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Tractor vs. animal: Rural reforms and technology adoption in China☆

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ABSTRACT

Better institutions do not always advance technologies. China's rural reforms during the early 1980s secured land tenure for peasants and dismantled large collective farms into small household farms, which transformed tillage technology. Using a novel data set of 1755 counties from 1976 to 1988, our event study exploits the county-by-county rollout of the reform. We find that the use of tractors plummeted after the reform, while the use of draft animals surged. Post-reform tractor use was more suitable to local factor endowments and farm size. Small tractors became more popular while the number of large tractors declined.

1. Introduction

This paper studies technology adoption in the context of China's rural reforms in the early 1980s, which laid the foundations for its later economic takeoff. Unlike its successful neighbors in East Asia, China launched its rural reforms by dismantling the collective farm, system adopted from the Soviet Union in the late 1950s.[1] Many of these big farms, equipped with large tractors in the late 1970s, symbolized the advantages of economies of scale and agricultural modernization. However, their productivity was low, in part because the peasants who farmed the collectives had few incentives to work hard. The rural reforms introduced throughout the country from 1978 to 1984 established the Household Responsibility System (HRS), in which each collective's land was divided and contracted to individual households. Since large tractors were inefficient on these small household farms, the percentage of land plowed by tractors plunged immediately after de-collectivization. Peasants switched to using draft animals, a primitive technology suitable to small farms. This labor-intensive technology was a good match for the abundance of laborers who were incentivized by the reform to work harder. The inventory of draft animals surged by 50 percent in the 1980s.

We use a novel and comprehensive county-by-year dataset to document these important technological transformations. We collect data for 1755 counties for the period from 1976 to 1988 from 178 recently declassified government documents and published compilations of official statistics, as well as 1755 county gazetteers. The sample covers 81 percent of China's counties and 85 percent of its rural population. We use an event study approach to exploit the county-by-county rollout of the HRS reform. This approach allows us to identify the technology evolution over time and to interpret the estimates as the causal effects of the reform. The large sample size also allows us to exploit rich regional variations in factor endowments and to estimate their impact on local technological choices.

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[1] Naughton (2007) provides a very informative introduction to China's post-1949 agricultural development. Perkins (2013) reviews the reform and development of East Asian countries and emphasizes the different experiences of China and Vietnam, which both had Soviet-style economic systems before the reform.

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We find that, compared to the year before the HRS reform, the percentage of tractor-plowed land dropped by 6–8 percentage points in the first year after the reform, and continued declining for six years by a total of 9–11 percentage points, or 25 percent of the pre-reform mean. During this time, the inventory of draft animals increased by about 50 percent. However, these radical changes underestimate the causal effects of the reform. The event study shows that before the reform, tractor use was rising and the number of draft animals was decreasing. Had these trends continued without disruption, the implied causal effects of the reform would have been much greater after six years.

The overall post-reform decline in tractor use reflects the combined effects of at least three factors: peasants' private ownership of production means, an increase in the effective labor supply from incentivized peasants, and reduced farm sizes. If private investment and technology adoption are more efficient than the government or collectives, we should observe that post-reform tractor use becomes more responsive to factor endowments in labor and land size. Indeed, we find that after the reform, tractor use declined more in counties with larger rural populations and in those with less arable land. It also decreased more where arable land was less accessible to tractors, such as in hilly or mountainous counties. After the reform, tractor use was also more prevalent in counties with larger average household farm. Small tractors, which are cheaper and more suitable to small household farms, became more popular while the number of large tractors declined after the reform.

Our findings add new evidence to the literature on endogenous technology adoption.[2] The main idea of the literature is that technology adoption responds to factor endowments and comparative advantage. Clemens et al. (2018) develop a model that is closely related to our findings. In their model, capital-intensive "advanced" agricultural technology can co-exist with labor-intensive "traditional" technology within a country. Because of this flexibility in technology combination, they find that the exclusion of Mexican immigrants fails to improve the wages and employments of American farm workers. While their theoretical mechanism is technology adoption, their empirical exercise focuses on the labor market and provides only suggestive evidence related to technology change. Our paper's focus is on technology change: when the reform reduced farm size and increased the effective labor supply by incentivizing farmers to work harder, the land-intensive technology (tractors) became less popular; while the labor-intensive technology (draft animals) became more popular.

