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Scale versus scope in the diffusion of new technology: evidence from the farm tractor

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Although 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. Early diffusion was accordingly rapid in these narrower applications but limited in scope until tractor technology generalized. The sequence of diffusion is consistent with a model of Research and Development (R&D) in specific- versus general-purpose attributes and with 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.

1. Introduction

■ 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 typically viewed as 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]

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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. These two parameters characterize what I refer to in this article as "scope" and "scale," respectively. Research on diffusion has overwhelmingly focused attention on the latter, which has been attributed to heterogeneous costs and benefits (Duflo, Kremer, and Robinson, 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

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This article shows that the historical diffusion of farm tractors—a technology which revolutionized 20th-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 existing complementary equipment, exogenously high demand, and relatively lower R&D costs, and initial diffusion was accordingly rapid for these applications, but otherwise limited in scope. Only later did tractor technology become sufficiently general in purpose for its diffusion to be broad based and pervasive. This pattern of expanding scope is consistent with other historical examples and with economic theory, which suggests that in this context, R&D will naturally progress from specific- to general-purpose variants of an innovation, and that these technical advances will (i) drive the development of additional complementary technologies, and (ii) and directly translate to an increasing scope of diffusion. Lags in diffusion can therefore be the result of hold-ups and market failures in R&D that stymie the generalization of existing technology.

The article 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 their horses and mules with one general-purpose tractor" (Sanders, 2009).

The era of the tractor in US 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 US 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, whereas 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. From 1930 to 1940, the pattern is precisely reversed, following the introduction of the general-purpose tractor and mechanical corn harvestor; in the 1940s, diffusion rounds out in counties with little of either crop and primarily growing hay. The results are robust to a wide variety of controls, sample restrictions, and definitions of diffusion—establishing that they are not due to changes in farm sizes, local factor prices, financial conditions, dealer networks, New Deal relief, the Dust Bowl, the contemporaneous diffusion of hybrid corn, or other features of Midwest agriculture that might have affected tractor demand in this period.

The question remains as to why the tractor's development followed this sequence. To put structure around this phenomenon, I introduce a model of innovation where a firm develops a technology with application-specific and general-purpose technological attributes, and where the value of the innovation depends on the evolving quality of complementary technologies. The model borrows ideas from the framework developed by Bresnahan and Trajtenberg (1995) to characterize general-purpose technologies, while endogenizing the path of product development. Intuitively, this model suggests that product features develop in the order in which they are most valuable, implying that new technologies will often first be invented for narrow applications where

to suboptimal decision-making due to credit constraints (Clarke, 1991), information spillovers (Conley and Udry, 2010; Dupas, 2014; Munshi, 2004), and individual biases (Duflo, Kremer, and Robinson, 2011).

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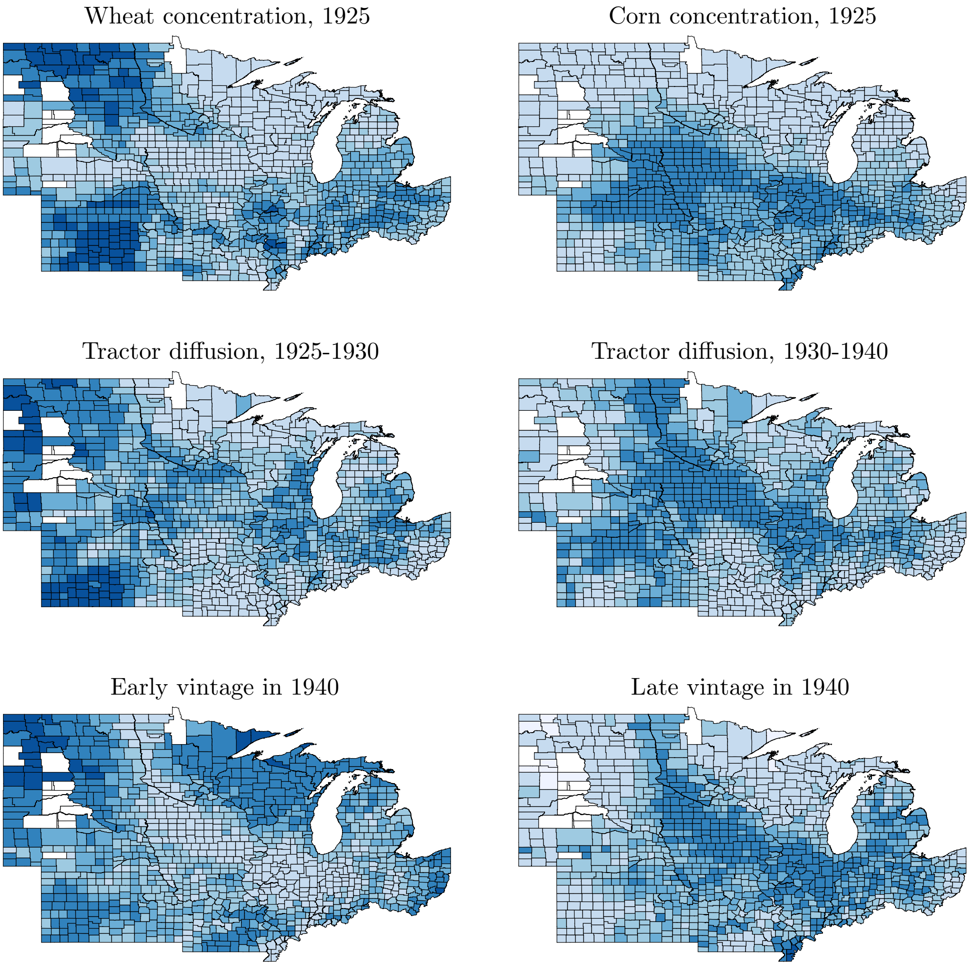
FIGURE 1

CROP MIX AND TRACTOR DIFFUSION IN US MIDWEST, 1925–1930 AND 1930–1940 [Color figure can be viewed at wileyonlinelibrary.com]



Notes: Figure shows the distribution of 1925 wheat and corn intensity across the US Midwest (top row), changes in tractor diffusion from 1925–1930 and 1930–1940 (middle row), and the fraction of mechanized farms in 1940 with pre-1930 versus post-1935 vintage tractors (bottom row). Crop concentrations calculated as the fraction of farmland in the given crop, and 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 1925 to 1940 Census of Agriculture.

complements are already available, and only later will they generalize for broader use. However, in this model, firms may be underincentivized to invest in R&D, especially general-purpose R&D, because they do not internalize the external returns of their R&D to complementors.

The narrative record suggests that the leading manufacturers of the era made a late and limited effort to invent a general-purpose model: International Harvester executives invested few resources in its general-purpose R&D program prior to its first breakthrough and nearly pulled the plug in the early 1920s, and Ford had no such program at all. The stakes, however, are not small: the baseline 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

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have generated annual labor savings equivalent to 10.2% of contemporary Midwest agricultural employment—the value of which, at contemporary wages and inflated to the present, is roughly 1.2% of current Midwest agricultural Gross Domestic Product (GDP).

