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Abstract: Using the farm tractor as a case study, I show that lags in technology diffusion arise along two distinct margins: scale and scope. Though tractors are now used in nearly every agricultural field operation and in the production of nearly all crops, they first developed with much more limited application, and early diffusion was accordingly limited in scope until tractor technology generalized. The results are consistent with theory and other historical examples, suggesting that the key to understanding technology diffusion lies not only in explaining the number of different users, but also in explaining the number of different *uses*.

JEL Classification: N52, O13, O32, O33, Q16

Keywords: Technology diffusion; Spatial technology diffusion;
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Technology diffusion is widely viewed as a leading explanation for productivity growth and productivity differences across industries, firms, and geographic regions. For example, it is frequently argued that facilitating the diffusion of modern production technologies to manufacturing and agriculture in developing countries is a key to lifting incomes and breaking a cycle of poverty; more generally, diffusion is often considered the fastest path to the technology frontier. Research on technology diffusion has made significant inroads in explaining variation in its scale, treating as fixed the total potential market. Considerably less attention has been paid to changes in scope – the set of potential applications, and thus the size of the market itself – despite that this extensive margin is one of the principal dimensions along which technologies spread.[1]

This paper shows that the historical diffusion of farm tractors – a technology which revolutionized twentieth-century crop production and is a fixture in modern agriculture – was the result of not only an increasing number of users, but also a growing number of *uses.* The tractor first developed for narrow applications with exogenously high demand, and initial diffusion was accordingly limited in scope; only later did tractor technology become sufficiently general to be useful for other purposes, its diffusion broad-based and pervasive. This sequence is consistent with other historical examples and with economic theory, which suggests that R&D will often progress from specific- to general-purpose variants of an innovation, and that these technical advances will directly translate to an increased scope for diffusion. Lags in diffusion can therefore be the consequence of holdups and market failures in R&D that stymie the generalization of existing technology.

The paper opens by reviewing the history of the farm tractor. Here it is useful to first clarify what the tractor is: farm tractors are vehicles that tow and power the agricultural implements that do the day-to-day work of plowing, planting, cultivating, and harvesting crops. Though now used in nearly every agricultural field operation and in the production of nearly all crops, tractors first developed for use in tillage and harvesting grain. Early, fixed-tread models could not navigate row crops without destroying the crop, and this generation of tractor technology was therefore not a candidate to replace draft power on corn-growing farms at *any* price. By the 1930s, however, a more versatile, general-purpose design had emerged, making it possible for these farms to "replace [all] their horses and mules with one general-purpose tractor" (Sanders 2009).

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[1] As Griliches (1957) shows, logistic models of technology diffusion are parametrized by (i) when it begins, and (ii) the rate at which it proceeds. Research on diffusion has overwhelmingly focused attention on the latter, which has been attributed to heterogeneous costs and benefits (Duflo et al. 2008, Suri 2011), fixed costs of adopting an indivisible technology (David 1966, Olmstead 1975), and changes in relative factor prices (Manuelli and Seshadri 2014), as well as to suboptimal decision-making due to credit constraints (Clarke 1991), information spillovers (Conley and Udry 2010, Dupas 2014, Munshi 2004), and individual biases (Duflo et al. 2011).

The era of the tractor in U.S. agriculture begins in the late 1910s, prior to which diffusion was effectively zero. Using serial numbers and production data from the four major manufacturers of this period, I first verify that fixed-tread models dominated tractor production up until the early 1930s, accounting for 96% of tractors manufactured from 1917 to 1928 and 91% through 1932. During the 1930s, the industry made a near-complete transition to general-purpose models, which comprised over 85% of units produced between 1933 and 1940.

I then use county-level data from the U.S. Census of Agriculture to show that the initial wave of tractor diffusion in the 1920s was concentrated in the Wheat Belt states of North Dakota, South Dakota, and Kansas, while a second wave from 1930 to 1940 was concentrated in the Corn Belt states of Iowa, Illinois, and Nebraska. This sequence is plainly visible in maps of wheat versus corn intensity and diffusion (Figure 1). Numerically, I find that county-level diffusion from 1925 to 1930 was 0.4 percentage points greater with every percent of farmland in wheat but did not vary with farmland in corn. Between 1930 and 1940, the pattern is precisely reversed. The results are robust to a wide variety of controls, sample restrictions, and definitions of diffusion – establishing that they are not the result of changes in farm sizes, local factor prices, financial conditions, New Deal relief, the Dust Bowl, the contemporaneous diffusion of hybrid corn, or other features of Midwest agriculture that may have affected tractor demand during this period.

The question remains as to why the tractor's development followed this sequence, and why general-purpose models were late to develop. To put structure around this phenomenon, I propose a model of innovation where firms invest in R&D in specific- and general-purpose technological attributes. The model builds on the theoretical framework developed by Bresnahan and Trajtenberg (1995) to characterize general-purpose technologies, while introducing endogenous product development. This model intuitively predicts that product features will be developed in the order in which they are most valuable, implying that new technologies will often first be invented for narrow, high-value applications and only later – if at all – generalize for broader use. However, complementarities between the given technology and other innovations can drive a wedge between the private and social returns to investing in a general-purpose variant, and inventing firms can therefore be under-incentivized to invest in expanding the scope of their technology to new domains.

Indeed, the narrative record suggests that the leading manufacturers of the era made a limited effort to invent a general-purpose model: International Harvester executives nearly pulled the plug on its R&D program, and Ford appears to have had no such program at all. The stakes are not small: the estimates suggest that had early tractor models diffused as quickly to corn-growing regions as to wheat-growing regions, aggregate diffusion in the Midwest would have been 25.7% greater in 1930. Back-of-the-envelope calculations suggest this increase would have generated annual labor savings equivalent to 10.2% of contemporary Midwest agricultural employment – the value of which, inflated to the present, is roughly 1.2% of current Midwest agricultural GDP.

Tractors have a rich history as the subject of studies in technology diffusion. Early contributions focused on fixed costs as a barrier to tractor diffusion (e.g., Ankli 1980), following the tradition of David (1966). Though recent research has emphasized the importance of factor price changes and quality improvements to explaining aggregate diffusion (Manuelli and Seshadri 2014), the literature is missing a crucial part of the story: tractor quality historically varied as much if not more across space as it did over time. Indeed, its significance today is the consequence of not only its mechanical efficiency, but also its versatility as a source of mechanical power in agriculture.

Though tractors are inherently important, the example serves to highlight scope as an economically significant but under-studied margin of technology diffusion: the idea that diffusion may be propelled by expanding capabilities, rather than uniform price or quality changes, is intuitive yet largely absent from this literature. A related line of work has introduced the idea of "appropriate technologies" to growth models as an explanation for uneven diffusion (Basu and Weil 1998), and the possibility of a mismatch between technological requirements and local factors of production (Acemoglu and Zilibotti 2001, Caselli and Coleman 2006). Yet in these papers, technologies are fixed, and countries adopt newly appropriate technologies as they develop (e.g., as skilled worker share or capital intensity increases). In the present paper, I instead show that technologies themselves can endogenously evolve from being narrowly to widely appropriate.

A natural implication of these results is that in addition to studying the population of users, researchers and policymakers should also focus attention on the firms performing R&D that increases the scope of existing technologies such that they can be used more broadly. Given the presence of externalities that decouple private returns to R&D from social returns, a second implication is that investment in technological generality may be a high-value target for R&D policy tools. The results of this paper might also be able to explain previously-documented spatial patterns in technology diffusion, such as the evidence from Comin and Hobijn (2004) that technology diffusion "trickles down" from more- to less-developed economies and from Keller (2002) that R&D spillovers appear to decline with distance: new technology is often first developed in more advanced regions and in many cases would have to be adapted to conform to local conditions, users' needs, and technology standards in other parts of the world in order to penetrate these markets.

The paper is organized as follows. In Section 1, I review the tractor's history from the 1890s to the 1940s. Section 2 describes the data, the sample, and the empirical strategy. Section 3 provides descriptive evidence that tractors diffused in sequence to wheat- and then corn-growing regions of the Midwest. Section 4 formalizes the relationship between crop intensities and tractor diffusion and presents a battery of robustness checks. In Section 5, I introduce the model, relate it to the history and the evidence, and discuss its implications. Section 6 considers the effects of accelerated generalization for Midwest agriculture. Section 7 concludes.

1 History of the Tractor

The modern tractor's history begins around 1870 with the invention of the steam tractor, which was effectively little more than a steam engine on wheels. These were equipped with a drawbar for towing portable implements and a belt pulley to power stationary equipment, and were primarily used for plowing and post-harvest threshing, with little portable use beyond tillage. They were also heavy, expensive to purchase and maintain, and prone to mechanical failures and explosion. Kerosone tractors succeeded steam models around 1890 but were similarly deficient.

Given their immense size, cost, and unreliability, these early models were never a serious threat to farms' dependence on draft power, and tractor diffusion was effectively zero prior to 1910 (Figure 2). The transition to small, lightweight, affordable tractors occurred in the 1910s, culminating in the development of a new standard-bearer, the Ford Fordson, in 1917.

[Figure 2 about here]

The Fordson was the first commercial hit in the tractor industry, and by all accounts – including Figure 2 above – it marked the beginning of the tractor era. By the end of 1918, Ford had overtaken its competitors in sales (Leffingwell 1998), and by the early 1920s, the Fordson accounted for 75% of all tractor sales in the U.S. (Leffingwell 2002). By the time Ford ended production of the Fordson in 1928, it had sold nearly half of *all* tractors sold in the 1920s (White 2010).[2]

The advantages of the Fordson were its size, agility, and low price, but its low clearance made it impractical for cultivating row crops such as corn or cotton, leading manufacturers to separately

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[2] Other sources agree with White's (2010) assessment: Gilbert's (1930) survey of four agricultural regions in New York in 1926 revealed that 54.7% of tractors used on surveyed farms were Fordsons.

develop and sell expensive, standalone cultivators (Sanders 2009) and Corn Belt farms to continue relying heavily on draft power. Contemporary observers remarked that "The possible market for tractors ... in the corn belt has hardly been scratched, for study reveals that only about six percent of the farms in these six states have tractors, while the other ninety-four percent still depend on horses for power" (Iverson 1922). The alleged "logical solution" was to "design a tractor that will do cultivating as well as plowing, disking, dragging, and other drawbar work."

Despite the large potential demand for a general-purpose model, they were slow to develop. In the words of one International Harvester (IHC) engineer, "there was talk about a new kind of tractor in the industry" at the end of the 1910s, but "no one had such a machine or even much of an idea on how to start building one" (Klancher 2008). Nevertheless, IHC took the lead in developing a general-purpose model. The first references to this project in IHC records appear in 1919, but it took many experimental prototypes, each built at considerable cost, to arrive at a commercially viable product. By 1921 executives were unenthusiastic about the odds of success and voted to pull funding; the project was saved only by executive action of the firm's president.

Other leading firms, including Ford, made no such effort – such that when IHC broke through with the Farmall in 1925, it quickly cornered the market. The Farmall had high clearance and adjustable-width treads for use in all of plowing, cultivating, and harvesting, with both row crops and small grains. It also had a more powerful engine, a belt pulley to power stationary equipment, and a motor-driven shaft that could power implements (power take-off). As Sanders (2009) describes it, "It was designed (and thus named) to accomplish all of the power needs on the farm. At last, farmers could replace their horses and mules with one general-purpose tractor."

The Farmall ushered in a new generation of tractor technology as competitors rushed to imitate the Farmall's design and develop their own general-purpose tractors. John Deere came out with a version in 1928, and Allis-Chalmers in 1930, but by that point the Farmall was already dominant, having overtaken Fordson sales in 1927/28. Further advances in tractors soon followed: in 1927, Deere invented the power lift for raising implements during turns – an enervating and time-consuming task; in 1931, Caterpillar built the first diesel-engine tractor; in 1932, Allis-Chalmers introduced pneumatic rubber tires that improved fuel efficiency and forward horsepower; and in 1938, Ford introduced the Ferguson three-point hitch for attaching implements, replacing the drawbar. Manufacturers quickly made these features standard, and by the early 1940s the industry had arrived at a dominant design: the main features of the modern tractor had been set. Over the following decades, general-purpose tractors "would change little, except for increasing in size and horsepower" (White 2010) and adding comfort and safety features.

Production totals confirm the historical narrative. Table 1 shows total production of fixed-tread and row-crop tractors by the most important manufacturers of the era (Ford, IHC, Deere, Allis-Chalmers), which collectively produced 80% of all tractors in each of the 1920s and 1930s (White 2010). These production counts are imputed from model-specific serial numbers that uniquely identify each manufactured unit. Serial numbers were gathered from various sources (see table notes), which provided the first and last numbers stamped for each year of production. The sample covers nearly all models manufactured by these firms from 1917 to 1940.

[Table 1 about here]

The table shows a clear transition from fixed-tread to general-purpose tractors between 1917 and 1940. Nearly all units produced from 1917 to 1924 were fixed-tread Fordsons, but following the Farmall's release in 1925, fixed-tread models' share of production began a gradual but permanent decline, as general-purpose purpose models grew from 0% to roughly 90% of all units manufactured by 1940.[3] In short, this paper argues that this technological transition is responsible for the ensuing broad-based diffusion of tractors across the U.S. Midwest.

Previous Research on Tractor Diffusion

Though a large body of research has studied the historical diffusion of tractors and other agricultural technologies, the distinction between scale and scope is missing from this literature. Most research treats the tractor as a product of uniform quality over time and across space and attributes lags in diffusion to fixed costs with indivisibility, credit constraints, or exogenous factor price changes. Even when the existing literature recognizes that "a 'tractor' in 1960 is not the same capital good as a 'tractor' in 1920" (Manuelli and Seshadri 2014), it tends to overlook the fact that tractor quality varied as much or even more in cross-section as it did over time.

David's (1966) study of antebellum reaper adoption introduced the neoclassical threshold model to this literature, asserting that reaper diffusion was driven by increasing farm sizes (scale economies). Olmstead (1975) questions the assumption of a static, indivisible technology, showing that joint ownership and contract work were common practice and that reapers were improving over time, and

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[3] Note that although 214 prototype Farmalls were manufactured by IHC in 1924 and given serial numbers, and thus appear in the table for that year, commercial production only began in 1925.

suggests that farm size was in fact simultaneous with the adoption decision. Ankli and Olmstead (1981), Clarke (1991), White (2000), and others have nevertheless attempted to calculate adoption thresholds for tractors in order to explain its delayed diffusion, despite the well-known critiques of David's (1966) model. Myers (1921) and Gilbert (1930) lend support to both advocates and critics of the threshold model, acknowledging that "the advantages of a tractor increase with [the] size of the farm" while also pointing out that contract work was common and that tractor adoption led farms to expand: "the ability to do more work with the tractor resulted in an increase in the amount of land worked on nearly one-third of the farms visited" (Gilbert 1930).

Clarke (1991) argues that financial barriers slowed tractor diffusion in Illinois and Iowa in the 1920s and that New Deal relief – rather than changes in farm size, factor prices, or technology – was responsible for a surge in diffusion in the 1930s. To support this claim, Clarke first calculates a 1929 adoption threshold of 100 acres for farms in Corn Belt states. Clarke then finds that only about half of the farms above this threshold owned a tractor in 1929, and that this gap narrowed over the subsequent decade. After correlating "underdiffusion"[4] with farmers' cash holdings and mortgage debt ratios and obtaining coefficients with the expected signs (negative and positive, respectively), she attributes the growth in diffusion to New Deal price supports and lending programs that might have improved Corn Belt farmers' financial positions and borrowing conditions.

Would-be adopters would have had to be credit-constrained for New Deal policies to cause a surge in tractor purchases. Yet farms in North and South Dakota were leading adopters of tractors in the 1920s, despite the post-WWI collapse in wheat prices and mortgage foreclosure rates near 50% (Alston 1983, Table 1). White (2000) further notes that "the same farmers that Clarke concluded might not have been able to obtain a loan for a tractor were cheerfully buying automobiles for cash" before 1930: roughly 80% of farms in Midwest states owned automobiles at that time, compared to only 25% owning tractors. The difference was not for a lack of manufacturer credit, as both Ford and IHC provided financing to their customers. Given these inconsistencies, the evidence that liquidity constraints can explain diffusion lags in the Corn Belt is questionable, though financing undoubtedly plays an important role in large equipment purchases.[5]

Manuelli and Seshadri (2014) counter the claim that tractor diffusion was inefficiently slow due to market imperfections such as credit constraints with the more traditional argument that exogenous

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[4] Defined in Clarke (1991) as the fraction of farms above the 100-acre threshold without tractors.

[5] Clarke's regressions also suffer common econometric shortcomings, as adoption thresholds are simultaneous with financial conditions: an increase in interest rates will necessarily raise the threshold, generating a mechanical decline in diffusion among 100+ acre farms, as farms just over 100 acres will no longer be in the adoption zone. Large and small farms may also be differentially likely to be mortgaged, an additional source of simultaneity.

changes in factor prices and improvements in tractor quality over time can rationalize the tractor's allegedly "slow" diffusion. Accounting for the tractor's improving quality over time is an important contribution, yet by modeling aggregate diffusion and ignoring variation in quality across space, it misses a crucial part of the story: tractors hardly diffused to farms growing row crops before the 1930s because they could not replace draft power *at any price*. Treating the tractor's quality as a unidimensional parameter that follows a secular process over time and using it to explain the scale of diffusion in the aggregate belies the true nature of the problem.

2 Data and Empirical Strategy

The paper draws on a panel of 1,059 counties in the U.S. Midwest from 1925 (the earliest date for which county-level diffusion data are available) to 1940, with the baseline sample restricted to the 1,035 counties whose borders were unchanged from 1910 to 1940.[6] The Midwest led the country in tractor adoption through WWII and exhibits sufficient spatial variation in diffusion early in the tractor era to be able to identify its expanding scope. The Midwest also spans the principal grain-producing counties in quantity and value, making it of inherent interest.

The analysis integrates data from several sources. I use county-level data in Midwest states from the 1910, 1920, 1930, and 1940 U.S. Census of Agriculture to measure tractor diffusion, investment in agricultural implements, farmland, crop mix, and other characteristics of farms and farmers.[7] I draw on the U.S. Census of Population in the same years for supplementary county-level data. The dataset also includes records of bank failures from the FDIC; county-level New Deal expenditures from Fishback, Kantor, and Wallis (2003); Dust Bowl soil erosion from Hornbeck (2012); average levels and variation in elevation and rainfall at the county-level, from the USGS and PRISM

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[6] The included states are: Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin. Together these states form the East and West North Central Census Divisions. In sum there are 1,059 uniquely defined counties over this period, and 1,035 with static borders. The 24 dropped counties are primarily in North and South Dakota. I forgo Hornbeck's (2010) border adjustment procedure to avoid synthetic observations that piece together fractions of counties under the assumption that county-level variables are evenly dispersed across space. The results are insensitive to this choice. Regression samples are further restricted to counties with data available for all robustness checks: 1,032 counties in 1925-30, and 943 counties in 1930-40. In both periods, St. Louis County and City are dropped because some data sources do not distinguish between them. The remaining reduction is the result of either missing or unreadable Census pages, or missing values for specific crops' acreage in counties where fewer than three farms reported in 1940 (primarily barley and rye).

[7] In most tables and figures, I define diffusion as the fraction of farms with a tractor. The 1925 Census of Agriculture is the first year that data on tractor ownership were reported and provides the number of tractors in a county. The 1930 and 1940 Censuses report both the number of tractors and the number of farms with tractors. I approximate diffusion in 1925 as the number of tractors over the number of farms, under the assumption that each farm owns at most one tractor. This assumption is almost certainly near truth, given patterns in later Censuses (e.g., in 1930, the mean number of tractors per farm with tractors is 1.04 (90th percentile 1.11).

Climate Group at Oregon State University, respectively; and state-level hybrid corn diffusion from the USDA Agricultural Statistics (Sutch 2011, 2014). I use these data to understand and control for other features of Midwest agriculture that may influence tractor adoption.

I use the NHGIS county boundary shapefiles (Minnesota Population Center 2011) for the 1910-1940 Census years to aggregate continuous geospatial data (elevation, rainfall) at the county level and drop all counties that merged or divided over the sample period as well as counties whose geographic centroids shifted more than 0.01 degrees in latitude or longitude between decades. The main analysis treats remaining counties' borders as static, reflecting the stability over these years of the centroids calculated by mapping software.

Empirical Methods and Identification

In the following sections, I compare tractor diffusion in counties with historically different concentrations of wheat and corn, the principal crops grown for harvest and sale in the Midwest and U.S. as a whole. If the historical account is true, diffusion in the 1920s should have occurred more rapidly in counties growing wheat and more slowly in counties concentrated in corn. Following the development of the general-purpose tractor in the late 1920s, the difference should then mitigate or reverse, with corn-heavy counties experiencing catch-up growth in diffusion.