Economists and historians have extensively studied the adoption of tractors and other agricultural machinery. Our study contributes to this literature by addressing two empirical challenges. First, tractor adoption, as a new technology, usually involves uncertainty and learning (Lew, 2000; Manuelli and Seshadri, 2014), which could confound the effects of fundamentals such as local conditions and access to technology.[3] Yet information barriers and learning are not important in our setting of technology reversion from tractors to draft animals: the post-reform plunge in tractor use was instant. In this context, we can focus on how technology adoption responds to institutional reforms and local conditions. Second, as a type of indivisible and labor-saving technology, tractor use is affected by farm size and labor prices (Whatley, 1985; Olmstead and Rhode, 2001; Hornbeck and Naidu, 2014; Foster and Rosenzweig, 2017). However, farm size and labor supply could also be influenced by the adoption and diffusion of tractors. To address this endogeneity, Olmstead and Rhode (2001) use simultaneous equations, and Hornbeck and Naidu (2014) exploit a natural experiment of black out-migration caused by the Great Mississippi Flood of 1927. In our setting, land sale was forbidden and labor migration was extremely restricted; therefore we can exclude endogenous changes in farm size and labor force and focus on their exogenous changes induced by the HRS reform.

Our findings also contribute to the large literature on the effects of institutional reforms on agricultural investments and technology adoption.[4] While most studies emphasize that secure private property rights are likely to induce more investments, we highlight that both collective and private property rights may induce large investments in technology, albeit in different forms.[5] Seemingly "better" institutions are not necessarily accompanied by more advanced technologies, but they do encourage more economically efficient technology choices. Compared to collectives and the government, individual households invested less in tractors and more in draft animals after the reform. But their tractor use was more efficient: it is more responsive to local factor endowments and farm size.

The HRS reform was one of the most fundamental and far-reaching reforms in the early stage of China's economic takeoff, and its effects on agricultural production have been intensely debated since the late 1980s.[6] We are the first to conduct a detailed analysis of the transformation of tillage technology, a crucial aspect of agricultural production that has been largely overlooked in the literature.[7] We also use a new disaggregate county-level dataset with unprecedented spatial and temporal coverage.

2. Agricultural mechanization and land reforms in China

Agricultural mechanization is a broad concept that covers the use of mechanical power in land preparation, pumping, harvesting, threshing, milling, etc.[8] The rapid mechanization of Chinese agriculture in the 1970s started with the month-long Second National Conference on Agricultural Mechanization in 1971. The conference announced that by 1980, all branches of agriculture - including cropping, forestry, animal husbandry, fishery, and other sideline productions - should be over 70 percent mechanized, and that 60 percent of all arable land should be

[2] The literature is influential in both macroeconomics (see Acemoglu and Zilibotti (2001); Caselli and John Coleman (2006)) and microeconomics (see Beaudry et al. (2010); Clemens et al. (2018)).

[3] The literature on technology adoption in agriculture is large. On the role of information and learning, see, for example, Foster and Rosenzweig (1996), Munshi (2004), Conley and Udry (2010), Hanna et al. (2014), and Bold et al. (2017). Even if there is no information barrier, cognitive capacity and behavioral biases could affect information processing and lead to sub-optimal technology choices (Duflo et al., 2011). On the role of local conditions and access to technology, see Emerick et al. (2016). For a literature review of microeconomic studies on technology adoption in agriculture, see Foster and Rosenzweig (2010).

[4] For some influential studies on private property rights and agricultural investments, see Besley (1995), Banerjee et al. (2002), Goldstein and Udry (2008), and Fenske (2011). Besley and Ghatak (2010) survey the literature. Jacoby, Li and Rozelle (2002) examine the China case. Our finding that de-collectivization caused a resurgence of draft animals complements the finding of the mass loss of draft animals caused by collectivization in the 1950s in China (Chen and Lan, 2017). The literature on the interactions between institutions and technology is vast. For some influential surveys of this literature, see Acemoglu et al. (2005), Mokyr (2005), and Ogilvie and Carus (2014).