Tractors have a rich history as the subject of research on technology diffusion. Early contributions focused on fixed costs as a barrier to tractor diffusion (e.g., Ankli, 1980), following the tradition of David (1966). Recent research has emphasized the importance of factor price changes and quality improvements to explaining aggregate diffusion (Manuelli and Seshadri, 2014), but 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 result of not only its mechanical efficiency, but also its versatility as a source of power in agriculture.

Though tractors are inherently important, the example serves to highlight scope as an economically significant but understudied 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 overlooked in the 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 articles, 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 article, I instead show that technologies themselves can endogenously evolve from being narrowly to widely appropriate, with diffusion following in turn.

An implication of the results is that in addition to studying the population of users, research on diffusion 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 potential 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 article might also 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 must 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 article is organized as follows. In Section 2, I review the tractor's history through the 1940s. Section 3 describes the data and estimation strategy. Section 4 provides descriptive evidence that tractors diffused in sequence to wheat- and corn-growing regions of the Midwest. Section 5 formalizes the relationship between crop intensities and tractor diffusion and presents a battery of robustness checks, and Section 6 extends these results. In Section 7, I develop the model, discuss its implications, and relate it to the history and evidence. Section 8 considers the effects of accelerated generalization for Midwest agriculture. Section 9 concludes.

2. History of the tractor

■ The modern tractor's history begins around 1870 with the invention of the steam tractor, which was in effect 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 postharvest threshing, with little portable use beyond tillage. They were also heavy, expensive, and prone to mechanical failure and explosion. Kerosone tractors succeeded steam models around 1890 but were similarly deficient. Given these deficiencies, these early models were never a serious threat to farms' dependence on draft power.

The transition to smaller, lighter-weight, more affordable tractors occurred in the 1910s. The first true commercially successful tractor was the Ford Fordson in 1917, and by all accounts it marked the beginning of the tractor era (Figure 2). By the end of 1918, Ford had overtaken its

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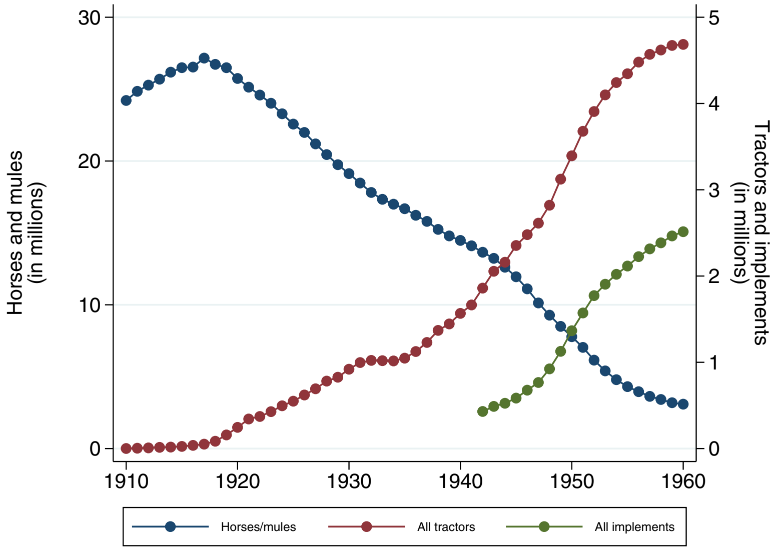
FIGURE 2

DRAFT ANIMALS, TRACTORS, AND IMPLEMENTS IN THE UNITED STATES [Color figure can be viewed at wileyonlinelibrary.com]



Notes: All implements refers to the sum of grain combines, corn harvesters, and pick-up hay balers owned by US 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 US farms is 0.996 over the 19 years for which data on all three implements are available. Data from Historical Statistics of the United States, Series Da623, Da629-631, Da983, Da985, Da987 (Carter et al., 2006).

competitors in sales (Leffingwell, 1998), and by the early 1920s, the Fordson accounted for 75% of tractor sales in the United States (Leffingwell, 2002). At the time Ford ended production in 1928, it had sold nearly half of all tractors sold in the 1920s (White, 2010).

The advantages of the Fordson were its size, agility, low price, and the fact that it could be used with existing plows, harrows, and grain combines (Williams, 1987). However, its low clearance made it impractical for cultivating row crops such as corn or cotton, leading manufacturers to separately develop and sell expensive, stand-alone cultivators, and Corn Belt farms to continue relying heavily on draft power. Contemporary studies found that the diversity of farm operations was one of the key impediments to tractor adoption: fixed-tread tractors could be used for 77% of field operations in raising common grains, but only 38% in row crops (Gunlogson, 1922), and this same study then noted that "since 4 to 6 horses are required to care properly for the corn crop on operations which cannot be done with the common type of tractor, and since the whole farm can be operated with five or six horses, the investment in a tractor is not justifiable on the basis of economy." Other contemporaries similarly observed that although this class of tractor had become popular in grain production, "the market for tractors in the Corn Belt . . . has hardly been scratched, for study reveals that only about 6% of the farms in these six states have tractors, while the other 94% still depend on horses for power" (Iverson, 1922), at a time when small grains and corn each comprised about 40% of US acreage in field crops (Gunlogson, 1922).

The "logical solution" (Iverson, 1922) was to design a tractor that could do it all. Despite the known, large potential demand for a general-purpose variant, it was 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 saw the Fordson's deficiencies for

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TABLE 1 Tractor Production from Select Manufacturers, Fixed-Tread versus General-Purpose

	Prestudy Period		Study Period			
Type	1917–1920	1921–1924	1925–1928	1929–1932	1933–1936	1937–1940
Fixed-tread	226,728	375,217	532,392	259,539	58,148	75,381
General-purpose	0	214	50,884	125,577	260,626	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 (for IHC models; IHC, 2015), thefordsonhouse.com (for Ford models; Fordson House, 2015), tractordata.com (for Deere, Allis-Chalmers models; TractorData, 2015), and tractors.wikia.com (for all makes and models; Tractor and Construction Plant Wiki, 2015). 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.

row crop production as targets (namely, low ground clearance and wheel placement, Leffingwell, 2002), and took the lead in developing a general-purpose model.

The first references to this project in IHC records appear in 1919, but by 1921, executives were unenthusiastic about the costs and lack of progress and voted to pull funding, and the project was saved only by special funding set aside by the firm's president (Klancher, 2008). Other leading firms, including Ford, made no such effort at all—such that when IHC broke through with the Farmall in 1925, it quickly overtook 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). In a 1940 testimony to Congress, the vice president of IHC described how "the Farmall made possible for the first time the application of tractor power to all field operations," and further stated it "had the greatest usefulness in farming areas where row crops predominate, particularly in the Corn Belt and Cotton Belt," where previous fixed-tread variants "had been of limited utility" (Fowler McCormick, in testimony to the TNEC, 1940).