I do so in a difference-in-differences framework, removing county-level fixed effects and identifying off county-level changes in diffusion over time. The identification strategy hinges on the fact that different areas are inherently better suited to growing wheat versus corn for exogenous reasons, such as soil type and climate, and that local crop choices reflect these advantages – a fact which is plainly visible in maps of spatial crop distributions and is hardly disputed. Formally, the assumption is that county-level wheat and corn concentrations are independent of unobserved factors that may influence changes in diffusion. To eliminate any possibility of simultaneity in crop choices and tractor adoption, I use pre-period (1925) crop intensities in regressions, though results are similar using other years (1910/1920). Appendix C provides evidence that crop shares are persistent over the sample period, both in cross-section and in the aggregate.

Characteristics of Sample

Table 2 shows descriptive statistics by year for the sampled counties, including: tractor diffusion, the fraction of farmland in each of the six most-common crops, the fraction of farms in six size categories, average farm size, and financial conditions. It is important to note that this period was a dynamic time in U.S. agriculture – by no means was the tractor the only change taking place – and it will therefore be important to control for concurrent trends.[8] Several patterns are present in this table, most notably a substantial, sustained increase in farm sizes.

[Table 2 about here]

To evaluate the confounding threats these trends may pose, Table 3 regresses changes in county characteristics between Agricultural Censuses on the fraction of farmland in wheat and corn (1925 values). Each outcome-year pair in this table constitutes a distinct regression. The table provides coefficients from these regressions, with the difference shown to their right.

[Table 3 about here]

The first result to note in this table is that between 1925 and 1930, tractor diffusion increased 0.4 percentage points with every percent of farmland in wheat but did not vary with corn. From 1930 to 1940, the difference is reversed. We also see that farms in corn-heavy counties grew more quickly than those in wheat-heavy counties, and this trend is amplified in the 1930-40 period, where we see a relative increase in very large farms (>260 acres). Corn-heavy counties also experienced larger increases in mortgage debt from 1925-30 and smaller increases from 1930-40, with interest rates moving in the inverse direction. This evidence underscores the importance of controlling for concurrent trends in agriculture, which is a focus of later sections.

3 Descriptive Evidence

The main empirical fact of this paper – that tractors diffused first to the Wheat Belt, and only later to the Corn Belt – is summarized by Figure 1. The top row of the figure maps the fraction of farmland in wheat and corn (left and right, respectively) across Midwest counties in 1925, with darker blues representing higher concentrations. The second row maps increases in tractor diffusion from 1925-30 (left) and 1930-40 (right). The third row maps the fraction of mechanized farms in 1940 whose latest vintage tractor was manufactured pre-1930 (left) versus between 1935-40 (right), using data on tractor vintages from the 1940 Agricultural Census.

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[8] Concurrent changes include growing farm sizes; changing financial conditions, particularly due to the Depression, New Deal, and Dust Bowl; and the diffusion of hybrid corn. These are discussed in depth in Section 4.

[Figure 1 about here]

Tractor diffusion through 1930 was visibly concentrated in wheat-growing states, while over the following decade it was almost fully coincident with the Corn Belt. As Section 4 will show, traditional explanations for technology diffusion cannot fully account for these patterns.

Figure 3 provides a more quantitative presentation of this pattern. The figure plots tractor diffusion between 1920 and 1940 for three state pairs: (i) North Dakota and Kansas, which are outliers in wheat intensity; (ii) Iowa and Illinois, which are outliers in corn intensity; and (iii) Michigan and Wisconsin, which grow little of either crop and thus serve as a control group.[9]

[Figure 3 about here]

The figure paints a clear quantitative picture of the story. Between 1920 and 1925, all three state pairs follow a similar trend, with the wheat and corn states tracking each other in both levels and changes. Over the next five years (to 1930), diffusion in the wheat states leaps past the corn states, which follow the control trend. The subsequent decade (to 1940), this pattern is precisely reversed: diffusion in the wheat states follows the control trend, and diffusion in the corn states catches up, to within two percentage points. This is the pattern that I will argue is explained by changes in the capabilities and limitations of tractor technology. The natural question for a counterfactual is then the value of accelerating the development of general-purpose tractors such that the 1930 wheat-corn gap is eliminated. This question is the subject of Section 6.

4 Regression Evidence

To formalize this evidence and control for contemporaneous conditions of Midwest agriculture, I turn to regressions. The main estimating equation throughout this section has the form:

$$\begin{aligned}\text{Diffusion}_{it} = \beta_0 + \beta_1 \cdot \text{PctWheat}_{i,1925} + \beta_2 \cdot \text{PctWheat}_{i,1925} + \beta_3 \cdot \text{Post}_t \\ + \beta_4 \cdot \text{PctWheat}_{i,1925} \cdot \text{Post}_t + \beta_5 \cdot \text{PctCorn}_{i,1925} \cdot \text{Post}_t + \mathbf{X}_{it}\theta + \varepsilon_{it}\end{aligned}$$

where i and t index counties and years. I estimate this difference-in-differences separately on the 1925-30 and 1930-40 samples (and in one case, over a pooled 1925-40 sample). Diffusion is measured

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[9] See Tables C.1 and C.2 for state-level crop intensities over this period.

as the fraction of farms in county c and year t with a tractor, and crop percentages are calculated as harvested acreage as a fraction of farmland. The $\mathbf{X}_{it}$ term represents a set of county-level controls, which are sequentially expanded over a set of several robustness checks.

Table 4 provides results from baseline specifications without controls. Column (1) shows difference-in-difference estimates for 1925-30, Column (2) for 1930-40, and Column (3) for the pooled sample. The important quantity in these models is not the point estimates per se, but rather the difference between them, and for each regression I calculate the difference in coefficients for corn and wheat, which is provided as a summary statistic at the bottom of the table.

[Table 4 about here]

In these baseline models, we see that diffusion increased 0.4 percentage points (p.p.) from 1925 to 1930 per p.p. in wheat intensity but did not vary with corn intensity. The following decade, this pattern reverses. The net effect is that cumulative diffusion from 1925 to 1940 co-varied with corn and wheat intensity at similar rates. Standard errors are sufficiently precise that we can assert the presence of a large divergence from 1925 to 1930 and re-convergence by 1940.[10]

However, this period was a dynamic era in U.S. agriculture, featuring expansion and consolidation, technical advances in plant breeding, and two economic shocks: the Depression and the Dust Bowl. To evaluate the robustness of these patterns to concurrent trends in agriculture, Table 5 presents a battery of additional checks. Each of these checks either adds controls – described in detail below – or restricts the sample to a focused subset of counties. The table is split into two Panels: Panel A estimates models for the 1925-30 period, and Panel B for the 1930-40 period. As before, the difference in coefficients for corn and wheat is provided as a summary statistic.

The first column of each panel presents the baseline result from Table 4. Each column thereafter cumulatively adds controls. Column (2) controls for the intensity of other crops (oats, barley, rye, and hay). Column (3) controls for farm size (fraction of farms <20 acres, 20-49 acres, 50-99 acres, 100-259 acres, and >260 acres, and log mean farm size). Column (4) controls for substitute inputs (horses, mules, and labor expenditure per acre). Column (5) controls for local financial conditions (farm mortgage interest rates and debt ratios). Column (6) controls for geographic and climatic variables (geographic coordinates, distance from Detroit [Ford] and Chicago [IHC], quadratics in county mean temperature and annual rainfall, and intra-county variation in elevation). Column

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[10] Figure 4 makes this point clear, plotting the estimated increase diffusion from 1925 to 1940 (with 95% confidence intervals) in a hypothetical county that is all-wheat versus all-corn.

(7) controls for local New Deal Relief (AAA spending and FCA lending per capita). The latter two columns in Panel B retain the controls but restrict to counties in the Hornbeck (2012) Dust Bowl sample or to states that were leading adopters of hybrid seed corn to evaluate whether the effects are explained by contemporaneous shocks to Midwest agriculture in the 1930s.

[Table 5 about here]

This battery of checks serves to rule out several competing explanations for the sequential diffusion of tractors to wheat- and corn-growing counties, including differential farm sizes, factor endowments and prices, credit constraints, trade costs, and more. In Panel A (1925-30), we see that the difference in coefficients on wheat and corn intensity are stable across specifications – matching the baseline result – and precisely estimated. The differece in Panel B (1930-40) is the inverse of that in Panel A and modestly more volatile, but still within the bounds of standard errors.

A different interpretation is that the advent of mechanical corn harvesters, which required a tractor to operate, triggered the wave of tractor diffusion in the Corn Belt. This story would quite literally put the cart before the horse, as the general-purpose tractor was necessary for a mechanical corn harvester to be of value. If anything, advances in tractor technology likely *inspired* R&D in corn harvesters, due to their complementarities. Though this potential confound is difficult to evaluate in regressions due to a lack of county-level data on harvester diffusion, Colbert (2000) provides enough information to do so for one state in the heart of the Corn Belt: Iowa.

According to Colbert (2000), there were 6,000 mechanical corn harvesters in use on Iowa farms in 1937, and by 1940 this count had reached only 21,934 – as compared to 128,516 tractors. Assuming each farm owned at most one corn harvester, a mere 10.3% of Iowa farms were mechanizing their corn harvest in 1940, up from 0% in 1930. In contrast, 55.3% of farms owned a tractor in 1940, up from 29.4% in 1930. The introduction of mechanical corn harvesters thus seems unable to explain either the level of or increase in tractor diffusion over the decade.

Data on tractor vintage from the 1940 Agricultural Census provide a distinct opportunity to connect advances in tractor technology to sequential diffusion across the Midwest, and perhaps the most direct test of the claims in this paper. This Census (and only this Census) reports the number of farms whose latest model-year tractor is pre-1930, 1931-1935, and 1936-1940. In Table 6, I replicate the previous table, replacing the dependent variable with the fraction of mechanized farms in 1940 whose latest-vintage tractor is pre-1930 (Panel A) and post-1935 (Panel B).

[Table 6 about here]

From Column (2) onwards, the results are statistically identical across specifications. Mechanized farms in wheat-growing counties were much more likely to own a pre-1930 vintage: these farms tended to adopt early *and* were unlikely to upgrade. Mechanized farms in corn-growing counties were much more likely to own a post-1935 vintage, which was presumably their first tractor. The magnitudes of these differences are large. In essence, as of 1940, wheat-growing counties were using Fordsons, and corn-growing counties were using Farmalls.

Additional Robustness Checks

The regressions in Tables 4 and 5 define diffusion as the fraction of farms in a county reporting a tractor, and model it as a linear function of observables. This definition imposes an assumption of perfect indivisibility, despite historical evidence of cooperative ownership (Myers 1921) and custom work (Gilbert 1930). Moreover, although the linear specification is easy to interpret, and can be a natural modeling choice over short time horizons, if diffusion is logistic in observables then it is the log-odds (rather than the adoption probability) that follows a linear model.

To evaluate whether the results are sensitive to these assumptions, Appendix D re-estimates the regressions in Table 5 using alternative definitions. Table D.1 replaces diffusion with the log-odds ratio. Table D.2 re-defines diffusion as the number of tractors per 100 acres of county farmland. This table excludes the Plains states from Panel A (1925-30), where farmland was rapidly expanding in the late 1920s, confounding the diffusion measure.[11] Both variants yield results similar to those in the tables above and are robust to controls and within subsamples.

I also test the sensitivity of the results to assumptions on the error structure. In Tables D.3 to D.5, I re-estimate Table 5 allowing for spatial correlation in the error term that declines linearly in the distance between county centroids up to 20-, 50-, and 100-mile cutoffs (Conley 1999), which may be desirable given the spatial nature of technology diffusion. Though standard errors increase with the cutoff distance, the results remain significant at the widest radius.

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[11] Counties in North Dakota, South Dakota, Nebraska, and Kansas on average increased their farmland by 12%, 8%, 7%, and 10% (respectively) from 1925 to 1930, whereas counties in other states were stable. Agriculture expansion was significantly more subdued from 1930 to 1940.

5 Theoretical Framework

To put more structure around and generalize these results, consider the following model. Suppose a monopolist inventing firm develops a technology, such as a tractor, that it sells to users in an arbitrary number of application sectors, which we can think of as distinct crops. The focal technology is characterized by general-purpose quality z_g and a vector of application-specific qualities $\{z_a\}_{a \in A}$ across a range of applications $a \in A$, with associated R&D costs $C^g(z_g)$ and $\{C^a(z_a)\}$, which are increasing and convex in z. General-purpose quality is embodied in features that are useful for many purposes, such as the rotary motion produced by a motor. Application-specific quality is embodied in features which have limited use and are valuable only in particular applications. Within such applications, this limited functionality can substitute for general functions (e.g., a self-powered component). The technology's total quality in application a can then be expressed as $\zeta_a(z_g, z_a) = z_g + z_a$. In this framework, general quality is special for two reasons: it is useful across many applications, and it complements sector-specific technologies of other firms. I assume the focal technology is produced at marginal cost c and sold at price w.

Developers in the application sectors create complementary products that serve a sector-specific need, such as attachments that cultivate corn or harvest grain. Each such product is characterized by quality T_a which has increasing and convex R&D costs. These firms' investment in quality generates private returns of $\pi^a(T_a | w, z_g, z_a)$. The exact form of π^a depends on the downstream market structure and is nonessential; the key assumptions are (1) that π^a is decreasing in w and increasing in z_g, z_a, and T_a, and (2) that $\pi^a_{z_g T_a} \geq 0$. This latter assumption implies innovational complementarity between the focal technology and sector-specific complements, as in Bresnahan and Trajtenberg (1995): improvements in the former make complementary innovation more profitable, and vice versa. Changes in the application-specific quality of the focal technology in other applications (i.e., changes in $z_{\tilde{a}}$ for $\tilde{a} \neq a$) have no direct bearing on π^a.

Each application sector is assumed to include a single sector-specific inventing firm. These firms undertake R&D to maximize firm-specific profits π^a, subject to a periodic budget constraint B_a. Within this framework, firm a's solution is to expend its R&D budget each period developing T_a up to the point where the marginal returns to R&D equal the incremental cost. Denote this solution as $T_a^* = T_a^*(w, z_g, z_a)$. This function is increasing in z_a and z_g, which can complement T_a, and decreasing in w, which reduces demand for the focal technology and in turn its complements. The presence of a budget constraint does not change this solution, but it does introduce the possibility for delays: difficult or expensive R&D will slow down product development. Although this feature isn't crucial to what follows, it is useful for explaining why the development of complementary equipment may lag advances in the focal technology.

Demand for the focal technology from each sector a takes the form $X^a(w, z_g, z_a, T_a^*)$, where $X_w^a < 0$, $X_z^a > 0$ and is smooth, symmetric and single-peaked, $X_T^a > 0$, and $X_{wz}^a < 0$ for $z \in \{z_g, z_a\}$ – in other words, demand is S-shaped in each quality $z \in \{z_g, z_a\}$.[12] It follows that the focal firm's marginal revenue has similar properties. The latter condition implies that the firm "cannot appropriate more than the incremental surplus" generated by quality improvements (Bresnahan and Trajtenberg 1995), leading it to undersupply quality. In essence, whenever the firm invests in quality improvements, a fraction of the ensuing rents will accrue to inventors of complements, and these rents cannot be fully re-appropriated: if the firm attempts to tax these developers (for example, with licensing fees) to re-appropriate this surplus, it will reduce their incentive to invest in T_a, and demand will accordingly decline. As a result, the focal firm's investment in expanding the scope of its technology will be below the social optimum.

5.1 The Path of Product Development

The focal inventing firm must choose how much general-purpose and application-specific quality to develop each period, subject to its own periodic R&D budget constraint B_g. If the returns to application-specific quality or the costs of developing general-purpose features are large, or if complementary technologies exist for only a handful of applications, the firm may prefer to invest in specific features in advance of more general features. Formally, the firm's problem is

$$\max_{z_g, z_{a_1}, \ldots, z_{a_n}} \Pi(z_g, z_{a_1}, \ldots, z_{a_n} | c, \mathbf{T}) - C^g(z_g) - \sum_a C^a(z_a) \ ,$$

where

$$\Pi(z_g, z_{a_1}, \ldots, z_{a_n} | c, \mathbf{T}) = (w^* - c) \sum_{a \in A} X^a(w^*, z_g, z_{a_1}, \ldots, z_{a_n}, T_a)$$

is the firm's return, w^* is the monopoly price, and $\mathbf{T}$ is a vector of complementary technologies' quality.[13] The firm's solution is $\mathbf{z}^* = \{z_g^*(c, \mathbf{T}), z_{a_1}^*(c, \mathbf{T}), \ldots, z_{a_n}^*(c, \mathbf{T})\}$. Due to innovational complementarities, each z^* is increasing in $\mathbf{T}$. As with the application sector firms, the budget

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[12] An S-shape for demand is consistent with a diffusion setting where consumers buy at most one unit.

[13] Note that since the firm takes the price w^* as given when solving for z_g and $\{z_a\}$, the assumption of monopoly is unnecessary as long as the firm can (even temporarily) retain rents from innovation.

constraint dictates the pace at which the firm converges to this solution – but not the form this solution takes – and explains why improvements are not instantaneous.

The long run solution has ${}^{\Pi_{z_\gamma}}/C^{\gamma}_{z_\gamma} = 1$ for all $\gamma = g, a_1, \ldots, a_n$. But with a binding R&D budget constraint, the adjustment path will have features with the highest shadow price being developed until others exceed them. In practice, this means that the focal technology will often first develop for applications with exogenously high demand or exogenously inexpensive development costs, and only when the gains to specialization are exhausted will product development proceed to general-purpose features. A typical path for product development will therefore be:

1. Invention for applications with exogenously high demand or inexpensive R&D
2. (Potentially) Develop general-purpose capabilities that serve a wide range of users
3. (Potentially) Round out development of remaining application-specific features

These results can be summarized with the following proposition.

Proposition 1.

1) In the long run, general and application-specific quality will develop up to an interior solution where marginal benefits equate to costs across all $z \in \{z_g, z_{a_1}, \ldots, z_{a_n}\}$ *for which* $z > 0$.

2) Product development will follow an adjustment path along which technological attributes with the highest shadow price are developed until others exceed it.

5.2 Implications for the Scope of Diffusion

The predictions are intuitive: product features develop in the order in which they are most valuable. In some cases, this process leads to a general-purpose variant, but externalities limit investment in scope relative to the social optimum, implying that there is a role in this setting for well-designed R&D policies. But the most important result is the implication for diffusion, and in particular for understanding cross-sectoral lags in diffusion, which will be shaped by the set of applications for which a given technology can be used at all. Since scope must precede scale, this margin can play a paramount role in explaining diffusion both in cross-section and in the aggregate.

In his canonical study of hybrid corn, Griliches (1957) recognizes this phenomenon, calling it the “availability” problem: the diffusion of hybrid corn at the level of crop reporting districts required seed varieties adapted to local growing conditions. The key insight is that cross-sectional variation in diffusion is driven not only by the rate at which it proceeds, but also by when it begins. Because product development often proceeds from specific- to general-purpose variants, diffusion may even follow the characteristic S-curve not only within applications, but also across them. This appears to have been the case for hybrid corn: for any fixed level of diffusion, and in particular for lower levels indicating availability of locally-adapted varieties, the number of states that had surpassed that level of diffusion forms an S-shape over time (Figure 6), much as diffusion within individual states followed an S-curve (Figure 5, reproducing Griliches' Figure 1).[14]

[Figures 5 and 6 about here]

The argument can be formalized as follows. Recall that the focal technology has quality $z_g + z_a$ for applications in sector a. We can write diffusion in sector a as $D_a = F(z_g + z_a)$, where $F(\cdot)$ is a characteristic S-shaped CDF. Diffusion in sector a is thus increasing in both z_g and z_a, while diffusion in sector b will be increasing in z_g but not directly affected by z_a. Since $F(\cdot)$ is one-to-one, it has a functional inverse $F^{-1}(\cdot)$, and we can write

$$\begin{bmatrix} F^{-1}(D_{a_1}) \\ \vdots \\ F^{-1}(D_{a_n}) \end{bmatrix} = \begin{bmatrix} z_g + z_{a_1} \\ \vdots \\ z_g + z_{a_n} \end{bmatrix}. \tag{1}$$

Equation (1) is a system of n equations with $(n+1)$ unknowns, one of which may be normalized to zero with no loss of generality. As z_g increases, diffusion will increase across all applications, including previously untapped markets, and as R&D proceeds from specific- to general-purpose features and back, so will the scope of diffusion begin with a narrow set of applications, accelerate to many others, and then top off with the remainder, as follows.

Proposition 2. *The scope of diffusion varies one-to-one with that of R&D. Diffusion may therefore follow an S-shaped pattern over time not only within applications, but also across them.*

In concept, the diffusion of the focal technology should also depend on the quality of complements. This parameter is omitted from equation (1), since it is fully determined by the characteristics of the focal technology itself. What this implies in practice is that when tractors improve in their

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[14] Discerning this S-shape requires diffusion data at relatively high frequency. Though the pattern is visible for hybrid corn (Figure 6), for which annual diffusion data are available at the state level, it is unfortunately not possible to detect for tractors, where data are only available at 5- to 10-year intervals: there are simply not enough datapoints to pin down the precise shape of the curve.

general-purpose quality, complements should soon develop to take advantage of these new features. Historical experience broadly concords: for example, mechanical corn harvesters were invented just five years after the general-purpose tractor. Firms similarly began attacking the cotton harvesting problem immediately following the development of the Farmall, but the mechanical cotton picker was slower to develop due to the difficulty of the engineering problem and institutional features of the U.S. South constraining demand (Whatley 1985, 1987).