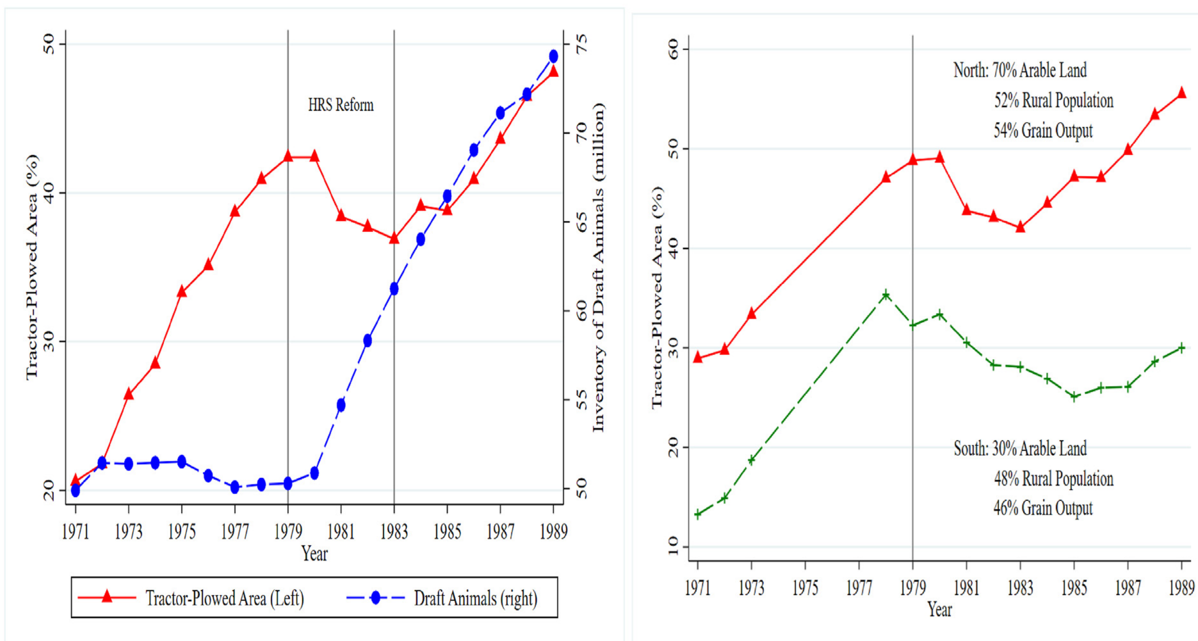
[5] It is difficult to compare the investment costs of a tractor and a draft animal. Though a tractor appears to be more expensive, the cost of fodder and disease prevention for a draft animal could be significant.

[6] Some examples of pioneering works are McMillan et al. (1989) and a series of papers by Justin Yifu Lin (1988, 1991, 1992). For more recent discussions, see Gong (2018) and the literature cited there.

[7] We are not the first to note the decline in tractor use after the HRS reform. Lin (1988) mentions this national trend to argue that labor inputs increased after the reform, which caused a drop in the demand for labor substitution factors such as tractors. But he does not use sub-national data to discuss tractor use in detail.

[8] Pingali (2010) provides a great introduction to agricultural mechanization in developing countries worldwide. The Editorial Board of Contemporary China Series (1991) contains comprehensive documentation of agricultural mechanization in China. Compendium (1988) collects many important documents and conference records on China's agricultural mechanization from 1949 to 1987. Our description relies heavily on the latter two sources.

Panel A. National Trends **Panel B. Provincial Trends in Tractor-plowed Area**



Notes: In Panel A, the percentage of arable land that is plowed by tractors is on the left axis. The stock of draft animals, in million head, is on the right. Panel B is the provincial means of northern and southern provinces, divided by the Qinling-Huaihe line. The statistics on the figure are from 1978, the last year before the HRS reform. Provincial-level data from 1974 to 1977 are not available.

Source: Ministry of Agriculture (1990); Ministry of Agriculture & China Association of Agricultural Machinery Manufacturers (2006)

Fig. 1. Macro-trends in Tractor Use and Draft Animals.

plowed by tractors. After Mao's death in 1976, however, the leadership was gradually shifted to Deng Xiaoping. When the Household Responsibility System (HRS) reform began to gain momentum, these targets were abandoned in 1980.

