: Cumulative Density Function

We use kernel density estimators to approximate the density function from observations on seeding rates. A kernel density estimator assigns a weight between zero and one sums the weighted values. We apply the kernel of Epanechnikov to determines the weights as it is the most efficient in minimizing the mean integrated squared error (Salgado-Ugarte, Shimizu and Taniuchi 1994). We also graph the empirical cumulative distribution of seeding rates. More kernel density estimates and cumulative distribution of seeding rates in different categories are presented below.

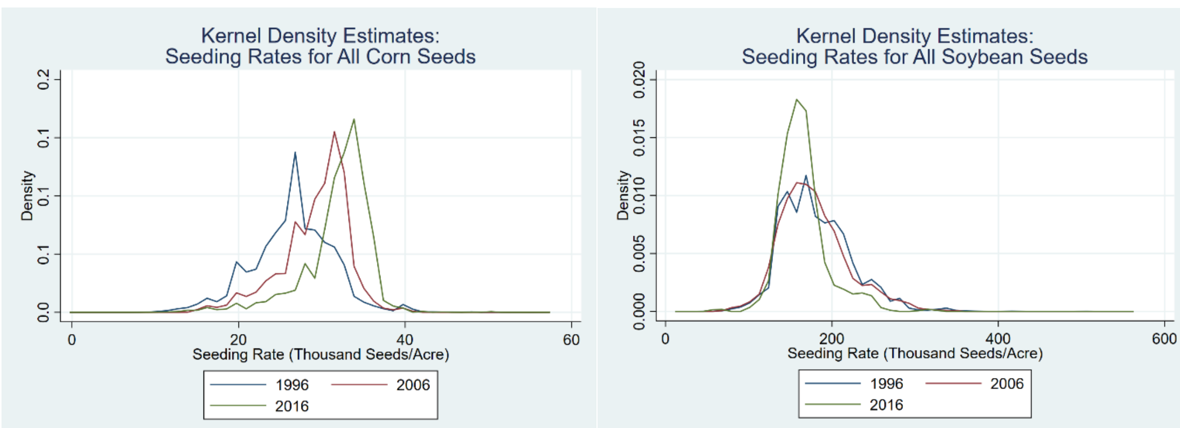

Figure A1 Kernel density estimates for corn and soybean seeding rates

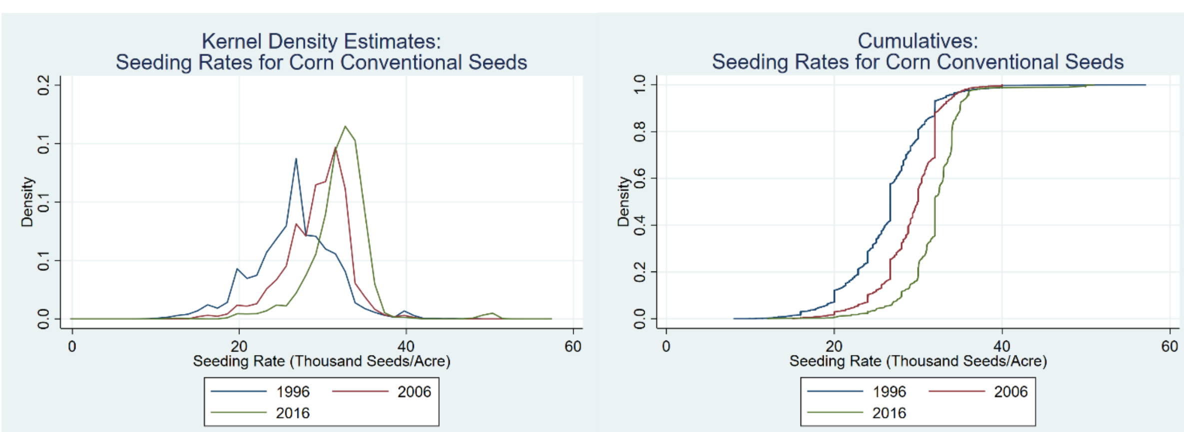

Figure A2 Kernel density estimates and cumulative distribution for corn conventional seeds seeding rates