The Theory in Relation to History

Several features of this model manifest in the tractor's history, particularly the sequence of the tractor's development and its co-evolution with implements. The tractor's earliest applications were in tillage: the physical requirements of plowing generated exogenously high demand for mechanical power and explains why the first steam tractors were invented to be, and termed, "plowing engines." Tractor development subsequently continued into grain production, where demand was relatively high, the engineering problem was easier, and complementary harvesting equipment was already available. Only when the marginal gains to improving fixed-tread models were exhausted, and specialized alternatives were deemed unprofitable, did manufacturers direct their research effort towards a general-purpose design – and its diffusion rapidly followed.

Once the tractor generalized, implements were invented to perform nearly every task in the field. Plows, harrows, planters, grain harvesters, threshers, and combines were all available for use with fixed-tread tractors. Following the advent of general-purpose models, there were then cultivators, corn harvesters (1930), cotton pickers (1942), and harvesters for many other crops. Indeed, mechanical corn harvesters entered production only a few years after the Farmall, supporting the theoretical assertion that manufacturers of complementary devices respond quickly to improvements in general-purpose functionality. IHC similarly began working on a mechanical cotton picker immediately after the Farmall and by the early 1930s believed it had solved the fundamental engineering problems for such a device (Whatley 1987, referencing the IHC "New Works Committee"). Tractors were in turn improved with power take-off and the three-point hitch to be used with such equipment, reflecting two-way innovational complementarities.

6 Counterfactual Diffusion

What if general-purpose tractors had developed earlier? In particular, what would be the welfare impact had diffusion in the Corn Belt kept pace with the Wheat Belt? This question is first-order to understanding the consequences of impediments to technology diffusion. In the case of tractors, it amounts to evaluating the effect of eliminating a transitory deficit in the late 1920s and 1930s, since corn-growing counties caught up to their wheat-growing counterparts by 1940.

To get a better handle on this question, I use the estimates from Table 4 to project diffusion in the counterfactual. Although these estimates are linear approximations, they can provide a sense of the magnitude of the effect. Figure 7 plots the cumulative increase in aggregate diffusion throughout the Midwest as (i) observed, (ii) as estimated, and (iii) in a counterfactual in which tractors diffuse at the same rate with respect to corn intensity as wheat intensity.

[Figure 7 about here]

The estimated increase in diffusion closely tracks observed values, affirming the model's predictive power. In the counterfactual, aggregate diffusion would have been roughly 6.6 p.p. (i.e., 25% on a base of 25.6 p.p.) higher than observed in 1930, but little different in 1940.

Given the tractor's impact on U.S. agriculture, a temporal shift of this magnitude would have had large (if transitory) effects on agricultural productivity. The tractor upended the organization of the sector, dramatically reducing labor inputs and increasing cropland available for human consumption (Olmstead and Rhode 2001). As Olmstead and Rhode (1994) describe, "the conversion from draft power to the internal combustion engine was one of the most far-reaching technological changes ever to occur in the United States." Steckel and White's (2012) estimates suggest that by 1954 the tractor was generating social savings of as much as 8.6 percent of GNP.

Using historical wages and estimates of the labor savings from mechanization, we can calculate a back-of-the-envelope estimate of the social savings from the reduction in labor inputs alone. Appendix F provides details of the calculations, and Table 7 the results.

[Table 7 about here]

The calculation begins with an estimate from Cooper et al. (1947) that tractors had reduced labor requirements in U.S. agriculture by 1.7 billion man-hours per year by 1944, roughly half of which is attributable to time-savings in field operations, and half to reduced time spent caring for horses and mules. I then allocate a fraction of these savings to the Midwest based on the region's share of mechanized farms in 1945. To obtain an estimate of the labor savings from tractors in 1930, I scale down this quantity by the proportionality factor $\text{Diffusion}_{1930}/\text{Diffusion}_{1945}$.

The calculations suggest that accelerated diffusion to the Corn Belt would have reduced agricultural labor inputs by 111 million man-hours in 1930, or 10.2% of hired labor in Midwest agriculture at that time. This labor would likely have reallocated to other sectors. At prevailing manufacturing and wholesale wages (and setting aside any potential general equilibrium effect), the value of these labor savings is approximately $83.3 million in 1930 dollars, equivalent to nearly $1 billion today – or 1.2% of current Midwest agricultural GDP.

7 Conclusion

This paper brings attention the importance of increasing scope to the diffusion of new technology, focusing on the history of the farm tractor. Though tractors are pervasive in modern agriculture, they were not born to be: the earliest models were first developed for tillage and harvesting small grains, and only in the late 1920s did the technology begin to generalize for use with row crops such as corn, cotton, and vegetables. Using county-level data on tractor ownership from the 1910 to 1940 Census of Agriculture, I show that tractors were consequently quick to diffuse to areas of the U.S. Midwest growing wheat and other small grains and slow to penetrate the Corn Belt. Had the tractor diffused at the same rate to counties with equal concentrations of wheat and corn, total diffusion in the Midwest would have been roughly 25% higher by 1930, generating annual savings of 10% of hired agricultural labor alone. Conversely, had the tractor not generalized, its impact would be so limited that it would most likely be an afterthought today.

The paper proposes a model of R&D in which firms develop technologies with general and application-specific features to explain these patterns. The model suggests that technologies often first develop for applications with high demand or low R&D costs, and only when the gains to specialization are exhausted will R&D proceed to general-purpose variants – and only if technically feasible. Diffusion will in turn be constrained to applications for which the technology can be used. Positive spillovers into the production of complementary technologies imply that inventing firms will typically have less than the socially-optimal incentives to generalize their technology for wider use, suggesting that generality may be a valuable target for R&D policy interventions.

The evidence supports a substantially different interpretation of lagging technology diffusion than what is typically found in the literature, which tends to focus on fixed costs, factor prices, credit constraints, information, and human capital. In the case of tractors, lags resulted from a fundamental mismatch between the technology's capabilities and the technical requirements of users in different settings, and were resolved only when the technology advanced to fulfill these demands. Indeed, the late-adopting U.S. Corn Belt had to wait for the row-crop tractor *to be invented* before farms growing corn for harvest could be fully mechanized. The results of this paper thus highlight the importance of product designs that meet the heterogeneous requirements of users in different settings, and they suggest that the most effective way to get technology into the hands of new users may simply be to develop a variant adapted to their needs.

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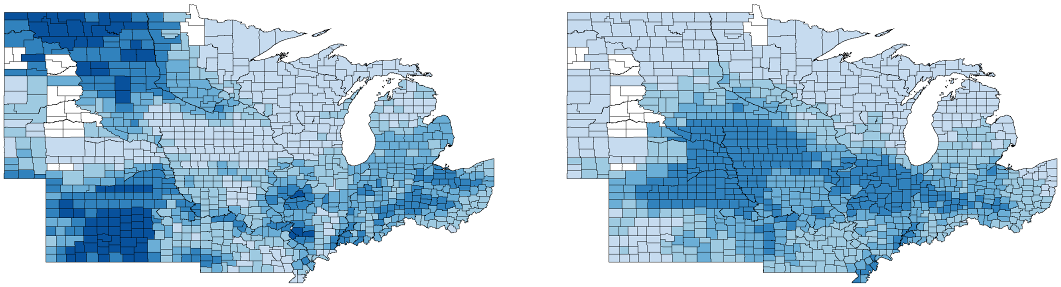
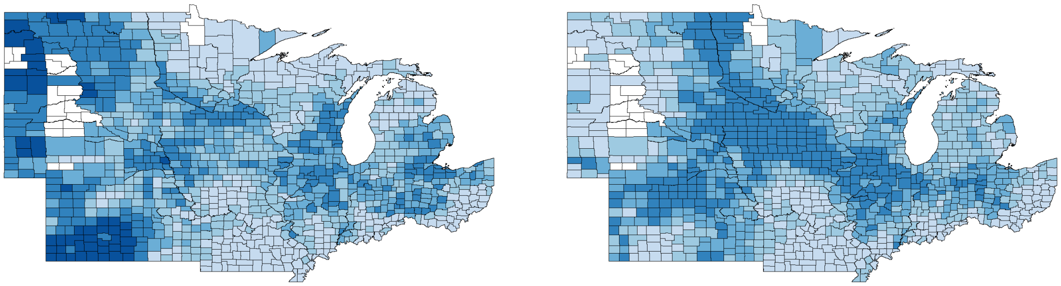
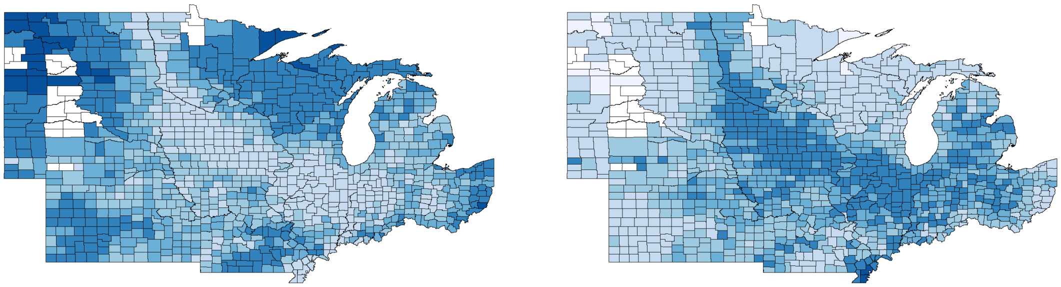
Figure 1: Crop Mix and Tractor diffusion in U.S. Midwest, 1925-1930 and 1930-1940


Wheat concentration, 1925

Corn concentration, 1925


Tractor diffusion, 1925-30

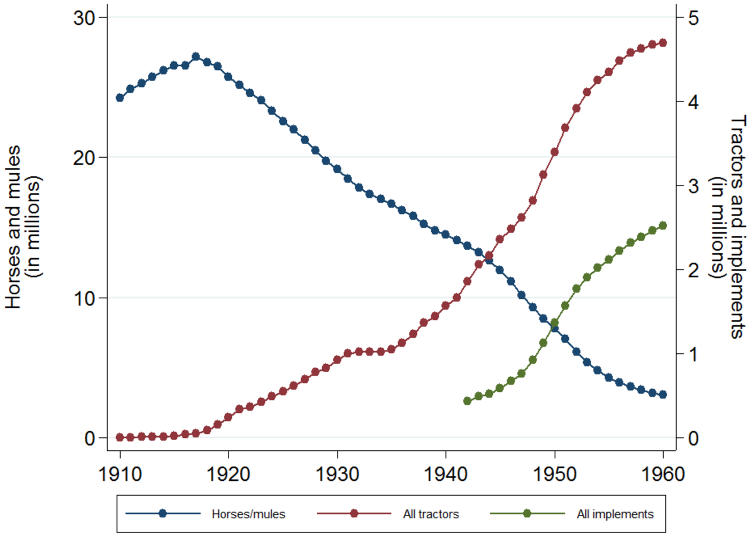
Tractor diffusion, 1930-40


Early Vintage in 1940

Late Vintage in 1940

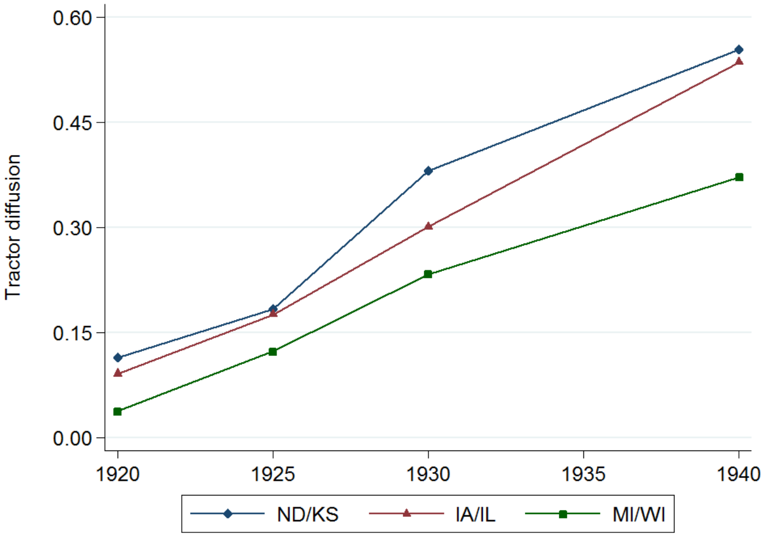
Notes: Figure shows the distribution of 1925 wheat and corn intensity (top row), changes in tractor diffusion from 1925-30 and 1930-40 (middle row), and early- and late-vintage tractors in use on farms in 1940 (bottom row) across the U.S. Midwest. Crop concentrations calculated as the fraction of farmland in the given crop; tractor diffusion as the fraction of farms owning a tractor. Darker blues represent higher values. Counties in white omitted due to missing data or because their borders changed over the sample period. Data from 1910 to 1940 Census of Agriculture.

Figure 2: Draft animals, tractors, and implements in the U.S.



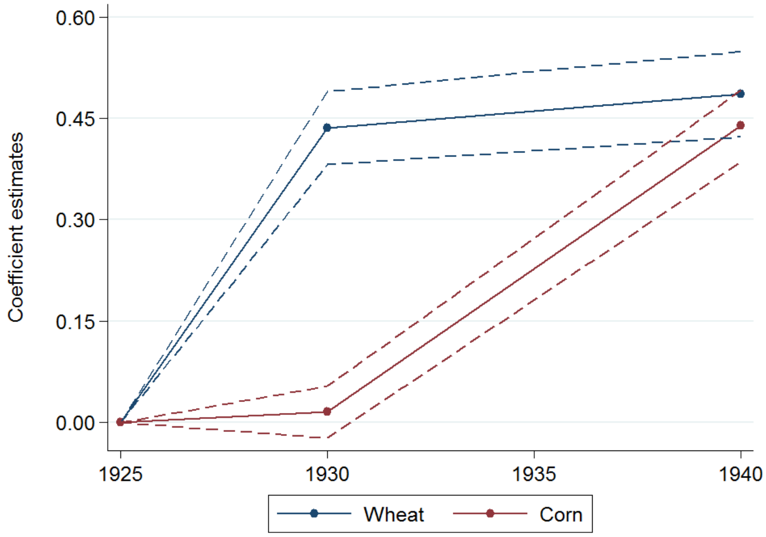
Notes: All implements refers to the sum of grain combines, corn harvesters, and pick-up hay balers owned by U.S. farms; this total does not include other implements not provided in the Historical Statistics or recorded in historical Censuses. Correlation of tractors and implements on U.S. farms is 0.996 over the 19 years for which data on all three implements are available. Data from Historical Statistics of the U.S., Series Da623, Da629-631, Da983, Da985, Da987.

Figure 3: Tractor diffusion in Midwest states, 1920-1940



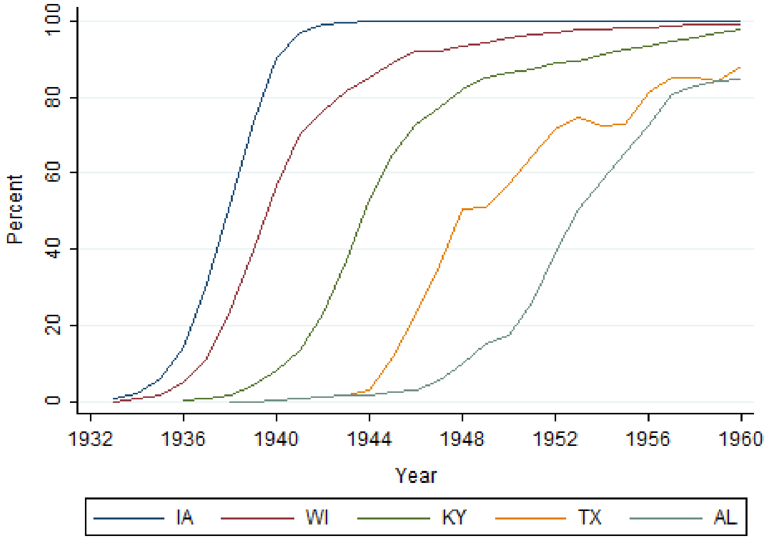
Notes: Figure shows the path of tractor diffusion from 1920 to 1940 in the states that form the core of the U.S. Corn Belt (IA/IL) and Wheat Belt (ND/KS), as well as in two states with low crop concentrations and little of either staple crop (MI/WI). Data from 1920 to 1940 Census of Agriculture.

Figure 4: Estimated cumulative change in tractor diffusion, 1925-1940, all-wheat vs. all-corn



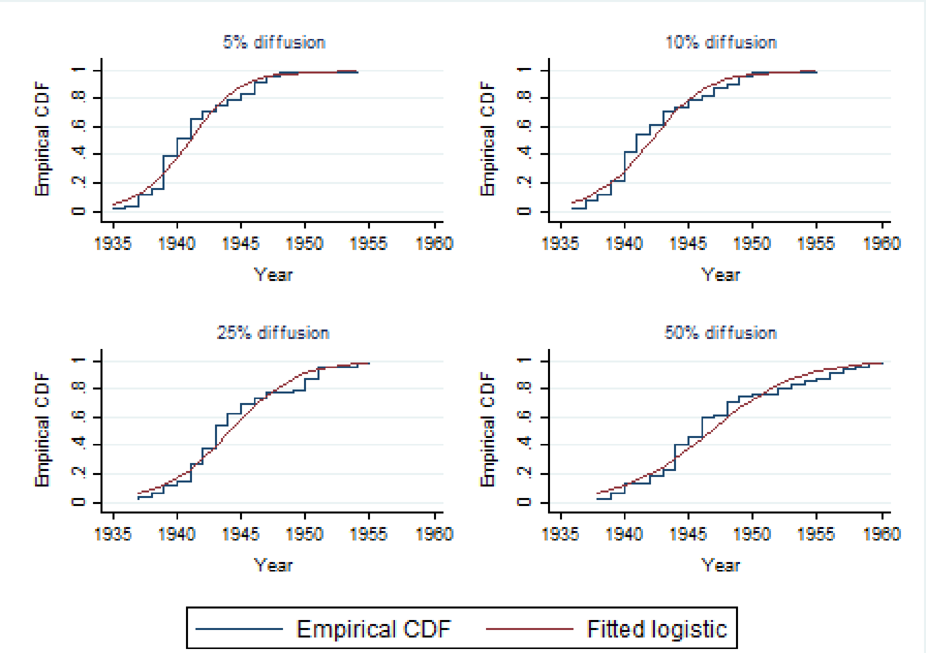
Notes: Figure plots the point estimates from the 1925-1940 specification in Table 5, Column 3, showing the cumulative change in diffusion for a county with all farmland planted to wheat versus all farmland planted to corn. The dashed lines bound the 95% confidence interval for each estimate.

Figure 5: Reproduction of Griliches (1957) Fig. 1:
Percentage of corn acreage planted to hybrids



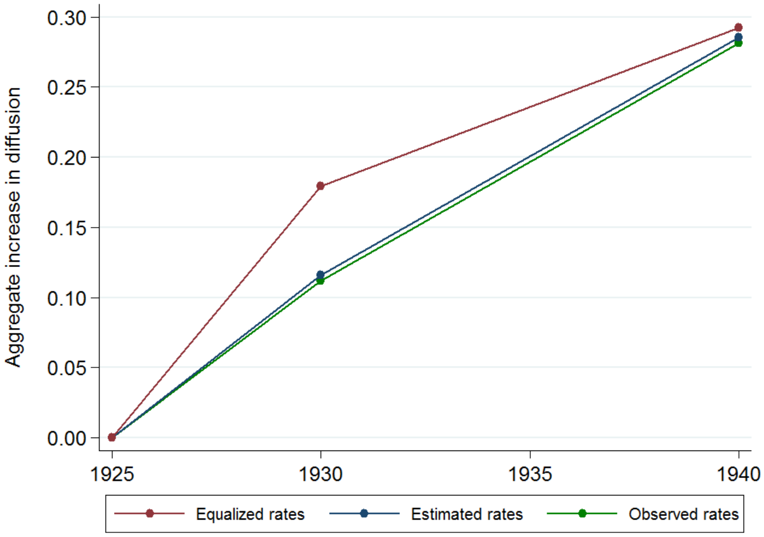
Notes: Figure shows the characteristic S-shaped hybrid corn diffusion curve for each of Iowa, Wisconsin, Kentucky, Texas, and Alabama, reproducing Figure 1 of Griliches (1957). Data from USDA Agricultural Statistics.

Figure 6: Distribution of states, by year at which given level of hybric corn diffusion attained



Notes: Figure shows the distribution of U.S. states by the year at which they attain a given level of hybrid corn diffusion, measured as the percentage of corn acreage planted to hybrids. Data from USDA Agricultural Statistics.

Figure 7: Est. differential increase in tractor diffusion in counterfactual, 1925-1940



Notes: Figure plots the aggregate difference in tractor diffusion implied by the estimates in Table 5, Column 3, had tractors diffused as rapidly in corn-growing regions as they did in wheat-growing regions. Calculated as described in text.