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 models, and it stimulated the invention of additional farm implements to be used with them. John Deere came out with a variant in 1928, and Allis-Chalmers in 1930. Further advances in tractors soon followed: in 1927, Deere invented the power lift for raising implements during turns; 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 main features of modern tractors were set.

Production totals confirm the historical narrative. Table 1 shows total output 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.

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 models grew from 0% to over 90% of units manufactured by 1940. This technological transition can also be seen in terms of the windows studied in this article: from 1925 to 1930, roughly 759,000 fixed-tread tractors were manufactured by these four

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firms (359,000 by IHC alone), versus 146,000 general-purpose units. In the next decade, from 1931 to 1940, 816,000 general-purpose tractors were produced, versus only 167,000 fixed-tread units. In short, this article argues that this technological transition is responsible for the ensuing broad-based diffusion of tractors across the US Midwest.

□ **Previous research on tractor diffusion.** Though a large body of research has studied the historical diffusion of tractors and other agricultural technologies, the importance of changes in scope – deriving from changes in the technology itself – is absent 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 and economies of scale, 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, arguing that reaper diffusion was driven by increasing farm sizes (scale economies). Olmstead (1975) questioned 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 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 critiques of David (1966). Myers (1921) and Gilbert (1930) lend support to both advocates and critics, 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"—defined in Clarke (1991) as the fraction of farms above 100 acres without tractors—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). 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.

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 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 modelling 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

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tractor's quality as a unidimensional parameter that increases over time and using it to explain the scale of diffusion in the aggregate belies the true nature of the problem.

3. Data and empirical strategy

■ The article draws on a panel of 1059 counties in the US Midwest from 1925 (the earliest date for which county-level diffusion data are available) to 1950, with the baseline sample restricted to the 1033 counties whose borders were unchanged from 1910 to 1950.[2] The Midwest led the country in tractor adoption through 1950 and exhibits sufficient spatial variation in diffusion throughout 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 to 1950 US Census of Agriculture (US Census Bureau, 1910-1954) to measure tractor diffusion, investment in agricultural implements, farmland, crop mix, and other characteristics of farms and farmers. In most tables and figures, I define diffusion as the fraction of farms with a tractor. However, the 1925 Census of Agriculture is the first year that data on tractor ownership were reported and provides only the number of tractors in a county, and I therefore approximate diffusion in 1925 with the number of tractors over the number of farms, assuming that each farm owns at most one tractor.[3] I draw on the US Census of Population in the same years for supplementary county-level data. The data set also includes county-level records of bank failures from the Federal Deposit Insurance Corporation (FDIC) from the National Historical Geographic Information System (NHGIS, Minnesota Population Center 2011); New Deal expenditures from Fishback, Kantor, and Wallis (2003); Dust Bowl soil erosion from Hornbeck (2012); average levels and variation in elevation and rainfall from the United States Geological Survey (USGS, 2009) and PRISM Climate Group at Oregon State University (2012), respectively; and state-level hybrid corn diffusion from the United States Department of Agriculture (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 1910–1950 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 the United States 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

[2] There are 1059 uniquely defined counties in the Midwest over this period, and 1033 with static borders. Regression samples are further restricted to counties with data available for all robustness checks: 1032 counties in 1925–1930, 942 counties in 1930–1940, and 943 counties in 1940–1950.

[3] This assumption approximates the reality on the ground, especially 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]).

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TABLE 2 Descriptive Statistics: Average Farm Characteristics, By Year

	Prestudy Period		Study Period		
	1910 (N = 1033)	1920 (N = 1033)	1925 (N = 1033)	1930 (N = 1033)	1940 (N = 1033)
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	194.33	220.470	212.24	224.47	248.03
	(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 US Census of Agriculture.

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 preperiod (1925) crop intensities in regressions, though results are similar using other years (1910/1920).[4]

□ **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.

[4] Appendix B provides evidence that crop shares are stable over the sample period, both in their distribution across space and the aggregated distribution across crops.

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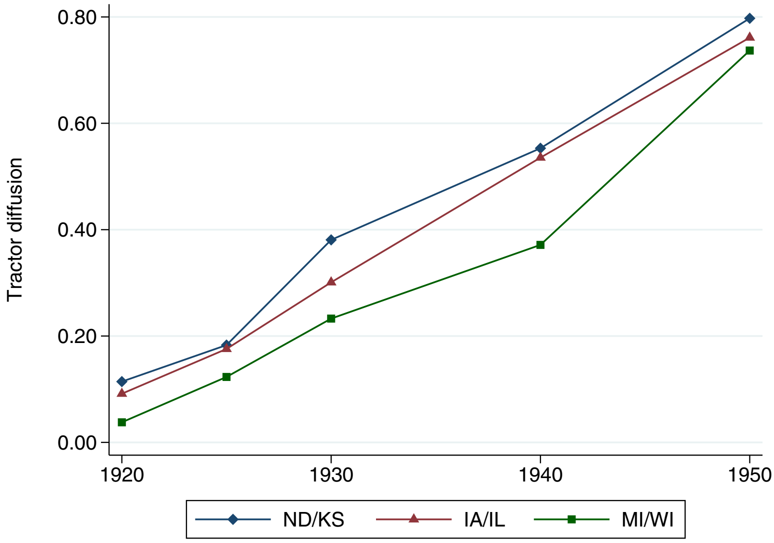
FIGURE 3

TRACTOR DIFFUSION IN MIDWEST STATES, 1920–1950 [Color figure can be viewed at wileyonlinelibrary.com]



Notes: Figure shows the path of tractor diffusion from 1920 to 1950 in the states that form the core of the US 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 1950 Census of Agriculture.

It is important to note that this period was a dynamic time in US agriculture—by no means was mechanization the only significant change underway—and it will therefore be important to control for concurrent trends.[5]

4. Descriptive evidence

■ The main empirical fact of this article—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 1925–1930 (left) and 1930–1940 (right). The third row maps the fraction of mechanized farms in 1940, whose latest vintage tractor was manufactured pre-1930 (left) versus between 1935–1940 (right), using data on tractor vintages from the 1940 Agricultural Census.

Tractor diffusion through 1930 was visibly concentrated in wheat-growing states, whereas over the following decade, it was almost fully coincident with the Corn Belt. As Section 5 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.[6]

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

[5] 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 5.

[6] See Appendix Figures B.5 and B.6 for a cross-sectional view of state-level crop intensities.

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TABLE 3 Crop Intensity and Changes in Tractor Diffusion from 1925 to 1940

	1925–1930	1930–1940	1925–1940
	(1)	(2)	(3)
Pct. in Wheat	0.437***		0.383***
x Year = 1930	(0.028)		(0.028)
Pct. in Corn	0.017		0.024
x Year = 1930	(0.020)		(0.020)
Pct. in Wheat		0.037	0.420***
x Year = 1940		(0.030)	(0.033)
Pct. in Corn		0.413***	0.437***
x Year = 1940		(0.021)	(0.028)
Difference	−0.42***	0.38***	
	(0.04)	(0.04)	
Diff. by 1930			−0.36***
			(0.04)
Diff. by 1940			0.02
			(0.04)
N	2064	1884	2826
R^2	0.56	0.61	0.68

Notes: Table shows the relationship between preperiod crop intensity and changes in county-level tractor diffusion from 1925–1930 and 1930–1940 (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 (1030 counties in 1925–1930; 942 counties in 1930–1940 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.