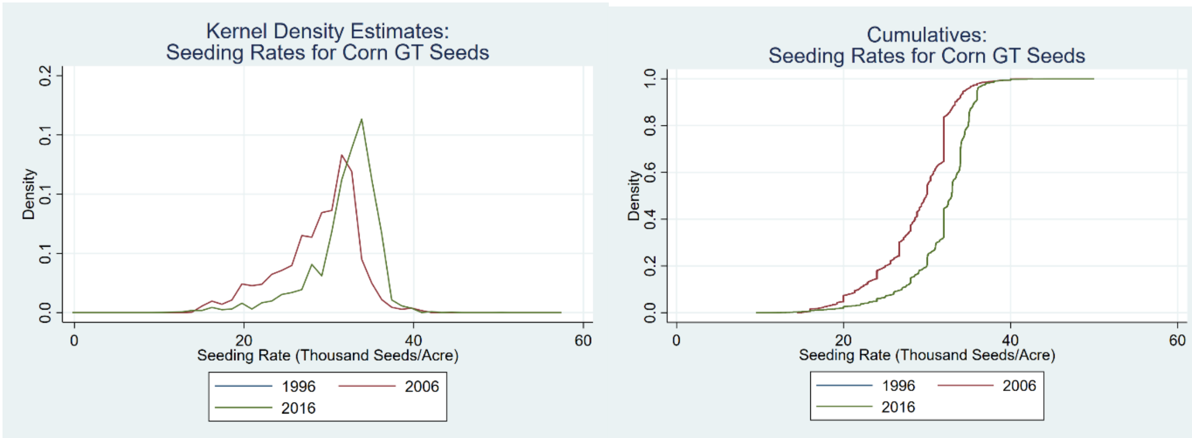

Figure A3 Kernel density estimates and cumulative distribution for corn GT seeds seeding rates

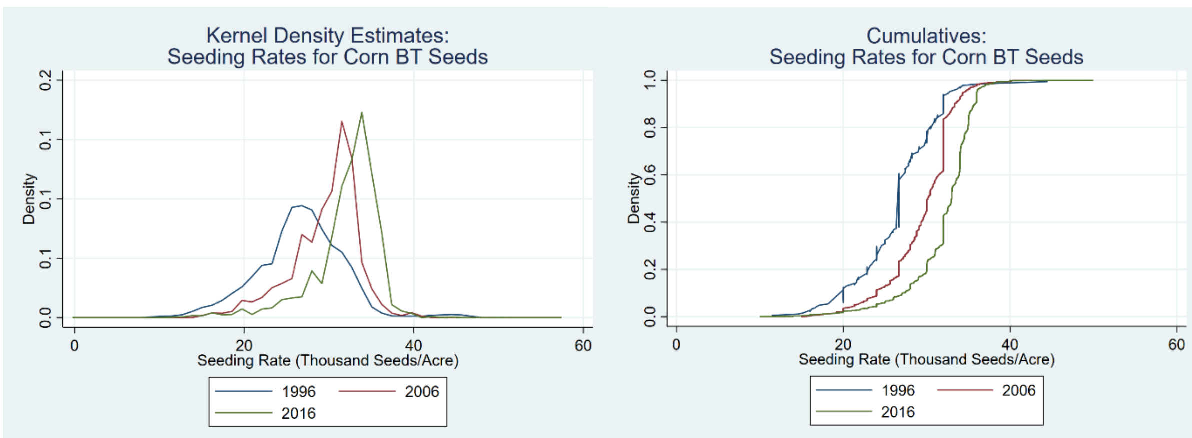

Figure A4 Kernel density estimates and cumulative distribution for corn *Bt* seeds seeding rates