Table 1: Tractor Production from Select Manufacturers, Fixed Tread vs. General-Purpose

	Pre-study period		**Study Period**			
Type	**1917-1920**	**1921-1924**	**1925-1928**	**1929-1932**	**1933-1936**	**1937-1940**
Fixed Tread	226,728	375,217	533,517	287,641	60,187	75,381
General-Purpose	0	214	49,759	92,365	258,443	524,666

Notes: Table shows total production of regular and general-purpose tractors by select manufacturers between 1917 and 1940. Sample covers production by Ford, IHC, Deere, and Allis-Chalmers, which account for 80% of tractors manufactured in each of the 1920s and 1930s (White 2010). Production totals calculated from manufacturer serial numbers, which were acquired from the McCormick collection at the Wisconsin Historical Society (IHC), thefordsonhouse.com (Ford), tractordata.com (Deere, Allis-Chalmers), and tractors.wikia.com (all).

Table 2: Descriptive Statistics: Average Farm Characteristics, by Year

	Pre-study period		**Study period**		
	1910	**1920**	**1925**	**1930**	**1940**
	(N=1035)	**(N=1035)**	**(N=1035)**	**(N=1035)**	**(N=1035)**
Fraction with tractors	–	–	0.149	0.267	0.437
	–	–	(0.10)	(0.16)	(0.21)
Crop percentages:					
Corn	0.168	0.143	0.145	0.145	0.128
	(0.12)	(0.11)	(0.11)	(0.12)	(0.10)
Wheat	0.080	0.122	0.078	0.082	0.070
	(0.09)	(0.10)	(0.09)	(0.11)	(0.08)
Oats	0.075	0.081	0.087	0.078	0.064
	(0.06)	(0.06)	(0.07)	(0.07)	(0.06)
Barley	0.014	0.011	0.010	0.021	0.019
	(0.03)	(0.02)	(0.02)	(0.03)	(0.03)
Rye	0.005	0.015	0.007	0.005	0.007
	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)
Hay	0.120	0.149	0.123	0.110	0.097
	(0.04)	(0.06)	(0.05)	(0.05)	(0.05)
Farm size distribution:					
Frac. $<$ 20 acres	0.061	0.054	0.064	0.064	0.085
	(0.06)	(0.05)	(0.06)	(0.06)	(0.08)
Frac. 20-49 acres	0.116	0.105	0.107	0.097	0.100
	(0.09)	(0.09)	(0.09)	(0.08)	(0.08)
Frac. 50-99 acres	0.206	0.204	0.201	0.191	0.180
	(0.12)	(0.13)	(0.12)	(0.12)	(0.11)
Frac. 100-174 acres	0.304	0.298	0.295	0.293	0.282
	(0.11)	(0.10)	(0.10)	(0.10)	(0.10)
Frac. 175-259 acres	0.121	0.128	0.128	0.135	0.124
	(0.06)	(0.07)	(0.07)	(0.07)	(0.06)
Frac. $>$ 260 acres	0.192	0.211	0.204	0.219	0.229
	(0.23)	(0.25)	(0.25)	(0.25)	(0.25)
Average farm acres	194.333	220.469	212.241	224.472	248.032
	(160.49)	(237.27)	(243.28)	(271.78)	(366.89)
Farm mortgages:					
Debt ratio	0.255	0.278	0.424	0.418	0.480
	(0.05)	(0.05)	(0.06)	(0.08)	(0.11)
Interest rate (p.p.)	–	5.941	–	6.022	5.023
	–	(0.50)	–	(0.44)	(0.44)

Notes: Table reports mean county characteristics in the sample from 1910 to 1940. Standard deviations shown in parentheses. Tractor diffusion is the fraction of farms reporting tractors, available for 1925, 1930, and 1940. Crop percentages calculated as the acreage planted, harvested, and in each of six principal crops as a fraction of total farmland. Farm size distribution calculated as the fraction of all farms in each of six size categories. Data on farm finances is reported in the Census of Agriculture for mortgaged farms and reflects local debt loads and access to capital. Data from 1910 to 1940 U.S. Census of Agriculture.

Table 3: Trends in Farm Characteristics, by Wheat/Corn Intensity

		Pre-study period					
		1910-20 (N=1035)			**1920-25 (N=1035)**		
		Crop intensity: Wheat	**Corn**	**Difference**	**Crop intensity: Wheat**	**Corn**	**Difference**
Outcomes: Farm Characteristics	Fraction with tractors	–	–	–	–	–	–
		–	–	–	–	–	–
	Farm size distribution:						
	Frac. > 100 acres	0.018	0.095	0.077***	0.009	0.036	0.027***
		(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
	Frac. > 260 acres	0.217	-0.167	-0.384***	0.009	0.004	-0.005
		(0.03)	(0.02)	(0.04)	(0.01)	(0.01)	(0.01)
	Farm mortgages:						
	Debt ratio	0.038	-0.191	-0.229***	0.004	0.275	0.271***
		(0.01)	(0.01)	(0.01)	(0.02)	(0.01)	(0.02)
	Interest rate (p.p.)	–	–	–	–	–	–
		–	–	–	–	–	–

		Study period					
		1925-30 (N=1035)			**1930-40 (N=1035)**		
		Crop intensity: Wheat	**Corn**	**Difference**	**Crop intensity: Wheat**	**Corn**	**Difference**
Outcomes: Farm Characteristics	Fraction with tractors	0.436	0.015	-0.420***	0.050	0.423	0.373***
		(0.03)	(0.02)	(0.04)	(0.03)	(0.02)	(0.04)
	Farm size distribution:						
	Frac. > 100 acres	-0.104	-0.050	0.054***	0.009	0.037	0.028***
		(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
	Frac. > 260 acres	0.032	0.028	-0.004	-0.008	0.093	0.101***
		(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
	Farm mortgages:						
	Debt ratio	-0.103	0.097	0.200***	0.308	-0.020	-0.328***
		(0.01)	(0.01)	(0.02)	(0.04)	(0.03)	(0.05)
	Interest rate (p.p.)	–	–	–	-0.895	0.711	1.606***
		–	–	–	(0.11)	(0.08)	(0.13)

Notes: Table provides estimates from a regression of changes in the given outcome (row) on the fraction of that county's farmland in wheat and corn, respectively (column) to identify agricultural trends in counties with different crop mix. County crop intensities are fixed at 1925 (pre-period) values in all specifications, though results are similar for 1910 or 1920 due to the stability of crop mix over time. Heteroskedasticity-robust standard errors shown in parentheses. *, **, *** represent significance at the 0.1, 0.05, and 0.01 levels, respectively.

Table 4: Crop Intensity and Changes in Tractor Diffusion from 1925 to 1940

	1925-1930	1930-1940	1925-1940
	(1)	(2)	(3)
Pct. in Wheat	0.436***		0.383***
x Year=1930	(0.028)		(0.028)
Pct. in Corn	0.015		0.023
x Year=1930	(0.020)		(0.020)
Pct. in Wheat		0.038	0.421***
x Year=1940		(0.030)	(0.032)
Pct. in Corn		0.414***	0.438***
x Year=1940		(0.021)	(0.028)
Difference	-0.42***	0.38***	
s.e.	(0.04)	(0.04)	
Diff. by 1930			-0.36***
s.e.			(0.04)
Diff. by 1940			0.02
s.e.			(0.04)
N	2064	1886	2829
R^2	0.41	0.41	0.54

Notes: Table shows the relationship between pre-period crop intensity and changes in county-level tractor diffusion from 1925-30 and 1930-40 (Columns 1 and 2) and for a pooled sample (Column 3). The sample is restricted to counties whose borders did not change over the sample period and for which data are available for all subsequent robustness checks (1,032 counties in 1925-30; 943 counties in 1930-40 and the pooled sample). The difference in the diffusion rates to wheat- vs. corn-intensive counties is provided below the regression estimates. *, **, *** represent significance at the 0.1, 0.05, and 0.01 levels, respectively. SEs clustered by county in parentheses.

Table 5: Crop Intensity and Changes in Tractor Diffusion from 1925 to 1940: Robustness to Alternative Specifications

		Additional controls for:						Restricted to:	
	Baseline (1)	Crop Mix (2)	Farm Size (3)	Other Farm Characteristics (4)	Financial Conditions (5)	Climate/ Geography (6)	New Deal Relief (7)	Dust Bowl Counties (8)	Early Hybrid Corn Adopters (9)
Panel A: Diffusion (levels) from 1925-1930									
Pct. in Wheat	0.436***	0.419***	0.407***	0.444***	0.390***	0.398***	0.371***		
x Year=1930	(0.028)	(0.031)	(0.030)	(0.030)	(0.030)	(0.030)	(0.029)		
Pct. in Corn	0.015	-0.005	0.001	0.024	0.036*	0.021	0.021		
x Year=1930	(0.020)	(0.021)	(0.021)	(0.021)	(0.021)	(0.022)	(0.022)		
Difference	-0.42***	-0.42***	-0.41***	-0.42***	-0.35***	-0.38***	-0.35***		
p-value	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)		
N	2064	2064	2064	2064	2064	2064	2064		
R^2	0.41	0.65	0.71	0.75	0.76	0.79	0.81		
Panel B: Diffusion (levels) from 1930-1940									
Pct. in Wheat	0.038	0.053	0.022	-0.046	-0.100***	-0.104***	-0.114***	-0.170***	-0.077
x Year=1940	(0.030)	(0.038)	(0.036)	(0.035)	(0.037)	(0.036)	(0.034)	(0.043)	(0.072)
Pct. in Corn	0.414***	0.473***	0.507***	0.319***	0.394***	0.408***	0.339***	0.205***	0.338***
x Year=1940	(0.021)	(0.031)	(0.031)	(0.038)	(0.035)	(0.035)	(0.036)	(0.054)	(0.051)
Difference	0.38***	0.42***	0.48***	0.36***	0.49***	0.51***	0.45***	0.38***	0.42***
p-value	(0.04)	(0.05)	(0.05)	(0.05)	(0.05)	(0.05)	(0.05)	(0.05)	(0.10)
N	1886	1886	1886	1886	1886	1886	1886	874	986
R^2	0.41	0.66	0.73	0.78	0.81	0.84	0.85	0.85	0.88

Notes: Table shows the relationship between pre-period crop intensity and changes in county-level tractor diffusion from 1925-30 and 1930-40 (Panels A and B, respectively). Column (1) repeats the baseline estimates from Table 4, and the remaining columns provide robustness checks. Column (2) adds controls for the intensity of other major Midwest crops (oats, barley, rye, hay); Column (3) adds further controls for the distribution of farms by size (i.e., fraction <20 acres, 20-49 acres, 50-99 acres, 100-259 acres, and >260 acres) and the log mean farm size; Column (4) adds controls for substitute inputs (horses per acre, mules per acre, labor expenditure per acre); Column (5) adds controls for financial variables (farm mortgage interest rates and debt ratios); Column (6) adds controls for geographic and climatological variables (centroid coordinates, distance from Detroit and Chicago, quadratics in county mean temperature and annual rainfall, and intra-county variation in elevation); Column (7) adds controls for local New Deal Relief (AAA spending and FCA lending per capita). The latter two columns in Panel B retain the controls but restrict to counties in the Hornbeck (2012) Dust Bowl sample or to states that were leading adopters of hybrid seed corn to evaluate whether the effects are explained by contemporaneous shocks to Midwest agriculture in the 1930s. The difference in the diffusion rates to wheat- vs. corn-intensive counties is provided below the regression estimates. *, **, *** represent significance at the 0.1, 0.05, and 0.01 levels, respectively. SEs clustered by county in parentheses.

Table 6: Crop Intensity and Tractor Vintages in 1940

		Additional controls for:						Restricted to:	
	Baseline (1)	Crop Mix (2)	Farm Size (3)	Other Farm Characteristics (4)	Financial Conditions (5)	Climate/ Geography (6)	New Deal Relief (7)	Dust Bowl Counties (8)	Early Hybrid Corn Adopters (9)
	Panel A: Frequency of pre-1930 vintages in 1940								
Pct. in Wheat	-0.061	-0.052	-0.155***	-0.113***	-0.083	-0.027	0.096	0.139*	-0.070
	(0.045)	(0.047)	(0.048)	(0.048)	(0.052)	(0.054)	(0.070)	(0.084)	(0.106)
Pct. in Corn	-0.807***	-0.545***	-0.620***	-0.572***	-0.635***	-0.584***	-0.466***	-0.353***	-0.507***
	(0.042)	(0.049)	(0.057)	(0.052)	(0.053)	(0.057)	(0.075)	(0.111)	(0.086)
Difference	-0.75***	-0.49***	-0.47***	-0.46***	-0.55***	-0.56***	-0.56***	-0.49***	-0.44***
s.e.	(0.06)	(0.06)	(0.06)	(0.06)	(0.06)	(0.07)	(0.07)	(0.10)	(0.12)
N	944	944	944	944	944	944	944	438	493
R^2	0.57	0.65	0.68	0.69	0.70	0.73	0.74	0.82	0.83
	Panel B: Frequency of post-1935 vintages in 1940								
Pct. in Wheat	0.012	0.035	0.108***	0.063	0.060	-0.006	-0.085	-0.092	0.012
	(0.040)	(0.041)	(0.044)	(0.043)	(0.046)	(0.048)	(0.061)	(0.075)	(0.092)
Pct. in Corn	0.638***	0.458***	0.463***	0.392***	0.454***	0.390***	0.315***	0.204*	0.365***
	(0.038)	(0.045)	(0.055)	(0.048)	(0.050)	(0.054)	(0.066)	(0.109)	(0.078)
Difference	0.63***	0.42***	0.36***	0.33***	0.40***	0.40***	0.40***	0.30***	0.35***
s.e.	(0.05)	(0.05)	(0.06)	(0.06)	(0.06)	(0.06)	(0.06)	(0.09)	(0.11)
N	944	944	944	944	944	944	944	438	493
R^2	0.53	0.60	0.64	0.66	0.67	0.70	0.71	0.80	0.76

Notes: Table shows the relationship between pre-period crop intensity and the fraction of mechanized farms in 1940 with an early-model (pre-1930) tractor versus a late-model (post-1935) tractor (Panels A and B, respectively). Column (1) regresses the diffusion variable on pre-period wheat and corn intensity and state fixed effects. Column (2) adds controls for the intensity of other major Midwest crops (oats, barley, rye, hay); Column (3) adds further controls for the distribution of farms by size (i.e., fraction <20 acres, 20-49 acres, 50-99 acres, 100-259 acres, and >260 acres) and the log mean farm size; Column (4) adds controls for substitute inputs (horses per acre, mules per acre, labor expenditure per acre); Column (5) adds controls for financial variables (farm mortgage interest rates and debt ratios); Column (6) adds controls for geographic and climatological variables (centroid coordinates, distance from Detroit and Chicago, quadratics in county mean temperature and annual rainfall, and intra-county variation in elevation); Column (7) adds controls for local New Deal Relief (AAA spending and FCA lending per capita). The latter two columns retain the controls but restrict to counties in the Hornbeck (2012) Dust Bowl sample or to states that were leading adopters of hybrid seed corn to evaluate whether the effects are explained by contemporaneous shocks to Midwest agriculture in the 1930s. The difference in the diffusion rates to wheat- vs. corn-intensive counties is provided below the regression estimates. *, **, *** represent significance at the 0.1, 0.05, and 0.01 levels, respectively. SEs clustered by county in parentheses.

Table 7: Regional Diffusion and Labor Savings in 1930 (counterfactual)

Panel A: Counterfactual increase in diffusion in 1930

	Pct. of farms	
Midwest diffusion, as observed, 1930	0.256	(1)
Estimated diffusion, 1930	0.259	(2)
Counterfactual diffusion, 1930	0.322	(3)
level increase [(3)-(1)]	0.066	(4)
pct. increase [(4)/(1)]	25.7%	

Panel B: Added labor savings

	Hours (mil.)	
Added labor savings under counterfactual	110.99	(5)
Labor employed in Midwest agriculture	1,088.35	(6)
as percent of labor employed [(5)/(6)]	10.2%	

Panel C: Value of added labor savings

Added labor savings, full-time equivalents	55,496	(7)
Average non-farm annual wage (see appendix)	$1,501.45	(8)
Value of labor savings (mil. $s, 1930) [(7)*(8)]	$83.32	
Value of labor savings (mil. $s, 2014)	$952.97	
as percent of Midwest Agricultural GDP	1.2%	

Notes: Table reports counterfactual diffusion and potential reductions in agricultural labor inputs and increases in regional output had the tractor diffused at the same rate to corn-growing regions as to wheat-growing areas of the Midwest 1930. Details of the calculations shown above are provided in the text and the appendix.

Appendix for Online Publication

A Data Appendix

The data in this paper are primarily from the U.S. Census of Agriculture for years 1910, 1920, 1925, 1930, and 1940. When possible, data were acquired from NHGIS; remaining variables were transcribed from PDFs obtained from the Census website.[1] Stock variables (e.g., farms, farmland, number and value of farm machinery and draft animals, etc.) are reported for the Census year; flows (inputs, outputs) are always from the preceding year. Where corn acreage is separately reported for corn harvested for grain, cut for silage, cut for fodder, and hogged or grazed off (1925 and later), I use the acreage of corn harvested for grain, which is typically around 90 percent of total corn acreage and the subset most relevant to mechanization. Certain crops are not reported for certain states in certain years (barley and rye in Missouri, rye in Kansas – both in 1930) due to omission from the state-specific questionnaire, which likely reflects low acreage; production of these crops in the affected counties is coded as zero. Occasionally, a page went missing in the Census documents; in these cases, the affected observations were coded as missing. Modern Agricultural Census data were obtained using the U.S. Department of Agriculture Desktop Data Query Tool.

U.S. county shapefiles were obtained from NHGIS for each decade from 1910 to 1940. These maps were used to calculate counties' geographic centroids, as well as mean and standard deviation elevation (from the USGS National Elevation Dataset), mean and standard deviation annual rainfall (PRISM Climate Group 30-year normals), soil quality indices (National Commodity Crop Productivity Index), and other soil characteristics (USGS State Soil Geographic Database). I use county entry and exit into/out of the dataset and movement in geographic centroids to identify counties that formed, merged, split, or dissolved between Census years; any such counties are dropped from the analysis. As the text explains, I also apply Hornbeck's (2010) county border fix algorithm as a robustness check. I calculate distance to the f.o.b. shipping locations of Ford (Detroit) and International Harvester (Chicago) as a proxy for freight costs; comparison with point-to-point freight rates from Hartman (1916) suggests distance is a reasonable proxy, with correlations between route distance and point-to-point rates >0.95 for routes originating in Detroit or Chicago.

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[1] Historical Censuses and associated documents are available at http://www.census.gov/prod/www/decennial.html. A complete collection of historical Agricultural Census publications can be found at http://www.agcensus.usda.gov/Publications/Historical_Publications/index.php.

The data used in the New Deal and Dust Bowl robustness checks were obtained from Fishback, Kantor, and Wallis (2003) and Hornbeck (2012), respectively. The New Deal robustness checks include the Fishback et al. measures of AAA relief spending and FCA lending by county, normalized by county farm acreage; the Dust Bowl robustness checks restrict to states in the Hornbeck dataset (Kansas, Nebraska, North and South Dakota, Iowa, Minnesota), which were those most affected by the Dust Bowl. The latter are restricted to Midwest counties for which soil erosion data were available (those in Kansas, Nebraska, North and South Dakota, Iowa, Minnesota). Hybrid corn diffusion was provided by Richard Sutch (Sutch 2011, 2014) and originally obtained from the USDA Agricultural Statistics; the hybrid corn adopter robustness checks are restricted to the six states that were leading adopters of hybrids (by a wide margin, see Table A.1) in 1940.

Table A.1: Diffusion of Hybrid Corn through 1940, Midwest States

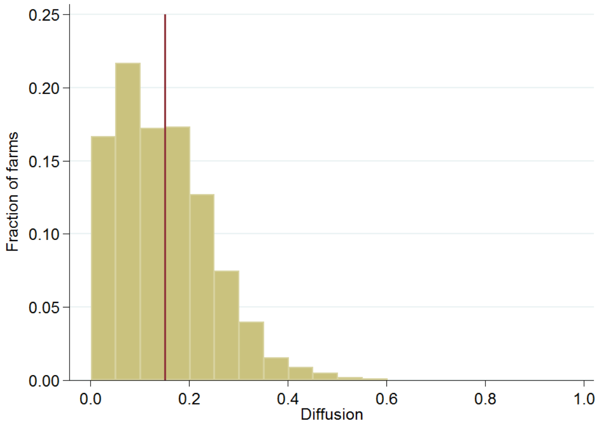
State	**1933**	**1934**	**1935**	**1936**	**1937**	**1938**	**1939**	**1940**
IA	0.7	2.1	6.0	14.4	30.7	51.9	73.4	90.3
IL	0.6	1.5	4.1	9.9	25.2	47.5	65.5	76.4
IN	–	0.3	1.0	3.5	11.1	28.5	50.8	63.1
MN	0.1	0.4	1.4	3.7	9.1	20.4	37.0	57.3
WI	0.1	0.6	1.8	5.0	11.1	24.0	39.7	56.6
OH	–	–	0.4	2.0	6.7	25.0	42.1	56.0
MO	–	–	–	0.3	0.6	1.8	12.1	26.9
NE	0.0	0.1	0.3	1.0	2.5	6.8	12.7	24.9
MI	–	–	0.1	0.5	1.1	3.2	8.1	20.9
SD	–	–	0.1	0.4	1.2	3.1	7.0	12.6
KS	–	–	–	–	0.2	1.6	5.3	10.9
ND	–	–	–	–	–	0.4	1.6	3.8

Notes: Table reports fraction of corn acreage planted to hybrids in each of the 12 Midwest states from 1933 – when records are first available – through 1940. Data from Sutch (2011, 2014).