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. Over the next decade (to 1950), the control states catch up to the wheat and corn states, which themselves follow a common trend. This is the pattern that I will argue is explained by changes in the capabilities and limitations of tractor technology, particularly in the earlier periods (through 1940), which are the focus of the article. The natural question for a counterfactual is then what would have been the effects of accelerating the development of general-purpose tractors such that the corn-growing states mechanized as quickly as the wheat-growing states—a question which is considered in Section 8.

5. 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:

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

where i and t index counties and years. I estimate this difference-in-differences separately on the 1925–1930 and 1930–1940 samples and on a pooled, 1925–1940 sample. Diffusion is measured as the fraction of farms in county i 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 3 provides results from baseline specifications without controls. Column (1) shows difference-in-difference estimates for 1925–1930, Column (2) for 1930–1940, and Column (3) for the pooled sample. The important quantity in these models is not the point estimates per

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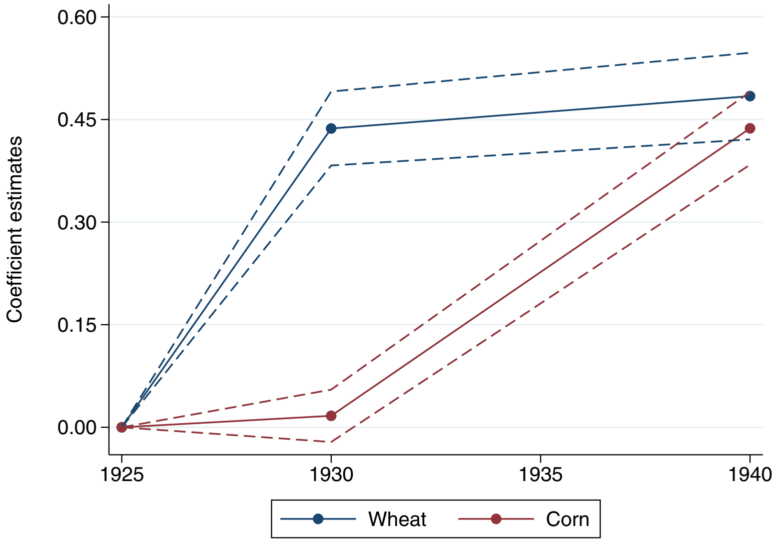
FIGURE 4

ESTIMATED CUMULATIVE CHANGE IN TRACTOR DIFFUSION, 1925–1940, ALL-WHEAT VERSUS ALL-CORN [Color figure can be viewed at wileyonlinelibrary.com]



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.

se, but rather the difference between them, and for each regression, I calculate the difference in coefficients for corn and wheat, which is shown at the bottom of the table.

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 covaried 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 reconvergence by 1940. Figure 4 makes this result visually apparent, plotting the estimated increase diffusion from 1925 to 1940 (with 95% confidence intervals) in a hypothetical all-wheat versus all-corn county.

However, this period was a dynamic era in US 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 4 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 1925–1930 period, and Panel B for the 1930–1940 period, with the difference in coefficients for corn and wheat provided.

The first column of each panel presents the baseline result from Table 3. Each column thereafter cumulatively adds controls. Column (2) controls for county-level changes in the stock of agricultural implements and machinery as a fraction of land values from 1910 to 1925, as a proxy for pretrends in mechanization. Column (3) controls for the intensity of other crops (oats, barley, rye, and hay). Column (4) 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 (5) controls for substitute inputs (horses, mules, and labor expenditure per acre). Column (6) controls for local financial conditions (farm mortgage interest rates and debt ratios). Column (7) controls for geographic and climatic variables (geographic coordinates; distance from Detroit and Chicago, which were the basis for calculating shipping charges; distance from the nearest

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TABLE 4 Crop Intensity and Changes in Tractor Diffusion from 1925 to 1940: Robustness to Alternative Specifications

		Additional Controls for:							Restricted to:	
	Baseline (1)	Pretrends (2)	Crop Mix (3)	Farm Size (4)	Other Farm Characteristics (5)	Financial Conditions (6)	Climate/ Geography (7)	New Deal Relief (8)	Dust Bowl Counties (9)	Early Hybrid Corn Adopters (10)
Panel A: Diffusion (levels) from 1925–1930										
Pct. in Wheat	0.437***	0.438***	0.427***	0.413***	0.403***	0.361***	0.353***			
x Year = 1930	(0.028)	(0.028)	(0.030)	(0.030)	(0.029)	(0.029)	(0.028)			
Pct. in Corn	0.017	0.034	0.010	0.024	0.028	0.054***	0.054***			
x Year = 1930	(0.020)	(0.023)	(0.023)	(0.023)	(0.024)	(0.023)	(0.023)			
Difference	−0.42***	−0.40***	−0.42***	−0.39***	−0.38***	−0.31***	−0.30***			
	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)	(0.04)			
N	2064	2064	2064	2064	2064	2064	2064			
R^2	0.56	0.56	0.71	0.76	0.77	0.78	0.81			
Panel B: Diffusion (levels) from 1930–1940										
Pct. in Wheat	0.037	0.040	0.048	0.030	−0.033	−0.102***	−0.109***	−0.153***	−0.237***	−0.120*
x Year = 1940	(0.030)	(0.030)	(0.037)	(0.036)	(0.034)	(0.035)	(0.034)	(0.040)	(0.051)	(0.070)
Pct. in Corn	0.413***	0.450***	0.543***	0.532***	0.384***	0.425***	0.373***	0.333***	0.221***	0.145**
x Year = 1940	(0.021)	(0.025)	(0.037)	(0.035)	(0.042)	(0.038)	(0.036)	(0.042)	(0.059)	(0.063)
Difference	0.38***	0.41***	0.50***	0.50***	0.42***	0.53***	0.48***	0.49***	0.46***	0.27***
	(0.04)	(0.04)	(0.06)	(0.05)	(0.05)	(0.05)	(0.05)	(0.05)	(0.06)	(0.10)
N	1884	1884	1884	1884	1884	1884	1884	1884	874	986
R^2	0.61	0.61	0.73	0.79	0.81	0.83	0.86	0.86	0.84	0.88

Notes: Table shows the relationship between preperiod crop intensity and changes in county-level tractor diffusion from 1925–1930 and 1930–1940 (Panels A and B, respectively). Column (1) repeats the baseline estimates from Table 3, and the remaining columns provide robustness checks. Column (2) controls for pre-1925 trends in the stock of farm machinery as a fraction of land values, a proxy for mechanization; Column (3) adds controls for the intensity of other major Midwest crops (oats, barley, rye, hay); Column (4) 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 (5) adds controls for substitute inputs (horses per acre, mules per acre, labor expenditure per acre); Column (6) adds controls for financial variables (farm mortgage interest rates and debt ratios); Column (7) adds controls for geographic and climatological variables (centroid coordinates, distance from Detroit and Chicago, quadratics in county mean temperature and annual rainfall, and intracounty variation in elevation); Column (8) adds controls for local New Deal Relief (AAA spending and FCA lending per harvested acre). 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- versus 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.