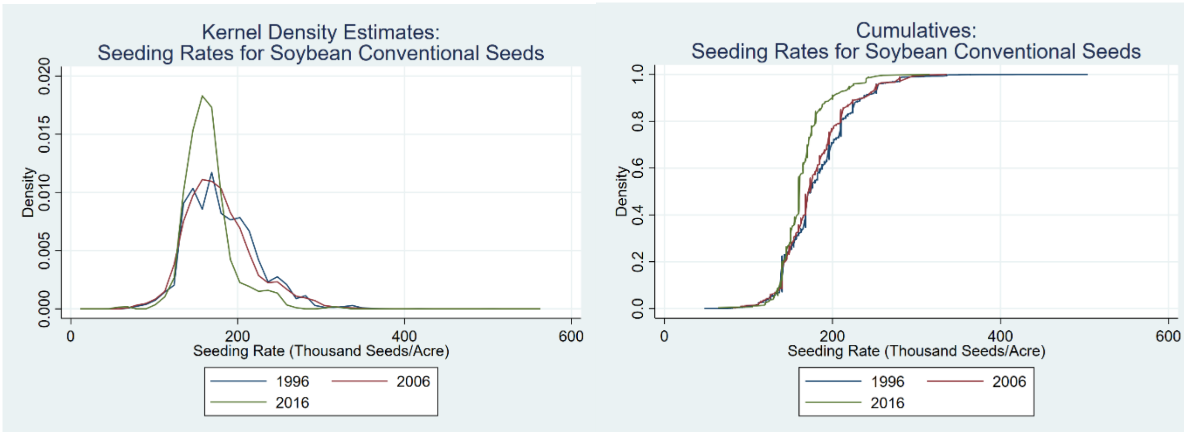

Figure A5 Kernel density estimates and cumulative distribution for soybean conventional seeds seeding rates

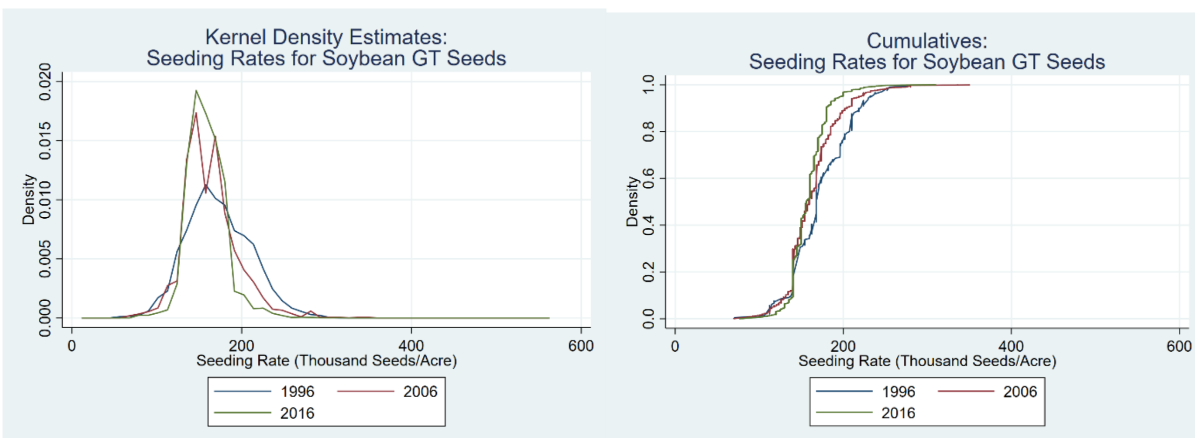

Figure A6 Kernel density estimates and cumulative distribution for soybean GT seeds seeding rates

APPENDIX B: Data Screening

Table B1 Data screening

Summary	Data Screening Details
Original observations	The original dataset reports 442,803 corn seed observations over 1995-2016 and 213,062 soybean seed observations over 1996-2016 across 235 CRDs in 31 states.
Remove observations with zero seeding rate	We remove 66 observations with zero seeding rate for corn. There is no soybean observation with zero seeding rate.
Remove observations with no seed variety identity	Some surveyed farmers did not report the identity of seed variety. We drop these observations because we cannot include variety fixed effects for them. Thus we obtain a reduced sample of 403,262 and 187,776 observations for corn and soybean, respectively.
Limited availability of tillage variable	The AgroTrak® data including tillage information has limited availability over the period 1998-2016, so combining seed and tillage data induces a further reduced sample size of 360,999 for corn and 173,056 for soybean.