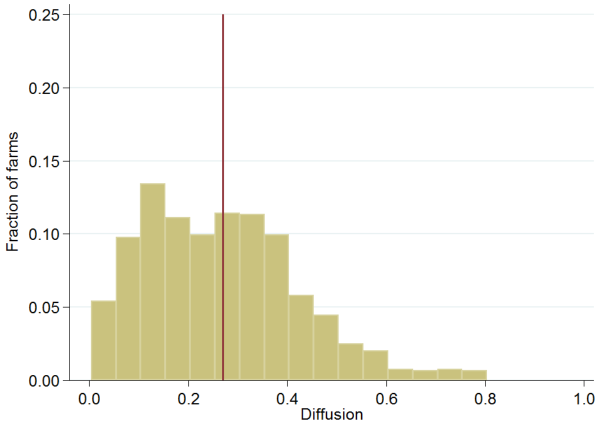
B Histograms of County-Level Diffusion, 1925-1940

Figure B.1: Tractor diffusion in U.S. Midwest, 1925-40: Histograms

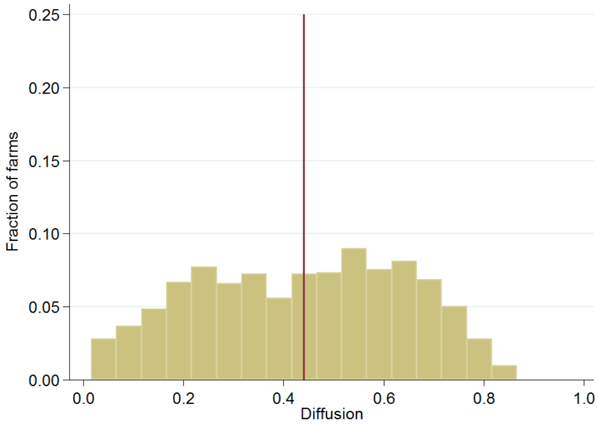
Panel (A): Distribution of counties in 1925



Panel (B): Distribution of counties in 1930



Panel (C): Distribution of counties in 1940



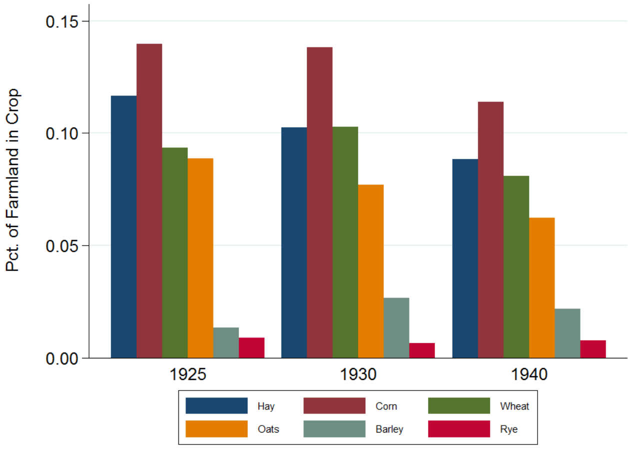
Notes: Figure shows the distribution of tractor diffusion across 1,035 counties in the U.S. Midwest in 1925, 1930, and 1940 (Panels A, B, and C, respectively). Mean county-level diffusion for each period is marked by the vertical line. Data from 1925 to 1940 Census of Agriculture.

C Persistence of Crop Shares Over Time

The following figures demonstrate the persistence of crop mix in the U.S. Midwest from 1910 to 1940. The six most common crops (by acreage) were corn, wheat, oats, barley, rye, and hay, which together comprised 85 percent of harvested acreage throughout the sample period.[2] Figure C.1 shows the percent of Midwest farmland in each of these crops, by decade, while Figures C.2 and C.3 repeat for planted and harvested acreage, respectively – by all measures, persistence in the relative intensity of each crop over the sample period is observed in the aggregate.

Tables C.1 and C.2 present state-level wheat and corn intensity for Midwest states, by decade. From these tables it can be seen that North Dakota and Kansas are the heart of the Wheat Belt, and Iowa and Illinois the heart of the Corn Belt, motivating the comparisons in Figure 3 in the body of the paper. The maps in Figures C.4 to C.27 then show the disaggregated spatial distribution of each crop, by decade, where the Corn Belt and Wheat Belt are plainly visible, as are the growing regions for the other principal Midwestern crops. Correlations between counties' crop shares over the sampling period confirm the spatial persistence visible in these figures.

Figure C.1: Crop shares of midwest farmland, 1910-1940



Notes: Percentages are measured as each crop's harvested acreage over total acres of farmland. Corn acreage is limited to corn harvested for grain only (versus silage). The six crops represented here constitute 46.1% of all acres of farmland in the Midwest in 1925, 45.4% in 1930, and 37.5% in 1940. Data from 1910 to 1940 Census of Agriculture.

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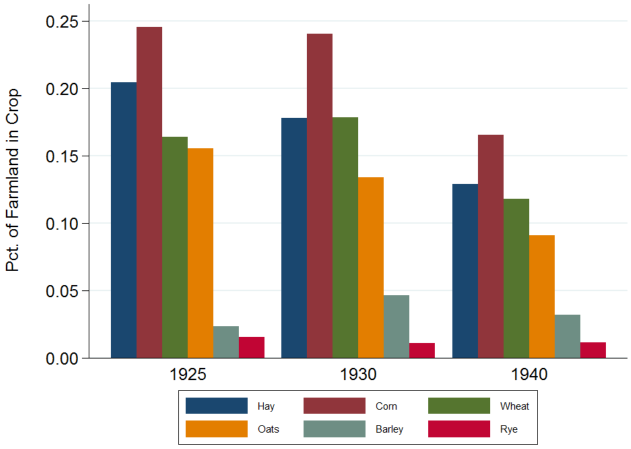
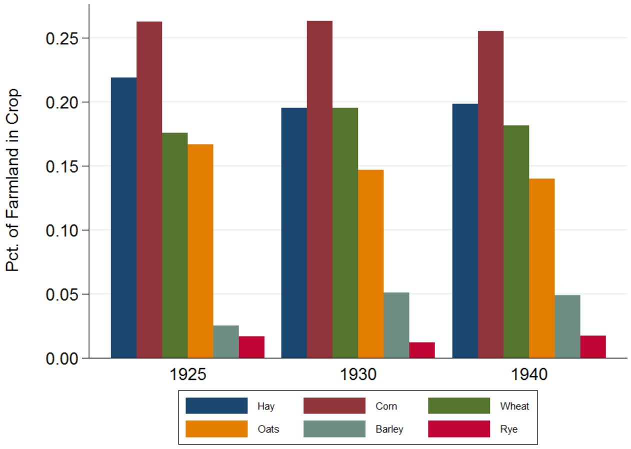
[2] Soybeans were not grown in large quantity until the 1940s, when wartime foreign supply disruptions led to a dramatic expansion in domestic production, primarily displacing corn acreage in the Corn Belt.

Figure C.2: Crop shares of midwest cropland, 1925-1940



Notes: Percentages are measured as each crop's harvested acreage over total acres of cropland. Cropland includes harvested crops, crop failure, and land idle or fallow. Corn acreage is limited to corn harvested for grain only (versus fodder or grazed). The six crops represented here constitute 80.8% of all acres of cropland in the Midwest in 1925, 78.9% in 1930, and 54.5% in 1940. The fraction of cropland in each crop is highly correlated with the fraction of farmland in each crop, with correlations of 0.94 for corn, 0.97 for wheat, 0.95 for oats, 0.97 for barley, 0.96 for rye, and 0.79 for hay. Data from 1925 to 1940 Census of Agriculture.

Figure C.3: Crop shares of midwest harvested acreage, 1925-1940



Notes: Percentages are measured as each crop's harvested acreage over total acres of cropland. Corn acreage is limited to corn harvested for grain only (versus fodder or grazed). The six crops represented here constitute 86.5% of all acres harvested in the Midwest in 1925, 86.3% in 1930, and 84.1% in 1940. The fraction of harvested acreage in each crop is highly correlated with the fraction of farmland in each crop, with correlations of 0.90 for corn, 0.90 for wheat, 0.94 for oats, 0.95 for barley, 0.95 for rye, and 0.73 for hay. Data from 1925 to 1940 Census of Agriculture."

Table C.1: Percent of Farmland in Wheat, State Totals, 1920-1940

State	**1920**	**1925**	**1930**	**1940**
ND	0.27	0.25	0.27	0.19
KS	0.25	0.22	0.26	0.19
IN	0.13	0.08	0.08	0.07
SD	0.13	0.08	0.11	0.06
MO	0.13	0.04	0.05	0.05
IL	0.13	0.07	0.07	0.06
MN	0.13	0.06	0.04	0.05
OH	0.12	0.08	0.07	0.08
NE	0.10	0.07	0.08	0.07
MI	0.06	0.04	0.05	0.04
IA	0.04	0.01	0.01	0.01
WI	0.02	0.01	0.00	0.00

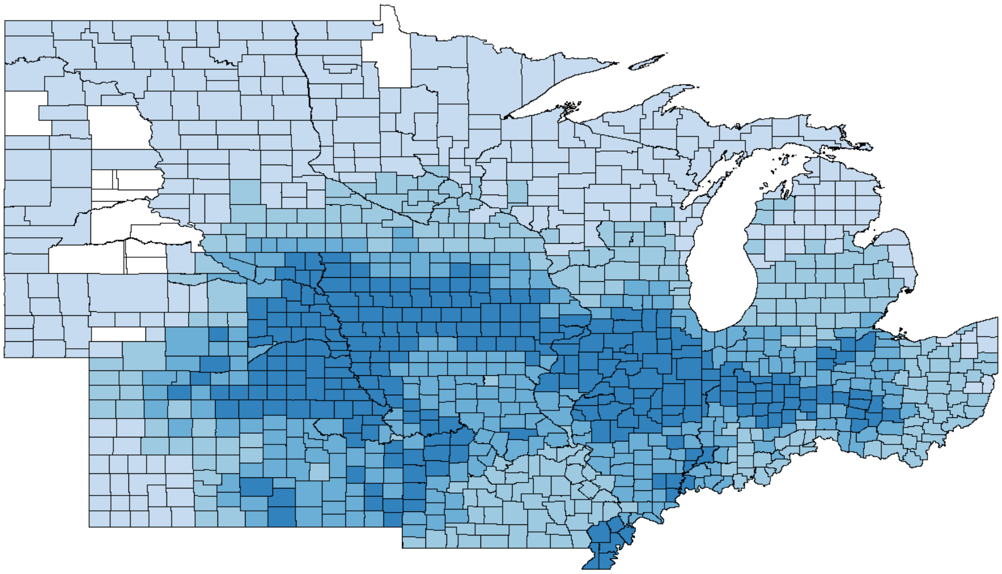
Notes: Table reports state-level wheat intensity as a fraction of farmland, by year, for the U.S. Midwest. Data from 1920 to 1940 Census of Agriculture.

Table C.2: Percent of Farmland in Corn, State Totals, 1920-1940

State	**1920**	**1925**	**1930**	**1940**
IA	0.27	0.26	0.28	0.26
IL	0.25	0.25	0.25	0.24
IN	0.21	0.18	0.19	0.20
NE	0.16	0.19	0.19	0.11
MO	0.16	0.17	0.14	0.12
OH	0.15	0.12	0.14	0.14
SD	0.09	0.12	0.11	0.06
KS	0.08	0.12	0.12	0.04
MN	0.08	0.09	0.09	0.11
MI	0.07	0.04	0.03	0.07
WI	0.05	0.03	0.03	0.05
ND	0.01	0.01	0.00	0.01

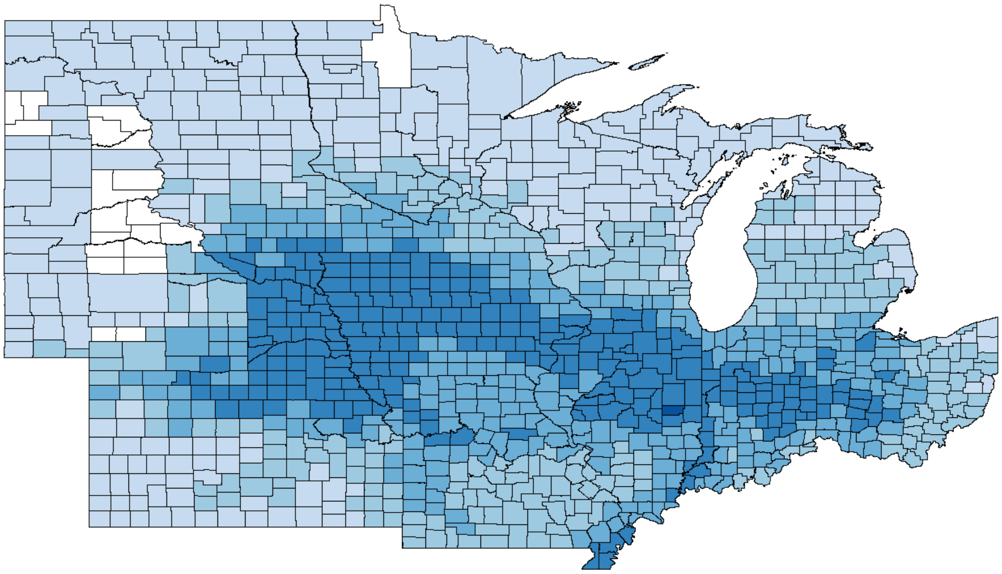
Notes: Table reports state-level corn intensity as a fraction of farmland, by year, for the U.S. Midwest. Data from 1920 to 1940 Census of Agriculture.

Figure C.4: Percent of farmland in corn, 1910



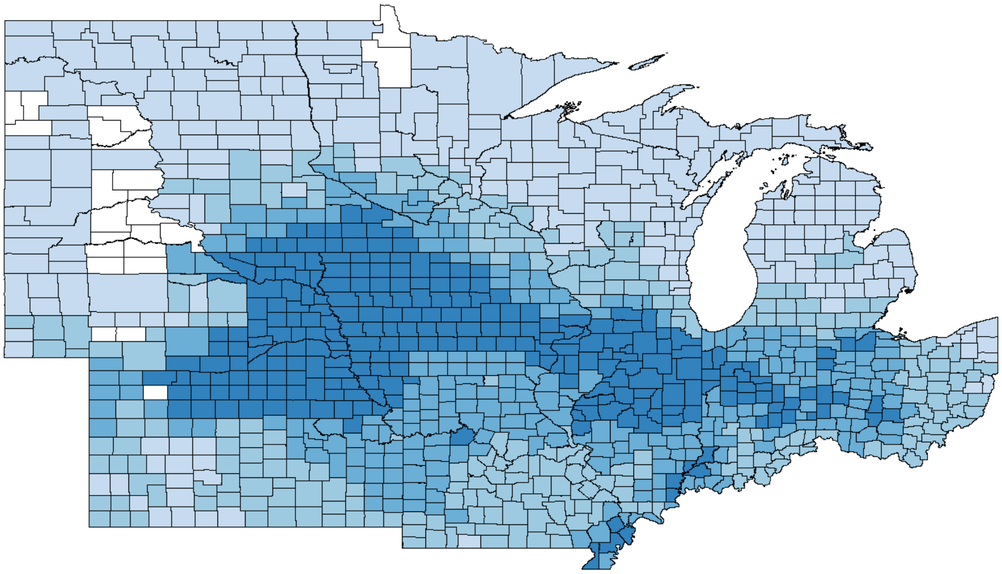
Notes: Map shows the percent of farmland planted in corn in 1910, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.5: Percent of farmland in corn, 1920



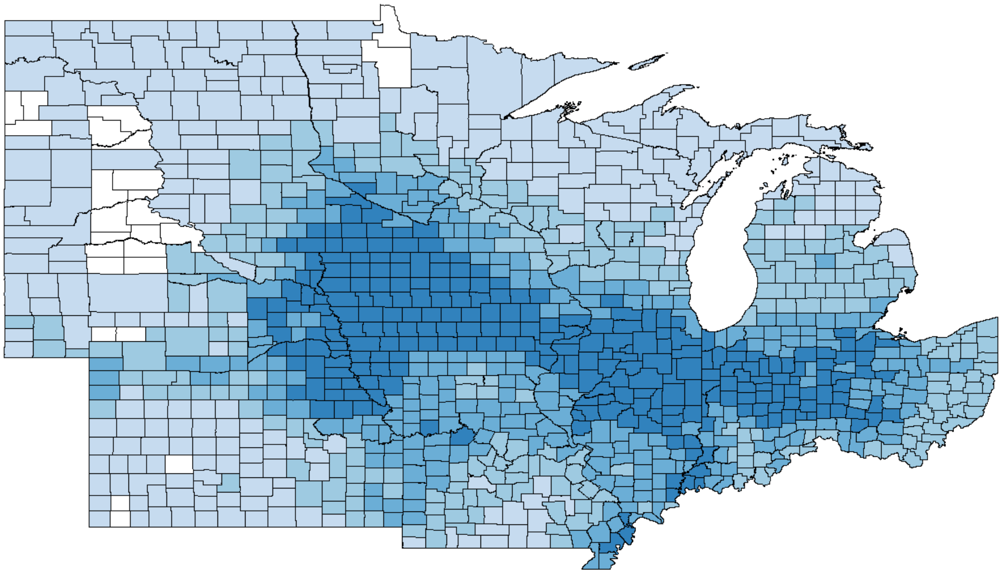
Notes: Map shows the percent of farmland planted in corn in 1920, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.6: Percent of farmland in corn, 1930



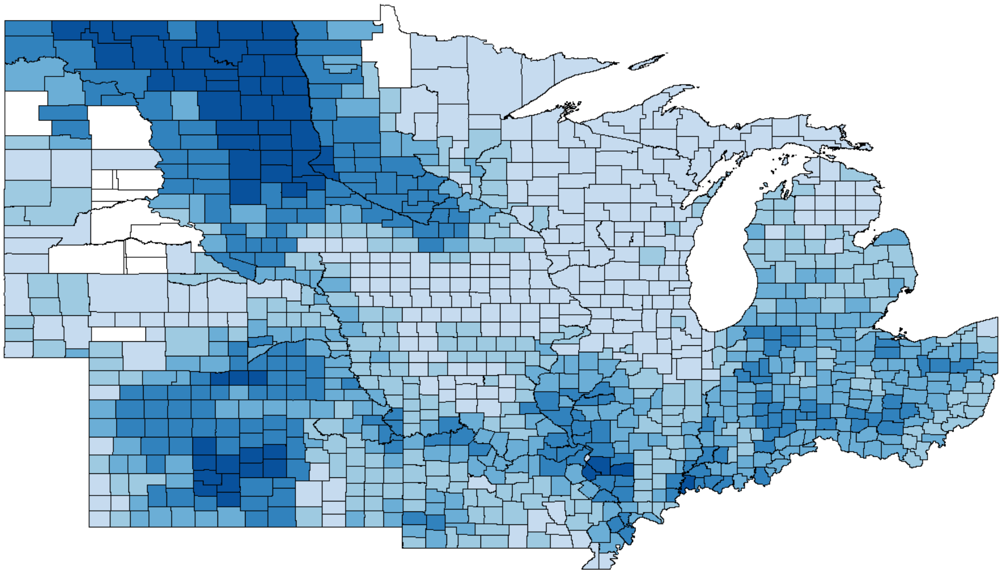
Notes: Map shows the percent of farmland planted in corn in 1930, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.7: Percent of farmland in corn, 1940



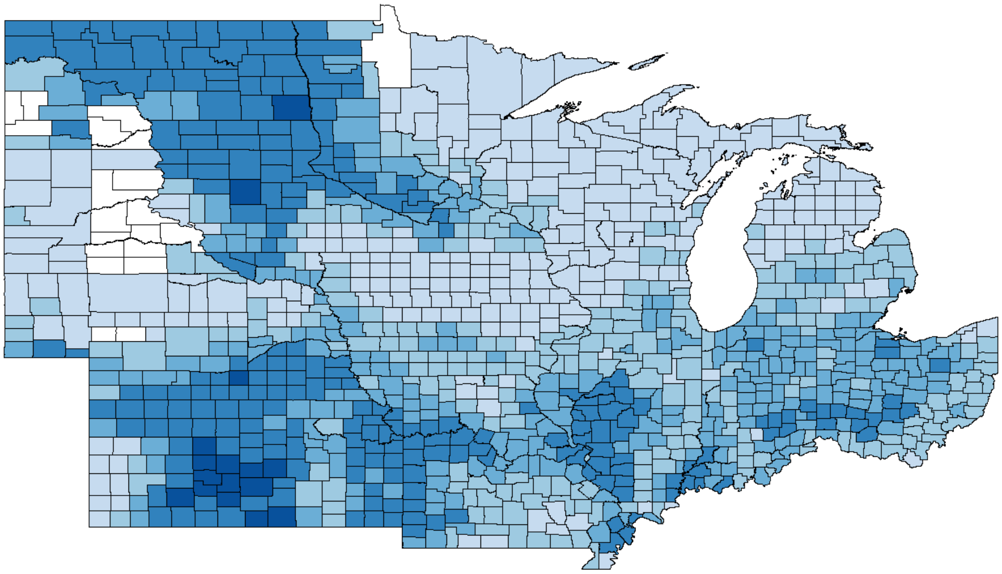
Notes: Map shows the percent of farmland planted in corn in 1940, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.8: Percent of farmland in wheat, 1910