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Ford and IHC branch houses; quadratics in county mean temperature and annual rainfall; and intracounty variation in elevation). Column (8) controls for local New Deal Relief in post-1930 samples (measured as Agricultural Adjustment Administration [AAA] spending and Farm Credit Administration [FCA] lending from 1933–1939, per harvested acre, from Fishback, Kantor, and Wallis, 2003). 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 might be explained by contemporaneous shocks to Midwest agriculture in the 1930s.

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 pretrends in mechanization and changes in farm sizes, substitute inputs, credit constraints, proximity to manufacturers' branch houses, and more. In Panel A (1925–1930), we see that the difference in coefficients on wheat and corn intensity are relatively stable across specifications—matching the baseline result—and precisely estimated. The differece in Panel B (1930–1940) is approximately the inverse of that in Panel A and similarly precise, although it varies modestly more with controls.

Another potential explanation is that the advent of the mechanical corn harvester, which required a tractor to operate, triggered the wave of tractor diffusion in the Corn Belt. This interpretation would in a literal sense 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 stimulated R&D in corn harvesters, due to their complementarities, and they diffused together (see Section 7). Though this question 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 6000 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 owned mechanical corn harvesters 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 harvesting thus seems unable to fully explain the 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 diffusion, and perhaps the most direct test of the claims in this article. 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 5, 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) or post-1935 (Panel B).

From Column (3) onward, the results are statistically similar 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 3 and 4 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 modelling 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 C reestimates the regressions in Table 4 using alternative definitions. Table C.1 replaces diffusion with the

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TABLE 5 Crop Intensity and Tractor Vintages in 1940

		Additional Controls for:							Restricted to:	
	Baseline (1)	Pretrends (2)	Crop Mix (3)	Farm Size (4)	Other Farm Characteristics (5)	Financial Conditions (6)	Climate/ Geography (7)	New Deal Relief (8)	Dust Bowl Counties (9)	Early Hybrid Corn Adopters (10)
Panel A: Frequency of pre-1930 vintages in 1940										
Pct. in Wheat	−0.060	−0.080*	−0.079*	−0.169***	−0.127***	−0.091*	−0.056	0.002	0.118*	−0.151
	(0.045)	(0.046)	(0.047)	(0.049)	(0.048)	(0.052)	(0.056)	(0.060)	(0.065)	(0.101)
Pct. in Corn	−0.807***	−0.784***	−0.514***	−0.601***	−0.548***	−0.606***	−0.543***	−0.515***	−0.236**	−0.500***
	(0.042)	(0.042)	(0.051)	(0.059)	(0.053)	(0.054)	(0.058)	(0.060)	(0.103)	(0.073)
Difference	−0.75***	−0.70***	−0.44***	−0.43***	−0.42***	−0.52***	−0.49***	−0.52***	−0.35***	−0.35***
	(0.06)	(0.06)	(0.06)	(0.07)	(0.07)	(0.07)	(0.07)	(0.07)	(0.10)	(0.13)
N	943	943	943	943	943	943	943	943	438	493
R^2	0.57	0.57	0.65	0.68	0.69	0.70	0.73	0.74	0.85	0.82
Panel B: Frequency of post-1935 vintages in 1940										
Pct. in Wheat	0.011	0.029	0.058	0.122***	0.076*	0.067	0.015	−0.014	−0.082	0.079
	(0.040)	(0.041)	(0.042)	(0.044)	(0.044)	(0.046)	(0.049)	(0.053)	(0.058)	(0.090)
Pct. in Corn	0.637***	0.616***	0.432***	0.444***	0.369***	0.428***	0.348***	0.334***	0.105	0.349***
	(0.038)	(0.038)	(0.046)	(0.057)	(0.049)	(0.051)	(0.054)	(0.055)	(0.103)	(0.071)
Difference	0.63***	0.59***	0.37***	0.32***	0.29***	0.36***	0.33***	0.35***	0.19**	0.27***
	(0.05)	(0.05)	(0.06)	(0.06)	(0.06)	(0.06)	(0.06)	(0.06)	(0.09)	(0.11)
N	943	943	943	943	943	943	943	943	438	493
R^2	0.53	0.54	0.61	0.64	0.66	0.67	0.70	0.70	0.83	0.76

Notes: Table shows the relationship between preperiod 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 preperiod wheat and corn intensity and state fixed effects. Column (2) controls for pre-1925 trends in the stock of farm machinery as a fraction of land values, a proxy for mechanization; Column (3) adds controls for the intensity of other major Midwest crops (oats, barley, rye, hay); Column (4) 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 (5) adds controls for substitute inputs (horses per acre, mules per acre, labor expenditure per acre); Column (6) adds controls for financial variables (farm mortgage interest rates and debt ratios); Column (7) adds controls for geographic and climatological variables (centroid coordinates, distance from Detroit and Chicago, quadratics in county mean temperature and annual rainfall, and intracounty variation in elevation); Column (8) adds controls for local New Deal Relief (AAA spending and FCA lending per harvested acre). 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- versus 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.

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log-odds ratio. Table C.2 redefines diffusion as the number of tractors per 100 acres of county farmland. This table excludes the Plains states from Panel A (1925–1930), where farmland was rapidly expanding in the late 1920s, confounding the diffusion measure.[7] 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 C.3 to C.5, I reestimate Table 4, 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.

6. Later periods and other regions

□ **Patterns in diffusion from 1940–1950.** Tractor diffusion continued briskly in most parts of the Midwest through the 1940s. By this time, tractors were in widespread use around the region, and the technology had matured, such that further increases in diffusion are unlikely to be the result of changes to tractors themselves. However, as an extension on the previous results, Table 6 estimates the same specifications for 1940–1950.[8] By 1950, diffusion reached 80% in many states, and was plateauing to its eventual ceiling of around 90% in all states (Appendix Table B.1).

Figure 3 already indicates that Midwest states previously lagging in diffusion, such as Michigan and Wisconsin—which produced little wheat or corn and primarily grew hay as fodder for livestock—experienced the largest increases over this period. The results across all specifications in Table 6 are consistent with this evidence, showing that diffusion increased the most in counties with little of either staple crop. In unreported regressions, I include counties' 1925 hay intensity as an explanatory variable, and find that diffusion in this period was particularly concentrated in counties with a relatively high percentage of farmland harvested as hay.