APPENDIX C: Detrend Median Planting Date

Let $d_{c,t}$ be median planting date in state *c* and year *t*. A linear trend equation will be estimated as adjusted in Deng, Barnett and Vedenov (2007):

(C1) $$d_{c,t} = \lambda_0 + \lambda_1(2017 - t) + \phi ,$$

where $t \in [1995, 2016]$ for corn and $t \in [1996, 2016]$ for soybean. Then the detrend median planting date is calculated as:

(C2) $$d_{c,t}^{D} = \frac{d_{c,t}}{\hat{d}_{c,t}} \times \hat{d}_{c,2017} ,$$

where $\hat{d}_{c,t}$ is the predicted median planting date. Thus the dates are adjusted to the year 2017 technological level. We then calculate the deviation of detrended median planting date $d_{c,t}^{D}$ from its mean value across all the study period as an explanatory variable in our seeding rate estimation.

APPENDIX D: T-test Results for Survey Questions

Table D1 T-test results of changes in corn seeding rates choices when faced with different environmental changes or agricultural practices

Corn	Environmental changes or agricultural practice changes	All samples		Operators	
		Mean	Pr(T > t)	Mean	Pr(T > t)
Land endowment	Soil quality was better.	0.872	0.000	0.889	0.000
	Soil moisture was higher.	0.128	0.016	0.111	0.052
	Soil moisture was lower.	-0.106	0.971	-0.111	0.978
	Soil varied greater.	-0.192	0.999	-0.194	0.997
	Tillage choice would be changed to be more intensive.	-0.021	0.839	N/A	N/A
	Tillage choice would be changed to be less intensive.	0.149	0.035	0.083	0.162
Seed endowment	Chemical treatment was changed from Yes to No.	0.106	0.067	0.139	0.048
	Chemical treatment was changed from No to Yes.	N/A	N/A	N/A	N/A
	Insect protection above ground trait choice was changed from Yes to No.	-0.081	0.908	-0.077	0.837
	Insect protection above ground trait choice was changed from No to Yes.	0.000	0.500	0.000	0.500
	Insect protection below ground trait choice was changed from Yes to No.	-0.048	0.667	0.000	0.500
	Insect protection below ground trait choice was changed from No to Yes.	0.111	0.297	0.125	0.299
Other agricultural practices	Planting date was earlier.	0.426	0.000	0.361	0.000
	Planting date was later.	-0.128	0.994	-0.111	0.978
	Tile drained was changed from Yes to No.	0.079	0.237	0.069	0.286
	Tile drained was changed from No to Yes.	0.444	0.017	0.571	0.015

Note: To test whether 'raise' exceeds 'lower', we set 'lower' = -1, 'same' = 0 and 'raise' =1. Then we test whether the mean exceeds 0. The following table shows the value of mean and one-tailed p-value for the difference from zero. "N/A" denotes no responses.

Table D2 T-test results of changes in soybean seeding rates choices when faced with different environmental changes or agricultural practices

Soybean	Environmental changes or agricultural practice changes	All samples		Operators	
		Mean	Pr(T > t)	Mean	Pr(T > t)
Land endowment	Soil quality was better.	-0.604	1.000	-0.622	1.000
	Soil moisture was higher.	0.163	0.016	0.135	0.048
	Soil moisture was lower.	0.082	0.052	0.108	0.022
	Soil varied greater.	0.204	0.001	0.216	0.002
	Tillage choice would be changed to be more intensive.	-0.286	1.000	-0.216	0.995
	Tillage choice would be changed to be less intensive.	0.225	0.000	0.162	0.006
Seed endowment	Chemical treatment was changed from Yes to No.	0.364	0.000	0.406	0.000
	Chemical treatment was changed from No to Yes.	-0.750	0.971	-0.750	0.971
Other agricultural practices	Planting date was earlier.	-0.041	0.656	-0.135	0.872
	Planting date was later.	0.408	0.000	0.460	0.000
	Tile drained was changed from Yes to No.	0.108	0.162	0.185	0.067
	Tile drained was changed from No to Yes.	-0.364	0.981	-0.333	0.960

Note: To test whether ‘raise’ exceeds ‘lower’, we set ‘lower’ = -1, ‘same’ = 0 and ‘raise’ =1. Then we test whether the mean exceeds 0. The following table shows the value of mean and one-tailed p-value for the difference from zero.

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