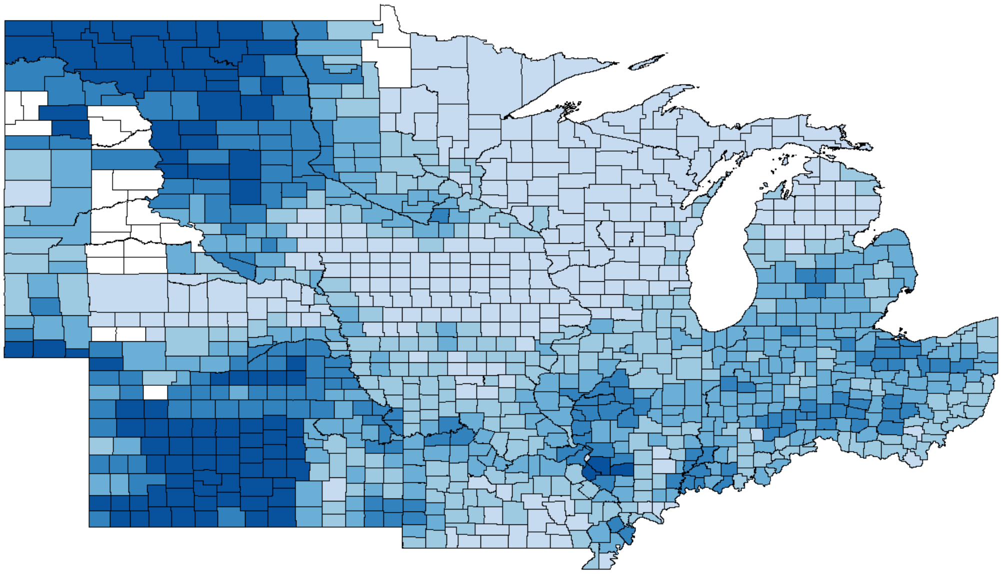
Notes: Map shows the percent of farmland planted in wheat in 1910, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.9: Percent of farmland in wheat, 1920



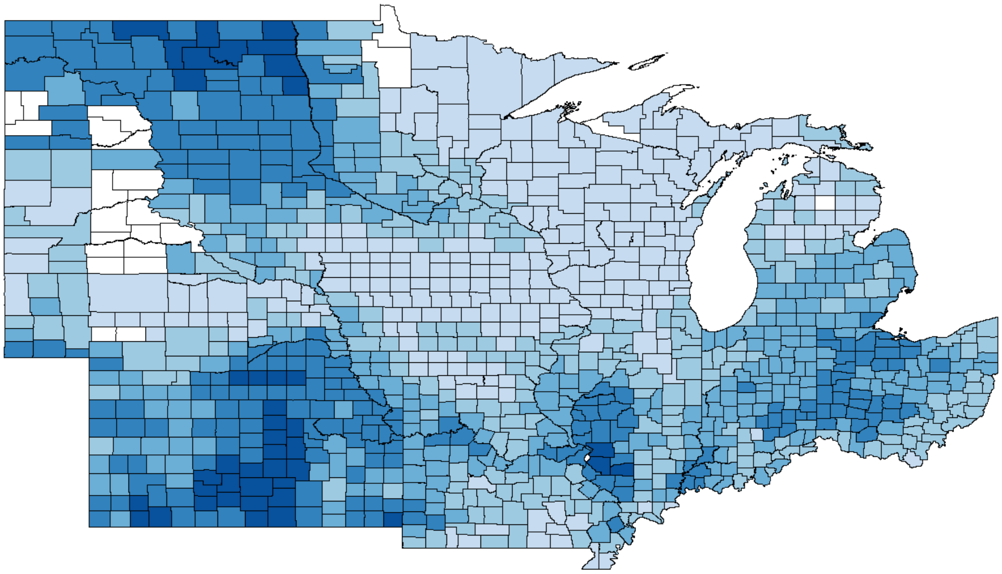
Notes: Map shows the percent of farmland planted in wheat in 1920, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.10: Percent of farmland in wheat, 1930



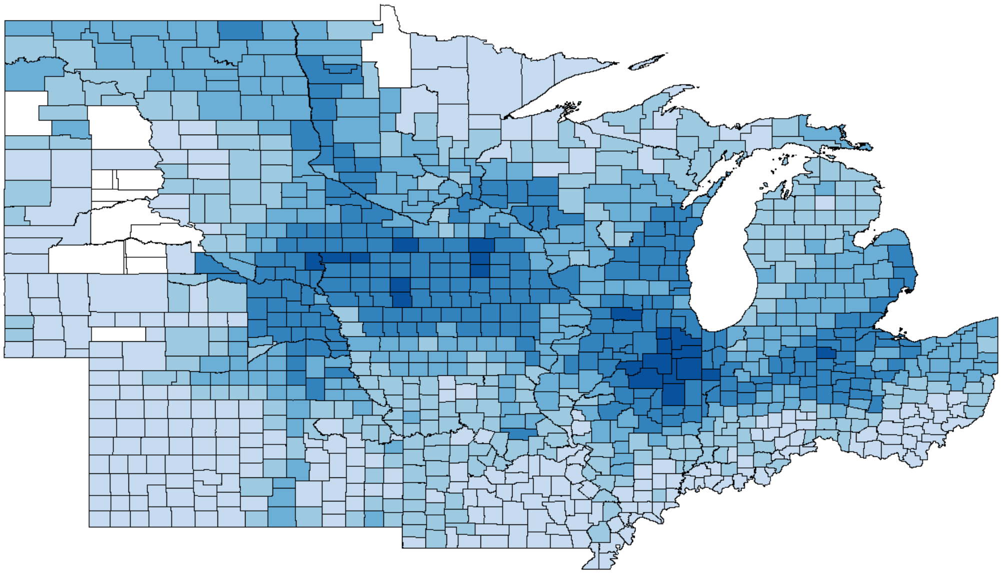
Notes: Map shows the percent of farmland planted in wheat in 1930, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.11: Percent of farmland in wheat, 1940



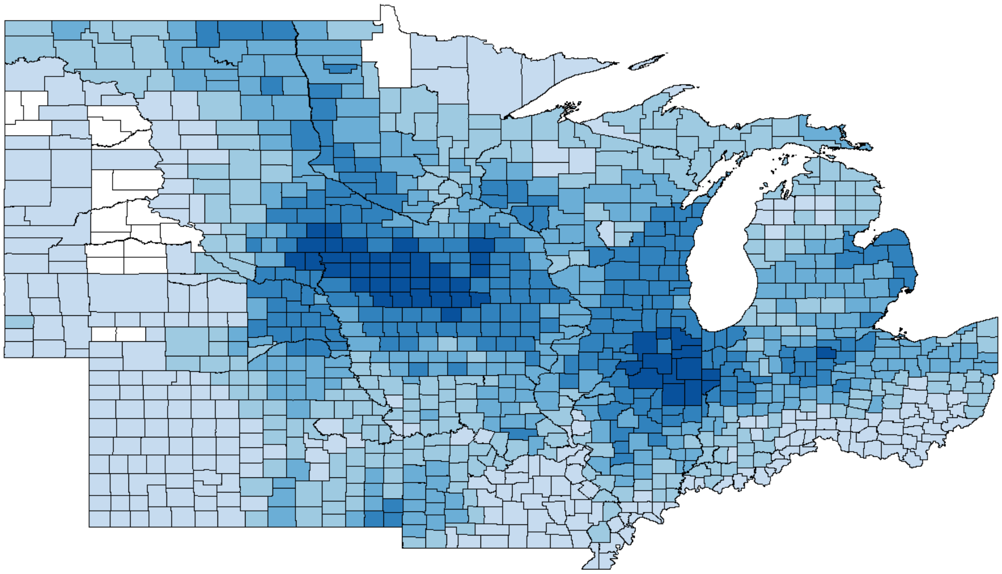
Notes: Map shows the percent of farmland planted in wheat in 1940, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.12: Percent of farmland in oats, 1910



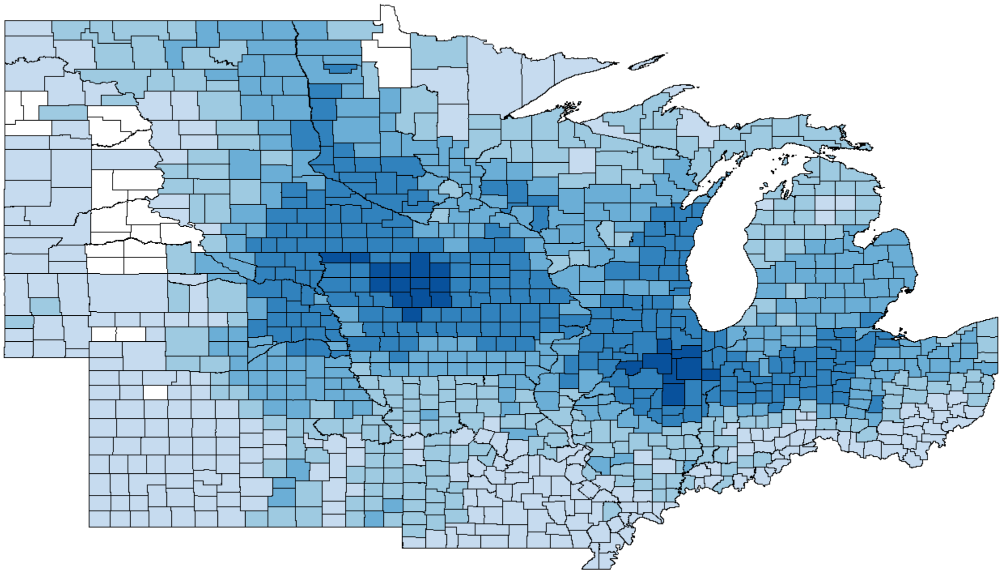
Notes: Map shows the percent of farmland planted in oats in 1910, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.13: Percent of farmland in oats, 1920



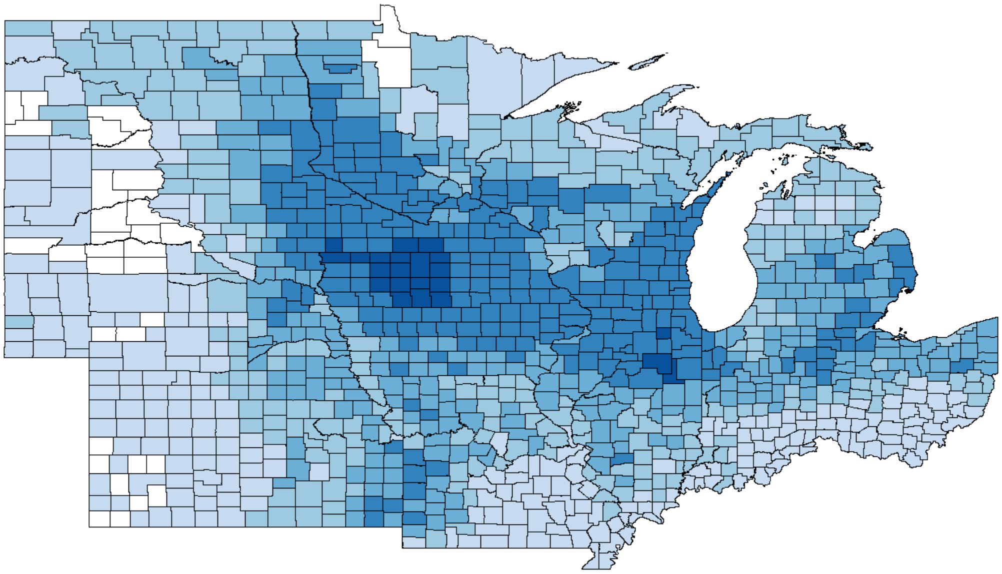
Notes: Map shows the percent of farmland planted in oats in 1920, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.14: Percent of farmland in oats, 1930



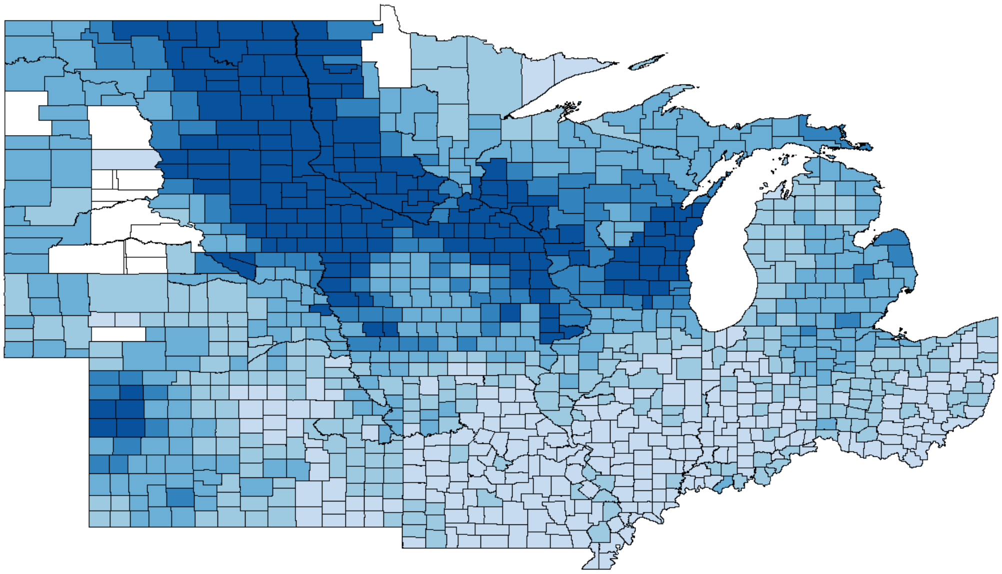
Notes: Map shows the percent of farmland planted in oats in 1930, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.15: Percent of farmland in oats, 1940



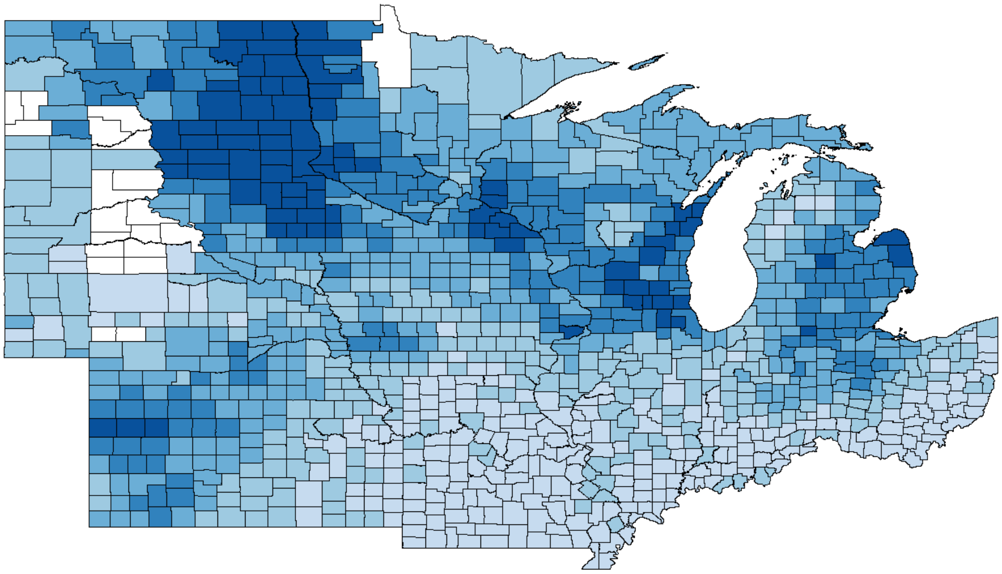
Notes: Map shows the percent of farmland planted in oats in 1940, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.16: Percent of farmland in barley, 1910



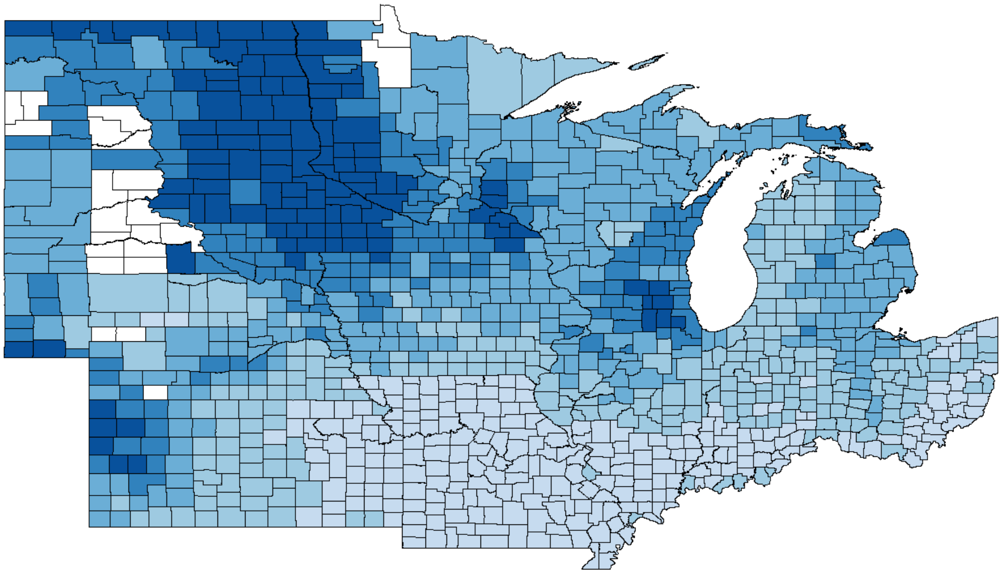
Notes: Map shows the percent of farmland planted in barley in 1910, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.17: Percent of farmland in barley, 1920



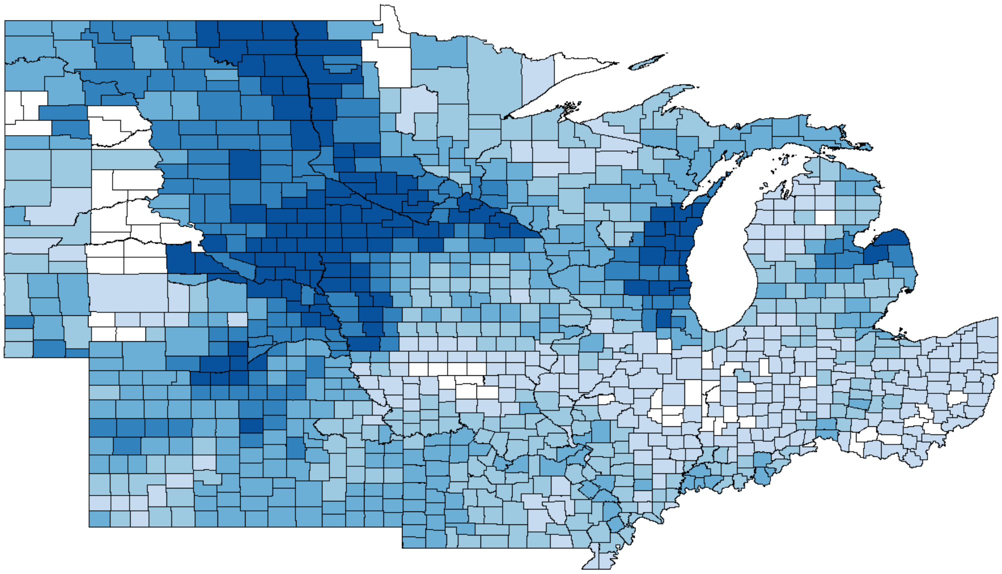
Notes: Map shows the percent of farmland planted in barley in 1920, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.18: Percent of farmland in barley, 1930