Although mechanical hay balers were invented in 1940 and were adopted over the decade, by 1950, only 5.3% of Midwest farms owned a hay baler, whereas tractor diffusion increased from 44.3% to 70.7% over this period—and the difference is even larger in hay-intensive states such as Michigan and Wisconsin. The relatively rapid diffusion from 1940 to 1950 in counties with little acreage in cash crops is more likely catch-up growth, fueled by labor shortages during World War II and a sharp decline in farm populations, which fell roughly 20% during the war both in the Midwest and across the country, and did not recover (Appendix Table B.3). County-level farm population is not available from the 1950 Census to formally test this hypothesis, but the negative aggregate shock to labor supply, interacted with the distribution of mechanization in 1940, lends itself to catch-up growth over the decade. This evidence is consistent with the central argument of this article: changes in a technology are first-order to explaining when its adoption for different applications or in different regions takes off, but it is only one of several possible explanations for the pace at which diffusion continues—what this article refers to as the scope and scale of diffusion, respectively.

□ **Diffusion in other regions.** As the locus of US agriculture, and the region where tractors were adopted most rapidly, the Midwest is a natural target for study—but evidence of expanding scope can also be seen in other regions. For example, tractors with continuous track were developed for regions with soft soils, and models with protective outer shells for navigating through delicate orchards and vineyards. Table 7 shows the fraction of farms in each Census Region with tractors from 1920 to 1940 and in 2002, incorporating data from the modern US Census of Agriculture

[7] 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.

[8] Table 6 repeats the specifications in previous tables but omits controls for farm mortgage interest rates and debt loads (Tables 4 and 5, Column 6), which are not reported in the 1950 Census of Agriculture.

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TABLE 6 Crop Intensity and Changes in Tractor Diffusion from 1940 to 1950

		Additional Controls for:						Restricted to:	
	Baseline (1)	Pretrends (2)	Crop Mix (3)	Farm Size (4)	Other Farm Characteristics (5)	Climate/ Geography (6)	New Deal Relief (7)	Dust Bowl Counties (8)	Early Hybrid Corn Adopters (9)
Diffusion (levels) from 1940–1950									
Pct. in Wheat	−0.278***	−0.277***	−0.210***	−0.254***	−0.206***	−0.210***	−0.097***	−0.133***	−0.059
x Year = 1950	(0.034)	(0.034)	(0.036)	(0.035)	(0.036)	(0.036)	(0.037)	(0.048)	(0.064)
Pct. in Corn	−0.358***	−0.341***	−0.382***	−0.341***	−0.408***	−0.360***	−0.268***	−0.232***	−0.470***
x Year = 1950	(0.029)	(0.031)	(0.035)	(0.035)	(0.040)	(0.041)	(0.044)	(0.055)	(0.059)
N	1886	1886	1886	1886	1886	1886	1886	876	986
R^2	0.74	0.74	0.82	0.87	0.88	0.89	0.90	0.86	0.91

Notes: Table shows the relationship between preperiod crop intensity and changes in county-level tractor diffusion from 1940–1950. Column (1) runs the baseline specification without controls, and the remaining columns provide robustness checks. Column (2) controls for pre-1925 trends in the stock of farm machinery as a fraction of land values, a proxy for mechanization; Column (3) adds controls for the intensity of other major Midwest crops (oats, barley, rye, hay); Column (4) 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 (5) adds controls for substitute inputs (horses per acre, mules per acre, labor expenditure per acre); 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 intracounty variation in elevation); Column (7) adds controls for local New Deal Relief (AAA spending and FCA lending per harvested acre). 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- versus 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.

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TABLE 7 Tractor Diffusion By Region, from 1920 to Present

Census Region	1920	1925	1930	1940	2002
Northeast	2.7	9.5	18.6	29.2	86.2
Midwest	6.8	13.6	25.7	42.4	89.6
South	1.0	2.3	4.0	7.9	91.8
excl. DE, MD, OK, TX	0.7	1.8	2.7	4.2	90.0
DE, MD alone	2.8	7.5	15.5	23.0	90.3
OK, TX alone	2.2	3.7	7.9	21.3	95.0
West	7.0	10.7	19.4	27.9	83.2

Notes: Table reports tractor diffusion by Census Region in 1920, 1925, 1930, 1940, and 2002. The table highlights the lagging adoption of tractors in Southern states through 1940, especially those with historically poor labor institutions (slavery and sharecropping), and their eventual catch-up to the rest of the country.

(US Census Bureau, 2002). Between 1920 and 1940, the Midwest led the country in tractor adoption, with 42.4% of farms adopting by 1940. Northeastern and Western states were also mechanizing at this time, albeit at a slower pace (29.2% and 27.9% of farms adopting by 1940, respectively), reflecting the increasing utility of tractors across regions. The exception to this trend was the South: in states where agriculture was sharecropped, less than 5% of farms owned a tractor in 1940.

The slow mechanization of Southern agriculture prior to World War II is the subject of a large existing literature.[9] Researchers have largely converged on two explanations: labor market institutions that discouraged the adoption of labor-saving machinery, and the difficulty of designing an affordable, functional mechanical cotton picker. The engineering problem is summarized by Fite (1980), who catalogs the many reasons why "the nature of the cotton plant made the invention of a successful harvesting machine especially difficult." Whatley (1985, 1987) explains how this obstacle, in conjunction with Southern labor institutions, inhibited even partial mechanization of cotton production: without a mechanical harvester, Southern farms required a large population of laborers to collect the harvest. In states where this labor was supplied by a migrant workforce, such as those on the Mexican border, cotton farms could mechanize preharvest operations without cutting into the harvest labor supply—but in most Southern states, labor was supplied by annual contract in the form of tenancy and sharecropping, which locked in labor supply for when it was needed most. Under these circumstances, mechanization was an all-or-nothing proposition: as long as the harvest technology was labor intensive, and labor could only be secured with annual contracts, year-round operations tended to remain labor intensive as well.

Whatley's argument is supported by the evidence in Table 7. In the cotton-heavy states of Texas and Oklahoma, where migrant labor was abundant, tractor diffusion increased between 1930 and 1940 to a level comparable to that in much of the rest of the country. According to Fite (1950), cotton mechanization in these states began in the late 1920s, following the development of general-purpose tractors, and with the subsequent development of implements for preharvest operations, "remarkable progress occurred in the mechanization of cotton" even prior to functional cotton pickers. Contemporaries observed that labor had been displaced "over large areas because of the introduction of all-purpose tractors and auxiliary equipment," even though the industry had believed that displacement "would not appear until the manufacture of mechanical cotton pickers" (Paul Taylor, UC Berkeley economist, in TNEC 1940).

Given that cotton farms in these states were using tractors, the lagging diffusion in the rest of the South cannot be explained by the technology alone, which was common to both regions. Whatley (1985) additionally argues that the delayed invention of the mechanical cotton picker was itself more the consequence of institutions than the engineering challenge: "the structure of

[9] For example see Fite (1980), Musoke (1981), Whatley (1985), Whatley (1987), and Hornbeck and Naidu (2014) for evidence and discussion of barriers to tractor diffusion in the South. Several of these articles, and others cited therein, also address the mechanization of the cotton harvest specifically.