The HRS reform started in 1978 and essentially finished in 1983. All collectively-owned land and production means were divided among member households. Production teams, collectives' basic production and management units, were dismantled. Individual households started to manage their own farms, under contracts granted for up to 15 years.[9] By the end of 1983, 98 percent of production teams, and 97 percent of rural households, had adopted the HRS system (China Agricultural Yearbook 1984).

The HRS reform had three far-reaching impacts on agricultural mechanization. First, it divided large collective farms into small household farms, which averaged only 0.6 ha.[10] Large tractors were inefficient for farms of this size. Second, the reform increased the effective labor inputs in agricultural production by incentivizing peasants to work harder (Lin, 1988, 1992), which reduced the demand for labor-saving technologies such as tractors. Third, before the reform, the collectives owned all machinery, which was jointly financed by the collective and the government, and private ownership was forbidden. Afterwards, individual households became the primary buyers and owners. By 1989, more than 92 percent of all tractors were privately owned (China Agriculture Yearbook, 1981–1990).

Panel A of Fig. 1 shows that during the rapid mechanization period of the 1970s, the area of tractor-plowed land doubled from 21 to 42 percent. After the HRS reform, it fell to 37 percent in 1983 but started to recover afterwards. As a replacement for tractors, the inventory of draft animals reversed its declining trend of the 1970s and surged by 50 percent from 1980 to 1989.[11] This seemingly modest drop in tractor use, and its rapid recovery after the reform, masks large differences across regions. The national pattern of tractor-plowed areas was largely driven by northern China, where 70 percent of the arable land was located. In the south, Panel B shows that the post-reform decrease in tractor use was much larger and the recovery much slower: it fell from 35 percent in 1978 to 25 percent in 1985 and had not returned to the pre-reform level by 1990.

Although these macro trends are quite informative, we need micro data to identify and estimate the causal effects of the HRS reform. We also need specific variables to measure the large differences between the north and south. The empirical analysis below explores the rich variations across counties. We start by introducing our data.

3. Data

We assemble a novel county-by-year dataset for 1755 counties from 1976 to 1988, the period after Mao's death and the Cultural Revolution. Our sample covers 81 percent of China's counties and 85 percent of its rural population.[12] Appendix Figure A2 shows the distribution of these counties on a map. Our sample does not include counties located on

[9] For more detailed discussions of the HRS reform, see Lin (1992) and Naughton (2007). In 1998, the Land Management Law secured land tenure and granted peasants 30-year formal land contracts.

[10] In 1978, the total area of arable land was 99.4 million hectares, and there were 173 million rural households (National Bureau of Statistics 1980).

[11] In the 1970s, the large increase of tractor use in tillage was not accompanied by a large decrease in the stock of draft animals because these animals could be used in other operations such as transportation. The sum of the percentage of tractor-plowed land and the percentage of animal-plowed land should always be 100 percent, since there is no alternative plowing method.

[12] A Chinese county is a large geographic and administrative unit. The average county includes about 396,000 rural residents and 46,000 ha of arable land. In 1988, China had 2184 counties or county-level cities (National Bureau of Statistics, 2010). About 85 percent of its 824 million rural population lived in the counties included in our data.

Table 1
Summary statistics.

Variables	Mean	Standard Deviation	Number of Counties[b]
Tractor-plowed area (%)[a]	31.5	26.3	1273
Number of draft animals	40,039	29,271	1550
Grain output/area of arable land (kg/hectare)	4060	2224	1690
Number of large or medium-sized tractors	374	432	962
Number of small tractors	1396	1890	946
Area of arable land (hectare)	45,529	38,082	1755
Rural population	396,293	275,469	1755
Flatness of land[a]	1.98	0.87	1755

[a] "*Tractor-plowed area*" is the percentage of tractor-plowed areas in all arable land. The numerator is the area that is plowed by tractors. Even if the same patch of land is plowed by tractors more than once in a year, it is counted only once. "*Flatness of land*" is a categorical variable: 1 for mountainous counties, 2 for hilly counties, and 3 for flat counties.