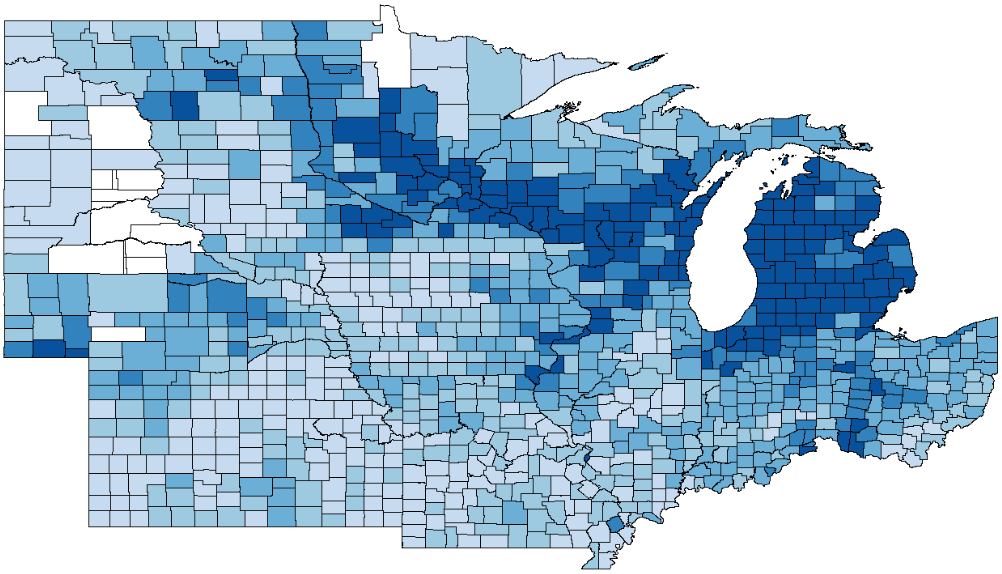
Notes: Map shows the percent of farmland planted in barley in 1930, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.19: Percent of farmland in barley, 1940



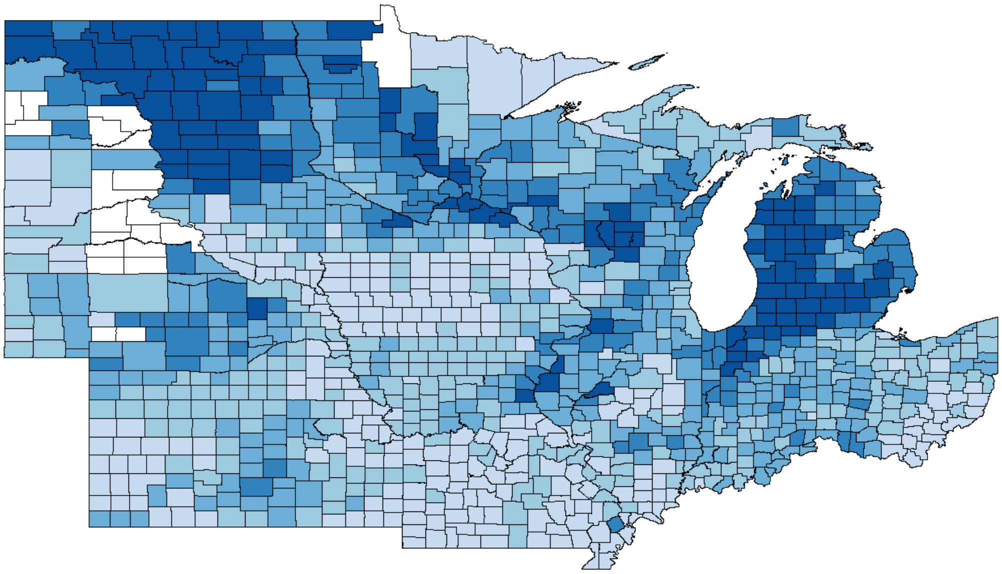
Notes: Map shows the percent of farmland planted in barley in 1940, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.20: Percent of farmland in rye, 1910



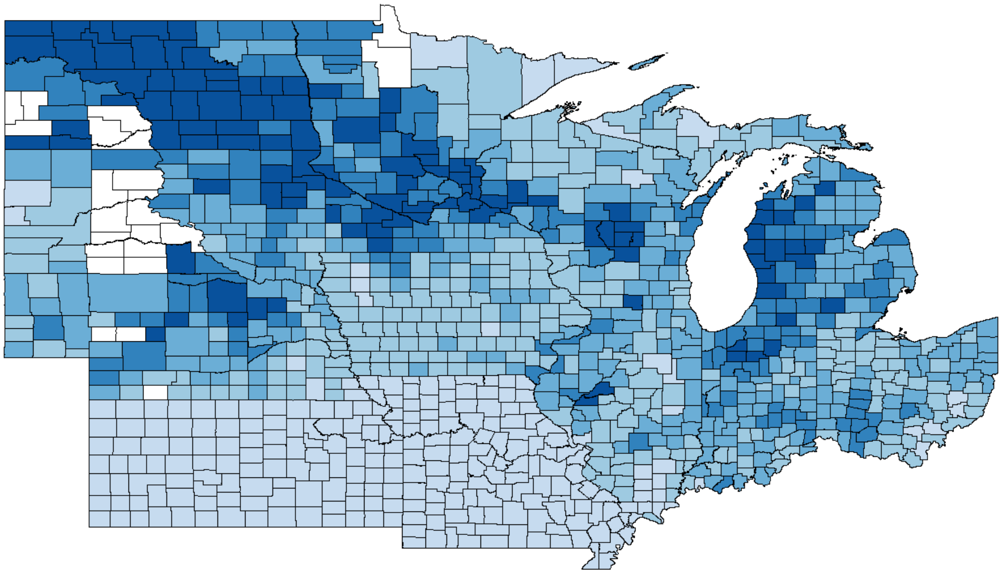
Notes: Map shows the percent of farmland planted in rye in 1910, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.21: Percent of farmland in rye, 1920



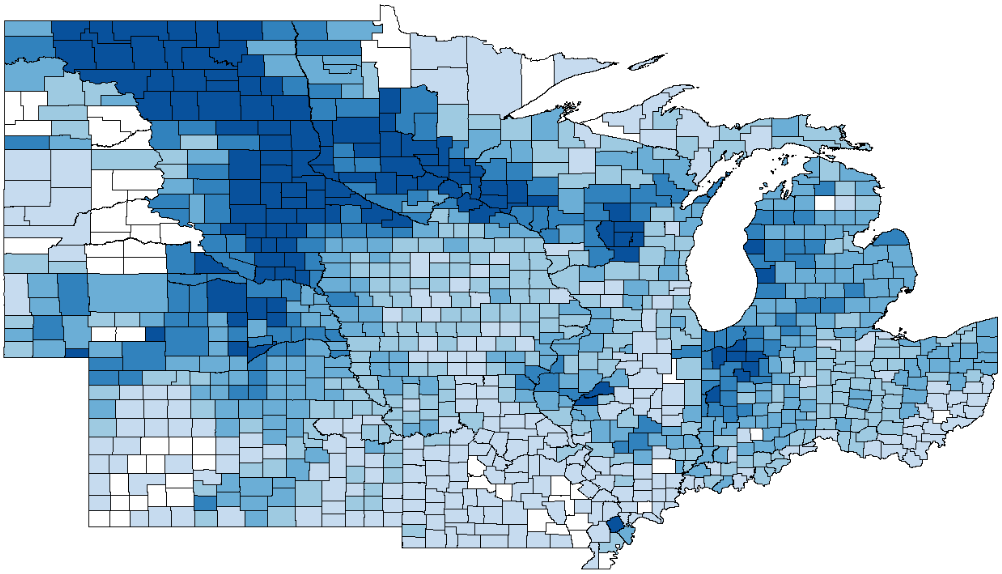
Notes: Map shows the percent of farmland planted in rye in 1920, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.22: Percent of farmland in rye, 1930



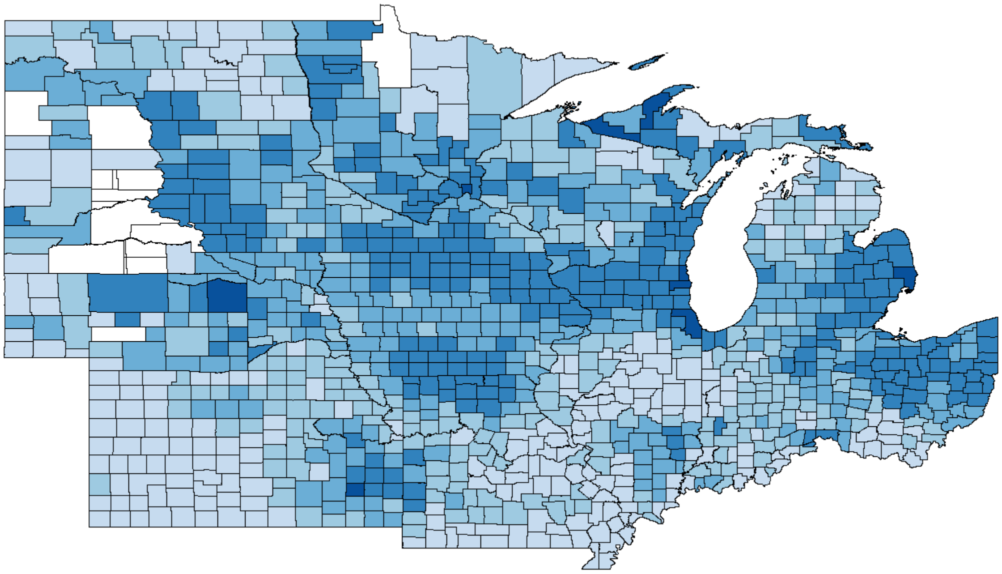
Notes: Map shows the percent of farmland planted in rye in 1930, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.23: Percent of farmland in rye, 1940



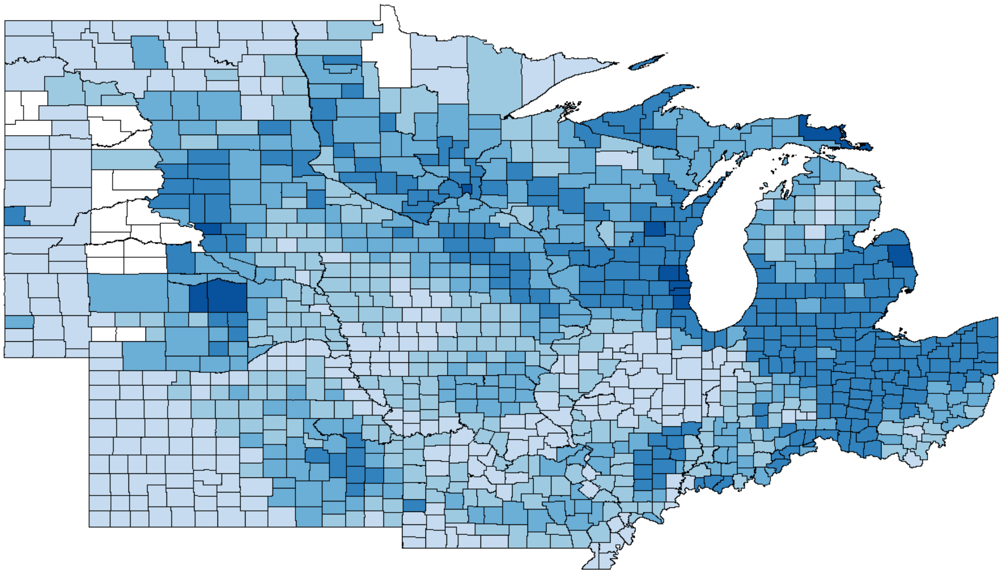
Notes: Map shows the percent of farmland planted in rye in 1940, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.24: Percent of farmland in hay, 1910



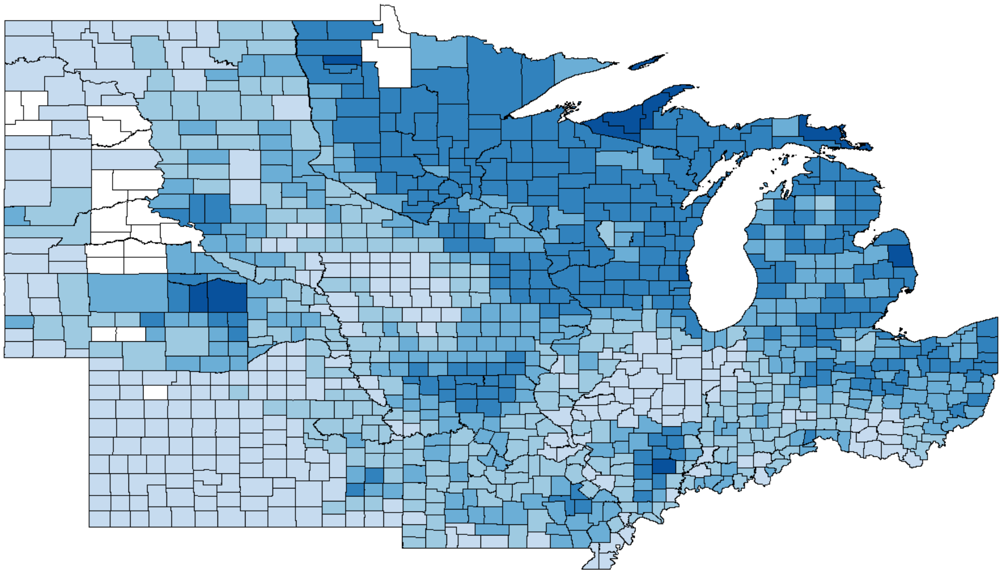
Notes: Map shows the percent of farmland planted in hay in 1910, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.25: Percent of farmland in hay, 1920



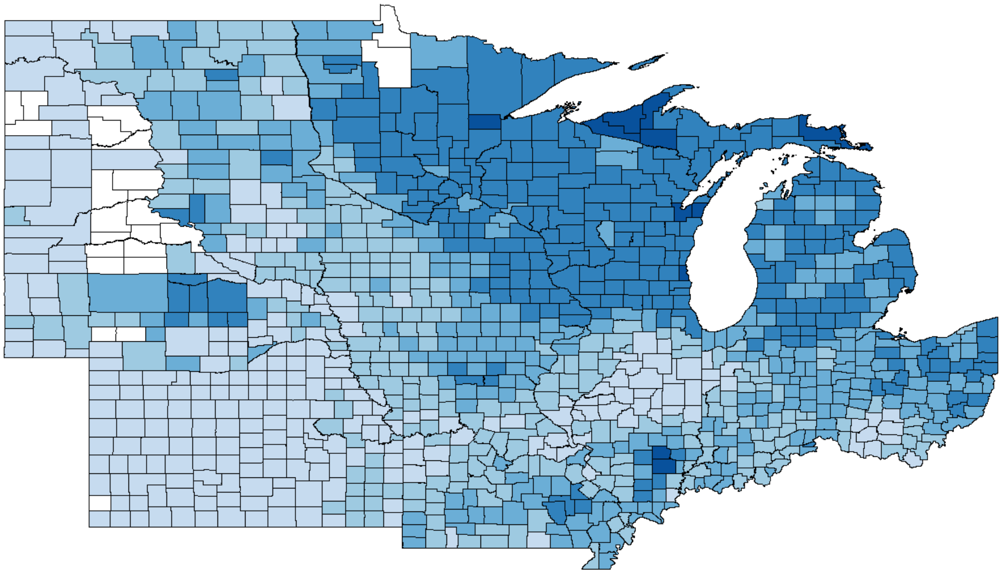
Notes: Map shows the percent of farmland planted in hay in 1920, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.26: Percent of farmland in hay, 1930



Notes: Map shows the percent of farmland planted in hay in 1930, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

Figure C.27: Percent of farmland in hay, 1940



Notes: Map shows the percent of farmland planted in hay in 1940, with darker colors indicating greater concentrations. Data from 1910 to 1940 Census of Agriculture.

D Alternative Dependent Variables

The specifications in the paper estimate linear models for the fraction of farms in a county reporting a tractor. This appendix repeats the exercise for alternative definitions of diffusion.

The next check replaces diffusion with the log-odds ratio: if diffusion follows a logistic pattern in the explanatory variables, then the log-odds ratio will be linear in these variables. Though Griliches (1957) demonstrates that diffusion follows a logistic pattern over time, it is not ex-ante obvious that it does so in other variables – but in the event that it does, the results in Table D.1 lay to rest any concerns that the results in the paper are driven by mismeasurement of the dependent variable, as the patterns persist for the log-odds measure.

As discussed in the paper, the focal definition also imposes an assumption of perfect indivisibility, despite evidence to the contrary of cooperative ownership (Myers 1921) and custom work (Gilbert 1930). To ensure that the results are not sensitive to this assumption, in Table D.2 I re-estimate these regressions defining diffusion as the number of tractors per 100 acres of county farmland. The regressions for 1925-1930 are estimated on a sample excluding the Plains states (North and South Dakota, Kansas, and Nebraska), where farmland was expanding rapidly at the time. The results are qualitatively similar to those in the body of the paper.

Tables D.3 to D.5 provide further checks on the main results, estimating specifications with Conley (1999) standard errors, which allow for spatial correlation in the error term that declines linearly in distance up to a fixed radius from the unit of observation. The tables set the cutoff radius to 20, 50, and 100 miles (respectively) from county centroids. Though the standard errors increase with the cutoff distance, the results continue to hold at the widest radius.

Table D.1: Crop Intensity and Changes in Tractor Diffusion from 1925 to 1940 (Log-Odds Ratio)

		Additional controls for:						Restricted to:	
	Baseline (1)	Crop Mix (2)	Farm Size (3)	Other Farm Characteristics (4)	Financial Conditions (5)	Climate/ Geography (6)	New Deal Relief (7)	Dust Bowl Counties (8)	Early Hybrid Corn Adopters (9)
Panel A: Diffusion (log-odds) from 1925-1930									
Pct. in Wheat	0.799***	0.783***	0.726***	1.086***	0.517***	0.593***	0.421***		
x Year=1930	(0.131)	(0.154)	(0.145)	(0.159)	(0.165)	(0.165)	(0.159)		
Pct. in Corn	-0.427***	-0.571***	-0.497***	-0.261**	-0.274**	-0.305***	-0.303***		
x Year=1930	(0.092)	(0.107)	(0.115)	(0.117)	(0.120)	(0.126)	(0.125)		
Difference	-1.23***	-1.35***	-1.22***	-1.35***	-0.79***	-0.90***	-0.72***		
p-value	(0.16)	(0.19)	(0.18)	(0.19)	(0.20)	(0.20)	(0.19)		
N	2064	2064	2064	2064	2064	2064	2064		
R^2	0.36	0.62	0.69	0.74	0.78	0.81	0.82		
Panel B: Diffusion (log-odds) from 1930-1940									
Pct. in Wheat	-0.506***	-0.438***	-0.607***	-0.809***	-1.278***	-1.202***	-1.249***	-0.986***	-1.033***
x Year=1940	(0.117)	(0.152)	(0.152)	(0.152)	(0.177)	(0.171)	(0.166)	(0.193)	(0.345)
Pct. in Corn	1.370***	1.754***	1.914***	1.241***	1.697***	1.845***	1.519***	0.628***	1.329***
x Year=1940	(0.095)	(0.145)	(0.149)	(0.205)	(0.189)	(0.187)	(0.196)	(0.253)	(0.260)
Difference	1.88***	2.19***	2.52***	2.05***	2.98***	3.05***	2.77***	1.61***	2.36***
p-value	(0.14)	(0.22)	(0.22)	(0.22)	(0.23)	(0.22)	(0.23)	(0.22)	(0.48)
N	1886	1886	1886	1886	1886	1886	1886	874	986
R^2	0.37	0.63	0.71	0.76	0.81	0.85	0.86	0.85	0.88

Notes: Table shows the relationship between pre-period crop intensity and changes in the log-odds ratio of county-level tractor diffusion from 1925-30 and 1930-40 (Panels A and B, respectively). Column (1) repeats the baseline estimates from Table 4, and the remaining columns provide robustness checks. Column (2) adds controls for the intensity of other major Midwest crops (oats, barley, rye, hay); Column (3) adds further controls for the distribution of farms by size (i.e., fraction <20 acres, 20-49 acres, 50-99 acres, 100-259 acres, and >260 acres) and the log mean farm size; Column (4) adds controls for substitute inputs (horses per acre, mules per acre, labor expenditure per acre); Column (5) adds controls for financial variables (farm mortgage interest rates and debt ratios); Column (6) adds controls for geographic and climatological variables (centroid coordinates, distance from Detroit and Chicago, quadratics in county mean temperature and annual rainfall, and intra-county variation in elevation); Column (7) adds controls for local New Deal Relief (AAA spending and FCA lending per capita). The latter two columns in Panel B retain the controls but restrict to counties in the Hornbeck (2012) Dust Bowl sample or to states that were leading adopters of hybrid seed corn to evaluate whether the effects are explained by contemporaneous shocks to Midwest agriculture in the 1930s. The difference in the diffusion rates to wheat- vs. corn-intensive counties is provided below the regression estimates. *, **, *** represent significance at the 0.1, 0.05, and 0.01 levels, respectively. SEs clustered by county in parentheses.