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the plantation economy reduced the Southern demand for new inventions," and it therefore "may have been no accident that the technical 'difficulties' of mechanizing the cotton harvest were solved soon after the tractor became available, sharetenancy began to disappear, and the locus of cotton production began moving westward, away from the traditional Cotton South."

7. Theoretical framework

■ To put more structure around these results, consider the following model. Suppose a given technology has the potential to serve two categories of users $a \in \{1, 2\}$. This technology is characterized by its quality for each application, z_1 and z_2, and its general-purpose quality z_g in all applications. General-purpose quality is embodied in features that are broadly useful, such as the rotary motion produced by a motor. Application-specific quality is embodied in features with more limited use (for an individual application). The technology is designed to be used with two application-specific complements, which themselves have qualities T_1 and T_2. We can think of the focal technology as the tractor, the complements as argicultural implements, and the sectors of users as wheat and corn farms.

Each sector has a total market size of M. Let the fraction of potential users in sector a adopting the technology be an increasing, convex function of the interaction of its total quality in application a $(z_g + z_a)$, and the quality of the sector-specific complement (T_a):

$$D_a = F((z_g + z_a)T_a), \quad \text{with } F'(x) > 0,\ F''(x) < 0,\ F(0) = 0 \quad \text{and} \quad \lim_{x\to\infty} F(x) = 1.$$

Total demand is $Q = \sum_a Q_a = M \sum_a F((z_g + z_a)T_a)$. Further suppose that the complements are perfect, and individually have identical demand Q_1 and Q_2.

To simplify the exposition, suppose there is one firm developing the focal technology, and one (distinct) firm developing the complementary technologies, and further suppose that R&D in the focal and complementary technologies occurs in alternating periods—such that developments in one may respond to developments in the other. The firm developing the focal technology can only develop one of $z \in \{z_1, z_2, z_g\}$ at a time. Firms which undertake R&D realize monopoly rents on the incremental sales (e.g., due to exclusivity), but these rents dissipate after one period (e.g., when competitors in the product market imitate or design around). Developing firms thus engage in R&D to maximize incremental demand, net of incremental R&D costs. Note that downstream prices are omitted, as they are nonessential to the intuition or the results.[10] Henceforth, we will include a subscript t on each parameter to denote time-varying values.

The final input to the model is then the cost of R&D. Suppose the total R&D cost for the focal technology through time t is the sum of the costs for developing each quality:

$$C_1(z_{1,t}) + C_2(z_{2,t}) + C_g(z_{g,t}),$$

where $C_1 = C_2 = C_z$, $C_g = \lambda C_z$ with $\lambda > 1$, $C_z' \geq 0$ and $C_z'' > 0$, and $C_z(0) = C_z'(0) = 0$. In words, R&D costs are increasing and convex, and general-purpose improvements are more difficult or expensive than application-specific improvements. The complements have similar cost functions, $\Gamma_1(T_{1,t})$ and $\Gamma_2(T_{2,t})$, where $\Gamma_1 = \Gamma_2 = \Gamma_T$, and Γ_T is increasing and convex.

As a final assumption, suppose that sector 1 initially has a complement available for use with the focal technology, with quality $T > 0$, whereas sector 2 does not (without loss of generality). For example, when tractors developed, there existed horse-drawn plows and grain harvesting equipment that could be used or easily adapted to the new technology—and in particular, when the Fordson developed, there was already a full line of implements in the small grains sector with which it could be used. Initial values of the quality parameters are thus as follows:

$$z_{1,0} = z_{2,0} = z_{g,0} = 0, \qquad T_{1,0} = T > 0, \qquad T_{2,0} = 0.$$

[10] Prices can be written into the model as being set downstream in the product market to maximize production profits, and taken as given or backward-inducted at the time R&D is allocated. Doing so would not affect the core results, which are driven by complementarities rather than the downstream market structure.

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□ **The path of product development.** The firm performing R&D on the focal technology must decide which features to develop each period: z_1, z_2, or z_g. Treating the quality parameters as state variables, in any given period, the returns to incrementing each one by δ_z are as follows:

$$z_1, z_2 : \Pi_{z_a}(\delta_z|\mathbf{z}, \mathbf{T}) = \underbrace{M \cdot [F((z_g + z_a + \delta_z)T_a) - F((z_g + z_a)T_a)]}_{\text{Incremental benefit}} - \underbrace{[C_a(z_a + \delta_z) - C_a(z_a)]}_{\text{Incremental cost}} \tag{1a}$$

$$z_g : \Pi_{z_g}(\delta_z|\mathbf{z}, \mathbf{T}) = M \sum_{a=1,2} [F((z_g + z_a + \delta_z)T_a) - F((z_g + z_a)T_a)] - [C_g(z_g + \delta_z) - C_g(z_g)]. \tag{1b}$$

In words, the expressions measure the incremental number of units sold, less the incremental cost of the R&D incurred to advance quality. Note that increasing z_a only yields benefits vis-à-vis sector a, whereas increasing z_g yields benefits across both sectors $a \in \{1, 2\}$.

Analogously, complementors must decide how much of T_1 and T_2 to develop each period, and the returns to incrementing each by δ_T are:

$$T_1, T_2 : \Pi_{T_a}(\delta_T|\mathbf{z}, \mathbf{T}) = M \cdot [F((z_g + z_a)(T_a + \delta_T)) - F((z_g + z_a)T_a)] \\ -[\Gamma_a(T_a + \delta_T) - \Gamma_a(T_a)]. \tag{3}$$

These ingredients lead directly to the first proposition:

Proposition 1. The Path of Product Development.

The focal technology will develop in the order of (i) z_1, (ii) z_g, and (iii) z_2. As such, it will develop as an application-specific technology before it becomes a general-purpose technology.

Proofs to propositions are provided in Appendix D. The intuition behind this result is simple: R&D in the focal technology follows the development of its complements. In period $t = 1$, because complements are available for sector 1 but not sector 2, and because application-specific R&D is *ceteris paribus* less expensive than general-purpose R&D, z_1 will be developed first. Once these returns are exhausted, z_g will develop next, taking advantage of its complementarity with T_1 as well. This development will spark investment in T_2, which in turn triggers investment in z_2. The three assumptions responsible for this result are that (i) general-purpose R&D is more costly than application-specific R&D, (ii) complements are initially available in one sector but not the other, and (iii) the rents from R&D are temporary (for example, technical advances are quickly imitated)—all of which are qualitatively consistent with the tractor's history.

A more relaxed set of assumptions can also generate this proposition under the right parametrizations. For example, if both sectors have preexisting complements, but one sector is larger, has lower R&D costs, or has higher quality complements than the other, then the same pattern may obtain: functionality for the advantaged sector will develop before that for the other sector *and* before general-purpose functionality, as long as general-purpose R&D is sufficiently expensive. In this case, R&D in z_1 will initially strictly dominate that in z_2, as well as that in z_g. These alternatives are discussed further in Appendix D.