Table D.2: Crop Intensity and Changes in Tractor Diffusion from 1925 to 1940 (Tractors per 100 Acres)

		Additional controls for:						Restricted to:	
	Baseline (1)	Crop Mix (2)	Farm Size (3)	Other Farm Characteristics (4)	Financial Conditions (5)	Climate/ Geography (6)	New Deal Relief (7)	Dust Bowl Counties (8)	Early Hybrid Corn Adopters (9)
Panel A: Diffusion (per 100 acres) from 1925-1930, excluding Plains states									
Pct. in Wheat	0.226***	0.229***	0.271***	0.277***	0.294***	0.300***	0.299***		
x Year=1930	(0.037)	(0.040)	(0.043)	(0.037)	(0.038)	(0.039)	(0.039)		
Pct. in Corn	0.039***	0.048***	-0.010	0.045***	0.025	0.033*	0.032*		
x Year=1930	(0.015)	(0.017)	(0.020)	(0.015)	(0.017)	(0.018)	(0.018)		
Difference	-0.19***	-0.18***	-0.28***	-0.23***	-0.27***	-0.27***	-0.27***		
s.e.	(0.04)	(0.05)	(0.05)	(0.04)	(0.04)	(0.05)	(0.05)		
N	1466	1466	1466	1466	1466	1466	1466		
R^2	0.21	0.45	0.66	0.76	0.77	0.79	0.79		
Panel B: Diffusion (per 100 acres) from 1930-1940									
Pct. in Wheat	-0.168***	-0.179***	-0.163***	-0.191***	-0.198***	-0.190***	-0.193***	-0.140***	0.033
x Year=1940	(0.020)	(0.024)	(0.023)	(0.024)	(0.026)	(0.025)	(0.025)	(0.027)	(0.055)
Pct. in Corn	0.215***	0.413***	0.325***	0.231***	0.285***	0.299***	0.277***	0.273***	0.217***
x Year=1940	(0.020)	(0.027)	(0.026)	(0.031)	(0.030)	(0.030)	(0.030)	(0.038)	(0.044)
Difference	0.38***	0.59***	0.49***	0.42***	0.48***	0.49***	0.47***	0.41***	0.18***
p-value	(0.02)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.07)
N	1886	1886	1886	1886	1886	1886	1886	874	986
R^2	0.20	0.46	0.68	0.76	0.78	0.82	0.82	0.88	0.85

Notes: Table shows the relationship between pre-period crop intensity and changes in county-level tractors per hundred farm acres from 1925-30 and 1930-40 (Panels A and B, respectively). Column (1) repeats the baseline estimates from Table 4, and the remaining columns provide robustness checks. Column (2) adds controls for the intensity of other major Midwest crops (oats, barley, rye, hay); Column (3) adds further controls for the distribution of farms by size (i.e., fraction <20 acres, 20-49 acres, 50-99 acres, 100-259 acres, and >260 acres) and the log mean farm size; Column (4) adds controls for substitute inputs (horses per acre, mules per acre, labor expenditure per acre); Column (5) adds controls for financial variables (farm mortgage interest rates and debt ratios); Column (6) adds controls for geographic and climatological variables (centroid coordinates, distance from Detroit and Chicago, quadratics in county mean temperature and annual rainfall, and intra-county variation in elevation); Column (7) adds controls for local New Deal Relief (AAA spending and FCA lending per capita). The latter two columns in Panel B retain the controls but restrict to counties in the Hornbeck (2012) Dust Bowl sample or to states that were leading adopters of hybrid seed corn to evaluate whether the effects are explained by contemporaneous shocks to Midwest agriculture in the 1930s. The difference in the diffusion rates to wheat- vs. corn-intensive counties is provided below the regression estimates. *, **, *** represent significance at the 0.1, 0.05, and 0.01 levels, respectively. SEs clustered by county in parentheses.

Table D.3: Crop Intensity and Changes in Tractor Diffusion from 1925 to 1940: All specifications, with 20-mile Conley s.e.

		Additional controls for:						Restricted to:	
	Baseline (1)	Crop Mix (2)	Farm Size (3)	Other Farm Characteristics (4)	Financial Conditions (5)	Climate/ Geography (6)	New Deal Relief (7)	Dust Bowl Counties (8)	Early Hybrid Corn Adopters (9)
				Panel A: Diffusion (levels) from 1925-1930					
Pct. in Wheat	0.436***	0.419***	0.407***	0.444***	0.390***	0.398***	0.371***		
x Year=1930	(0.028)	(0.031)	(0.030)	(0.030)	(0.030)	(0.030)	(0.029)		
Pct. in Corn	0.015	-0.005	0.001	0.024	0.036*	0.021	0.021		
x Year=1930	(0.020)	(0.021)	(0.021)	(0.022)	(0.021)	(0.022)	(0.022)		
Difference	-0.42***	-0.42***	-0.41***	-0.42***	-0.35***	-0.38***	-0.35***		
p-value	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)		
N	2064	2064	2064	2064	2064	2064	2064		
R^2	0.81	0.89	0.91	0.92	0.92	0.93	0.94		
				Panel B: Diffusion (levels) from 1930-1940					
Pct. in Wheat	0.038	0.053	0.022	-0.046	-0.100***	-0.104***	-0.114***	-0.170***	-0.077
x Year=1940	(0.030)	(0.038)	(0.036)	(0.035)	(0.037)	(0.035)	(0.034)	(0.042)	(0.072)
Pct. in Corn	0.414***	0.473***	0.507***	0.319***	0.394***	0.408***	0.339***	0.205***	0.338***
x Year=1940	(0.022)	(0.032)	(0.032)	(0.038)	(0.035)	(0.035)	(0.036)	(0.053)	(0.051)
Difference	0.38***	0.42***	0.48***	0.36***	0.49***	0.51***	0.45***	0.38***	0.42***
p-value	(0.04)	(0.05)	(0.05)	(0.05)	(0.05)	(0.05)	(0.05)	(0.05)	(0.10)
N	1886	1886	1886	1886	1886	1886	1886	874	986
R^2	0.86	0.92	0.94	0.95	0.96	0.96	0.97	0.98	0.97

Notes: Table shows the estimates from Table 5 in the paper with Conley (1999) standard errors, which allow for spatial correlation in the error term that declines linearly in distance up to a fixed cutoff point. The difference in the diffusion rates to wheat- vs. corn-intensive counties is provided below the regression estimates. *, **, *** represent significance at the 0.1, 0.05, and 0.01 levels, respectively. Conley SEs in parentheses.

Table D.4: Crop Intensity and Changes in Tractor Diffusion from 1925 to 1940: All specifications, with 50-mile Conley s.e.

		Additional controls for:						Restricted to:	
	Baseline (1)	Crop Mix (2)	Farm Size (3)	Other Farm Characteristics (4)	Financial Conditions (5)	Climate/ Geography (6)	New Deal Relief (7)	Dust Bowl Counties (8)	Early Hybrid Corn Adopters (9)
Panel A: Diffusion (levels) from 1925-1930									
Pct. in Wheat	0.436***	0.419***	0.407***	0.444***	0.390***	0.398***	0.371***		
x Year=1930	(0.039)	(0.045)	(0.042)	(0.042)	(0.041)	(0.040)	(0.039)		
Pct. in Corn	0.015	-0.005	0.001	0.024	0.036	0.021	0.021		
x Year=1930	(0.030)	(0.031)	(0.031)	(0.032)	(0.031)	(0.032)	(0.032)		
Difference	-0.42***	-0.42***	-0.41***	-0.42***	-0.35***	-0.38***	-0.35***		
p-value	(0.05)	(0.06)	(0.06)	(0.06)	(0.05)	(0.05)	(0.05)		
N	2064	2064	2064	2064	2064	2064	2064		
R^2	0.81	0.89	0.91	0.92	0.92	0.93	0.94		
Panel B: Diffusion (levels) from 1930-1940									
Pct. in Wheat	0.038	0.053	0.022	-0.046	-0.100*	-0.104**	-0.114***	-0.170***	-0.077
x Year=1940	(0.045)	(0.058)	(0.053)	(0.051)	(0.053)	(0.051)	(0.049)	(0.057)	(0.103)
Pct. in Corn	0.414***	0.473***	0.507***	0.319***	0.394***	0.408***	0.339***	0.205***	0.338***
x Year=1940	(0.033)	(0.051)	(0.049)	(0.054)	(0.048)	(0.048)	(0.047)	(0.061)	(0.068)
Difference	0.38***	0.42***	0.48***	0.36***	0.49***	0.51***	0.45***	0.38***	0.42***
p-value	(0.06)	(0.09)	(0.08)	(0.08)	(0.07)	(0.07)	(0.07)	(0.06)	(0.14)
N	1886	1886	1886	1886	1886	1886	1886	874	986
R^2	0.86	0.92	0.94	0.95	0.96	0.96	0.97	0.98	0.97

Notes: Table shows the estimates from Table 5 in the paper with Conley (1999) standard errors, which allow for spatial correlation in the error term that declines linearly in distance up to a fixed cutoff point. The difference in the diffusion rates to wheat- vs. corn-intensive counties is provided below the regression estimates. *, **, *** represent significance at the 0.1, 0.05, and 0.01 levels, respectively. Conley SEs in parentheses.

Table D.5: Crop Intensity and Changes in Tractor Diffusion from 1925 to 1940: All specifications, with 100-mile Conley s.e.

		Additional controls for:						Restricted to:	
	Baseline (1)	Crop Mix (2)	Farm Size (3)	Other Farm Characteristics (4)	Financial Conditions (5)	Climate/ Geography (6)	New Deal Relief (7)	Dust Bowl Counties (8)	Early Hybrid Corn Adopters (9)
Panel A: Diffusion (levels) from 1925-1930									
Pct. in Wheat	0.436***	0.419***	0.407***	0.444***	0.390***	0.398***	0.371***		
x Year=1930	(0.056)	(0.066)	(0.061)	(0.058)	(0.056)	(0.056)	(0.052)		
Pct. in Corn	0.015	-0.005	0.001	0.024	0.036	0.021	0.021		
x Year=1930	(0.045)	(0.046)	(0.046)	(0.047)	(0.047)	(0.048)	(0.048)		
Difference	-0.42***	-0.42***	-0.41***	-0.42***	-0.35***	-0.38***	-0.35***		
p-value	(0.08)	(0.09)	(0.08)	(0.08)	(0.08)	(0.08)	(0.07)		
N	2064	2064	2064	2064	2064	2064	2064		
R^2	0.81	0.89	0.91	0.92	0.92	0.93	0.94		
Panel B: Diffusion (levels) from 1930-1940									
Pct. in Wheat	0.038	0.053	0.022	-0.046	-0.100	-0.104	-0.114	-0.170**	-0.077
x Year=1940	(0.065)	(0.087)	(0.078)	(0.074)	(0.077)	(0.072)	(0.070)	(0.077)	(0.138)
Pct. in Corn	0.414***	0.473***	0.507***	0.319***	0.394***	0.408***	0.339***	0.205***	0.338***
x Year=1940	(0.051)	(0.082)	(0.076)	(0.082)	(0.068)	(0.067)	(0.063)	(0.070)	(0.089)
Difference	0.38***	0.42***	0.48***	0.36***	0.49***	0.51***	0.45***	0.38***	0.42**
p-value	(0.09)	(0.14)	(0.13)	(0.12)	(0.10)	(0.10)	(0.10)	(0.09)	(0.19)
N	1886	1886	1886	1886	1886	1886	1886	874	986
R^2	0.86	0.92	0.94	0.95	0.96	0.96	0.97	0.98	0.97

Notes: Table shows the estimates from Table 5 in the paper with Conley (1999) standard errors, which allow for spatial correlation in the error term that declines linearly in distance up to a fixed cutoff point. The difference in the diffusion rates to wheat- vs. corn-intensive counties is provided below the regression estimates. *, **, *** represent significance at the 0.1, 0.05, and 0.01 levels, respectively. Conley SEs in parentheses.

E Proofs of Propositions

Proposition 1:

1) In the long run, general and application-specific quality will develop up to an interior solution where marginal benefits equate to costs across all $z \in \{z_g, z_{a_1}, \ldots, z_{a_n}\}$ for which $z > 0$.

2) Product development will follow an adjustment path along which technological attributes with the highest shadow price are developed until others exceed it.

Proof/explanation:

Part (1): For the long run solution, the firm faces an unconstrained optimization, with $n+1$ first-order conditions, one for each $z \in \{z_g, z_{a_1}, \ldots, z_{a_n}\}$. Each of these FOCs will equate Π_{z_γ} (marginal benefits to the firm of increasing z_γ) to $C^\gamma_{z_\gamma}$ (the marginal costs). These FOCs will yield an interior solution because Π is concave in z_γ at the limit and C^γ is convex in z_γ.

Part (2): In the short run, the budget constraint is binding. The firm then faces a constrained optimization, again with $n+1$ first-order conditions, but the budget constraint will induce a sequence of corner solutions until the unconstrained interior solution is achieved.

To simplify notation, let: $\Pi_\gamma = \Pi_{z_\gamma}$, $\Pi_{\gamma\gamma} = \Pi_{z_\gamma z_\gamma}$, $C^\gamma_\gamma = C^\gamma_{z_\gamma}$, and $C^\gamma_{\gamma\gamma} = C^\gamma_{z_\gamma z_\gamma}$.

To begin, suppose $\exists\ \delta > 0$ such that $\forall\ \epsilon \in (0, \delta)$, $\exists\ \gamma \in \{g, a_1, \ldots, a_n\}$ such that:

1. $\frac{\Pi_\gamma(\epsilon)}{C^\gamma_\gamma(\epsilon)} > 1$
2. $\frac{\Pi_\gamma(\epsilon)}{C^\gamma_\gamma(\epsilon)} > \frac{\Pi_\kappa(\epsilon)}{C^\kappa_\kappa(\epsilon)}$ for all $\kappa \neq \gamma$

In words, some attribute will have a positive shadow price at the onset, and this shadow price is higher than that of any other attribute. Then the technology will be be invented, and will first develop z_γ, with $z_\gamma > 0$ by the end of the first period. (Note that there may be some κ's such that $\forall\ \epsilon > 0$, $\Pi_\kappa(\epsilon)/C^\kappa_\kappa(\epsilon) < 1$: these qualities z_κ will never develop.)

At this point, we have qualities developed up to $\{z_\gamma > 0;\ z_\kappa = 0\ \forall\ \kappa \neq \gamma\}$. If $\Pi_{\gamma\gamma}(z_\gamma) > C^\gamma_{\gamma\gamma}(z_\gamma)$, the shadow price of developing γ further will continue rising: $\exists\ \delta > 0$ such that $\forall\ \epsilon \in (0, \delta)$,

$$\frac{\Pi_\gamma(z_\gamma + \epsilon)}{C^\gamma_\gamma(z_\gamma + \epsilon)} > \frac{\Pi_\gamma(z_\gamma)}{C^\gamma_\gamma(z_\gamma)} > \frac{\Pi_\kappa(\epsilon)}{C^\kappa_\kappa(\epsilon)}\ \ \forall\ \kappa \neq \gamma$$

The net returns to investing in γ will continue to grow as long as $\Pi_{\gamma\gamma}(\gamma) > C^\gamma_{\gamma\gamma}(\gamma)$. But because $\lim_{\gamma \longrightarrow \infty} \Pi_{\gamma\gamma} = 0$, we will eventually have $\Pi_{\gamma\gamma}(\gamma) < C^\gamma_{\gamma\gamma}(\gamma)$ (recall that Π is S-shaped in z and C^z is strictly convex, such that their levels, and first and second derivatives, cross).

Once this is true, z_γ will continue to develop as long as its shadow price exceeds that of all other $\kappa \neq \gamma$, but eventually, $\exists\ \delta > 0$ such that $\forall\ \epsilon \in (0, \delta)$,

$$\frac{\Pi_\gamma(z_\gamma + \epsilon)}{C^\gamma_\gamma(z_\gamma + \epsilon)} < \frac{\Pi_\kappa(\epsilon)}{C^\kappa_\kappa(\epsilon)}\ \ \text{for some } \kappa \neq \gamma$$

Then z_κ will develop, and due to increasing returns, this process will feed on itself, until $\Pi_{\kappa\kappa}(z_\kappa) < C^\kappa_{\kappa\kappa}(z_\kappa)$, beyond which the shadow price of another attribute may exceed it, etc.

Though not included in the proposition, we can also note that eventually, all qualities for which ${}^{\Pi_\kappa(\epsilon)}/_{C^\kappa_\kappa(\epsilon)} > 1$ for some $\epsilon > 0$ will have developed, their shadow values will be equalized, and increasing returns will be exhausted. From this point forward, these qualities incrementally advance in tandem up to the unconstrained interior solution.

Proposition 2:

The scope of diffusion varies one-to-one with that of R&D. Diffusion may therefore follow an S-shaped pattern over time not only within applications, but also across them.

Proof/explanation:

As a matter of definition, the scope of R&D is the number of applications for which a technology has nonzero quality, and the scope of diffusion is the number of applications in which it has positive diffusion. Recall that the diffusion function is $D_a = F(z_g + z_a)$, with $F(\cdot)$ a CDF, such that

$$\begin{bmatrix} F^{-1}(D_{a_1}) \\ \vdots \\ F^{-1}(D_{a_n}) \end{bmatrix} = \begin{bmatrix} z_g + z_{a_1} \\ \vdots \\ z_g + z_{a_n} \end{bmatrix}.$$

Quality $\zeta_a = z_g + z_a$ will increment for all $a \in \{a_1, \ldots, a_n\}$ when (i) z_g increments, or (ii) z_a increments for all $a \in \{a_1, \ldots, a_n\}$. Because D_a is one-to-one in ζ_a, D_a will then increment for all $a \in \{a_1, \ldots, a_n\}$ as well. Conversely, when D_a increments for all a, then ζ_a must have incremented for all a, impliying that either (i) z_g incremented, or (ii) z_a incremented for all a.

An implication of Proposition 1 is that the technology may first develop some application-specific qualities, then develop general-purpose quality, then develop more application-specific qualities. Because general-purpose quality increases diffusion across all applications, its growth will accelerate diffusion in scope, and its dormancy will decelerate diffusion in scope. In this scenario, the number of applications to which the technology has spread will resemble an S-shape over time.

F Details of Labor Savings Calculations

Starting point: U.S. labor savings from tractorization in 1944

(1)	1,700	Labor savings from tractorization, 1944 (millions of hours)	Cooper-Barton-Brodell (1947)

Calculation: Subset of U.S. labor savings in 1944 from Midwest

(2)	1,169,154	Farms in Midwest with tractors, 1945	U.S. Ag Census (1945)
(3)	2,002,662	Farms in U.S. with tractors, 1945	U.S. Ag Census (1945)
(4)	58.4%	Midwest share of adopting farms, 1945	Calculated: (2)/(3)
(5)	992.46	Midwest share of labor savings, 1944 (millions of hours) (Assumes labor savings constant across mechanized farms. Note that this is likely to be a lower bound, as labor savings should be relatively larger in the Midwest, where the crop mix is more amenable to mechanization.)	Calculated: (1)*(4)

Calculation: Added labor savings in 1930 under counterfactual

(6)	11.4%	Increase in diffusion from 1925-30, actual	U.S. Ag Census (1930)
(7)	25.6%	Resulting diffusion in 1930, actual	U.S. Ag Census (1930)
(8)	0.4351	Diffusion in 1930 (actual) : Diffusion in 1945	U.S. Ag Census (1930, 1945)
(9)	431.86	Multiplied by 1944 Midwest labor savings	Calculated: (5)*(8)
(10)	431.86	Midwest labor savings in 1930, actual (millions of hours)	Repeated from above
(11)	18.0%	Increase in diffusion from 1925-30, c.f.	U.S. Ag Census (1930)
(12)	32.2%	Resulting diffusion in 1930, c.f.	U.S. Ag Census (1930)
(13)	0.5470	Diffusion in 1930 (c.f.) : Diffusion in 1945	U.S. Ag Census (1930, 1945)
(14)	542.85	Multiplied by 1944 Midwest labor savings	Calculated: (5)*(13)
(15)	542.85	Midwest labor savings in 1930, c.f. (millions of hours)	Repeated from above
(16)	110.99	Increase in labor savings in counterfactual (millions of hours)	Calculated: (15)-(10)

Calculation: Added labor savings in 1930 as fraction of hired labor

(17)	136.04	Days of labor employed in Midwest agriculture, 1930 (millions)	U.S. Ag Census (1930)
(18)	1,088.35	Hours of labor employed in Midwest agriculture, 1930 (millions)	Calculated: (17)*8
(19)	10.2%	Labor savings as a percent of hired labor	Calculated: (16)/(18)

Calculation: Value of added labor savings, at prevailing market wages

(20)	55,496	Increase in labor savings in counterfactual (FTEs) (Assumes FTE works 2000 hrs/yr, or 50 weeks at 40 hrs/wk)	Calculated: (16)/2000
(21)	0.845	Fraction of non-farm labor in manufacturing	U.S. Pop Census (1930)
(22)	1437	Average wage in Midwest manufacturing	U.S. Pop Census (1930)
(23)	67.35	Increase in output, manufacturing (million $s)	Calculated: (20)*(21)*(22)
(24)	0.155	Fraction of non-farm labor in wholesale	U.S. Pop Census (1930)
(25)	1854	Average wage in Midwest wholesale	U.S. Pop Census (1930)
(26)	15.97	Increase in output, wholesale (million $s)	Calculated: (20)*(24)*(25)
(27)	83.32	Sum: Value of labor savings (million $s)	Calculated: (23)+(26)

Calculation: Added labor savings, rel. to 2014 Midwest agricultural output

(28)	11.44	Inflating factor: 1930 to 2014	BEA GNP Price Deflator
(29)	952.97	Value of labor savings, 2014 dollars (millions)	Calculated: (27)*(28)
(30)	80,606	Agricultural GDP in Midwest, 2014 (millions)	BEA GDP by State tables
(31)	1.2%	Labor savings as percent of current regional output	Calculated: (29)*(30)