□ **Implications for the scope of diffusion.** The most important result of the model, as it relates to the evidence above, is its implication for diffusion—and in particular, for explaining the scope of diffusion and cross-sectoral lags in diffusion, which are shaped by the set of applications for which a given technology can be used. It follows mechanically from Proposition 1 that the

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focal technology will initially be adopted by users in sector 1 and only later by those in sector 2, following that technology's generalization.

In his canonical study of hybrid corn, Griliches (1957) recognized 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 suitable varieties, the number of states that had surpassed that level of diffusion forms an S-shape over time (see Appendix E).

An additional implication of the model that emerges in the proof to Proposition 1 is that when the general-purpose quality of tractors increases, complements should soon develop to exploit these new features. Historical experience broadly concords: for example, R&D efforts at mechanical corn and cotton harvesting equipment immediately followed the Farmall. Williams (1987) recounts that the introduction of the three-point hitch prompted a "frantic race" to develop additional implements to exploit the tractor's increased utility, including some implements never seen before, such as tanks, pumps, and spray booms for fertilizers and pesticides.

□ **Extensions and policy implications: R&D spillovers.** Suppose now that firms can also earn positive returns on the incremental diffusion of their technology in periods when they are not actively performing R&D. An extension on these results brings into focus R&D spillovers between complementors, which drive a wedge between private and social returns to R&D and can result in suboptimal R&D investment.

Proposition 2. R&D spillovers (complementors' rents from own R&D).

If developers can earn rents on the contemporaneous, incremental sales of complements generated by their own R&D, then firms would invest more heavily in R&D in each period.

Recall that the focal and secondary technologies are perfect complements, such that improvements in one generate additional sales of both, as they are used jointly. Because the inventing firm can neither realize nor appropriate returns to its R&D from diffusion of complements, it will tend to undersupply quality, by not factoring in the effects of its own R&D on complements when making R&D investments (similar to Bresnahan and Trajtenberg, 1995). This will especially lead to the firms undersupplying general-purpose quality, which generates the most spillovers—suggesting that generality may be a potential target for R&D policy intervention.

In the tractor industry, this inefficiency was in part relieved by the presence of long-line firms which manufactured both tractors and implements. Ford notoriously left the production of implements for its tractors to others, but IHC, Deere, Allis-Chalmers, and others began as or evolved into long-line implement manufacturers. This organizational form might thus serve as a model for similar cases. Even so, vertical integration is only a partial solution and not a panacea, as it does not internalize the returns to other firms—or in many cases, farmers themselves—inventing implements which these farmers might use with the given firm's tractors.

8. 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, as 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 3 to project diffusion in the counterfactual. Although these estimates are linear approximations, they can provide a

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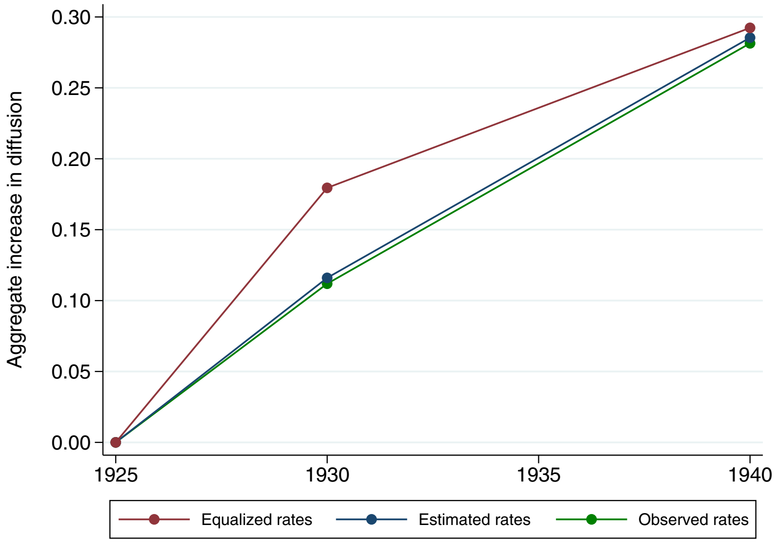
FIGURE 5

ESTIMATED DIFFERENTIAL INCREASE IN TRACTOR DIFFUSION IN COUNTERFACTUAL, 1925–1940
[Color figure can be viewed at wileyonlinelibrary.com]



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

sense of the magnitude of the effect. Figure 5 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.

The estimated increase in diffusion closely tracks observed values, validating 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 US 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, which was no longer needed to grow feed crops for draft animals (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 savings of as much as 8.6% of Gross National Product (GNP).

Using historical wages and estimates of the labor savings from mechanization, we can calculate a back-of-the-envelope estimate of the savings from the reduction in labor inputs alone. Appendix F provides details of the calculations, and Table 8 the results.

The calculation begins with an estimate from Cooper, Barton, and Brodell (1947) that tractors had reduced labor requirements in US 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 an proportionality factor based on aggregate Midwest diffusion in 1930 and 1945, ($\text{Diffusion}_{1930}/\text{Diffusion}_{1945}$).

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

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TABLE 8 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	1088.35	(6)
as percent of labor employed [(5)/(6)]	10.2%	
Panel C: Gross value of added labor savings		
Added labor savings, full-time equivalents	55,496	(7)
Average nonfarm annual wage (see the Appendix)	$1501.45	(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.

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. Note that this figure does not reflect a pure productivity increase, as it do not account for the purchase and operating costs of the additional tractors—though these costs would be offset by analogous savings from the reduced use of draft animals and other nonlabor inputs, which could yield even further savings (e.g., see Johnson, 1922; Ankli and Olmstead, 1981; Clarke, 1991; or White, 2000).

9. Conclusion

■ In his seminal work, Griliches (1957) showed that differences in the adoption of hybrid seed corn across US states and crop reporting districts were a function of both (i) when it began in each state or district, and (ii) the rate at which it proceeded. This article brings into focus the distinction between these two margins, which this article refers to as scope and scale, respectively: the former defines the set of potential adopters, and the latter describes what fraction of them are adopting. Since Griliches (1957), researchers have largely sought to explain differences in scale, leaving the determinants of the scope of diffusion less well understood.

The farm tractor is a case in point: although tractors are now pervasive in agriculture, they were not born to be. The earliest models were suitable only 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 1950 Census of Agriculture, I show that tractors were accordingly quick to diffuse to areas of the US Midwest growing wheat and other small grains, and slower to penetrate the Corn Belt. Had the tractor diffused at the same rate for corn-intensive counties as for wheat-intensive counties, total diffusion in the Midwest would have been roughly 25% higher by 1930, generating annual labor 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.

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To explain these patterns, the article proposes a model of R&D in which firms develop technologies with general-purpose and application-specific features. The model suggests that technologies will first develop for applications with existing complements, high demand, and low R&D costs, and only when the gains to specialization are exhausted will R&D proceed to a general-purpose variant. Diffusion is, in turn, constrained to applications for which the technology can be used. The presence of positive spillovers to the developers of complementary technologies implies that inventors are underincentivized to generalize their technology for broader use.

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 US 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 article 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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