[b] This column lists the number of counties for which we have data.

pastureland that specialized in animal husbandry instead of cropping.[13] We collected the agricultural data from a wide variety of official sources, including 178 recently declassified government reports and published compilations of statistics, plus 1755 county gazetteers. The Data Appendix documents the data sources and variable definitions in detail.

Table 1 reports the summary statistics of this sample. A key dependent variable is the percentage of arable land that is plowed by tractors. Even if the same patch of land is plowed by tractors more than once in a given year, it is counted only once.[14] Another key dependent variable is the year-end inventory of draft animals: oxen, horses, and mules in the north, and oxen and water buffaloes in the south. We define a categorical variable of land topography, based on the Ministry of Agriculture's designation of counties (National Bureau of Statistics, 1989): 1 for 676 mountainous counties, 2 for 430 hilly counties, and 3 for 649 flat counties.

Our identification strategy explores variation across counties in the year the HRS was established. We extract this information from county gazetteers. China has a thousand-year-long tradition of recording local history in gazetteers. Every gazetteer has a section on agriculture, which contains a subsection on landmark agricultural reforms. The basic unit of the HRS reform was a production team, not a county; counties had an average of 1826 production teams in 1978 (National Bureau of Statistics 1980). It usually took one or two years for most teams in a county to adopt the HRS. We define the establishment year as the year in which over half of the production teams in the county had adopted the HRS.[15] The effects of early HRS experiments by a few teams were hardly reflected in the county-level data, since most other teams continued operating under the old system. Until a production team was officially dismantled and all the means of production were redistributed to individual households, the private ownership of tractors or draft animals was forbidden. Thus our interested outcomes were driven by real reform, not by a mere expectation of the upcoming reform. The earliest establishment year by our definition was 1980, and the latest year was 1983. By the end of 1983, only 2 percent of production teams and 3 percent of rural households had not adopted the HRS (China Agricultural Yearbook 1984). Most of these households were in pastoral counties not included in this study.

4. Tractors vs. draft animals

4.1. Descriptive patterns

Panel A of Fig. 2 shows the county-level means of tractor-plowed areas, grouped by year of HRS establishment. All counties followed a similar rising trend in the use of tractors until the reform generated an immediate downturn and reversed the trend. Panel B shows that the inventories of draft animals were quite stable until the reform. Unlike the immediate plunge in tractor use, the inventory of draft animals increased gradually after the reform because it was restricted by the animals' birth rates.

The HRS was first established in counties with the lowest intensity of tractor use and the highest intensity of animal use. This is consistent with the fact that the reform was first adopted in some hilly or mountainous counties in southern provinces such as Anhui and Guizhou. Their topography and the wetland rice production system restricted the use of tractors. They relied on draft animals, particularly water buffalos, for tillage. The reform gradually spread to more northern counties where the land was flat and the main crop was wheat, and tractor use increased accordingly. These patterns suggest that our empirical exercises must control for county fixed effects in order to filter out differences in the levels of outcome variables. The timing of the reform, however, appears to be unrelated to the deviation from the common pre-trends in all four groups of counties.

4.2. Econometric models

Our empirical models are the same as those used in Dobkin et al. (2018). We first use the nonparametric approach to estimate the coefficients on indicators for year relative to the establishment year of the HRS, or *event time*. We focus on the event period spanning from four years before to six years after the reform.[16] The basic specification is the following equation:

$$Y_{it} = \alpha_i + \lambda_t + \sum_{k\geq -4, k\neq -1}^{5} \mu_k + \varepsilon_{it}, \tag{1}$$

where α_i and λ_t are coefficients on county and calendar year fixed effects. The key coefficients of interest are μ_ks, the coefficients on event years relative to the omitted event year μ_{-1}, the year immediately before the HRS reform. Standard errors are clustered at the county level. In most estimations, we do not include other control variables. The dependent variables, such as the percentage of tractor-plowed land and the inventory of draft animals, are normalized by land size and thus comparable across counties. Natural conditions, which are important determinants of technology adoption, are absorbed by county fixed effects.

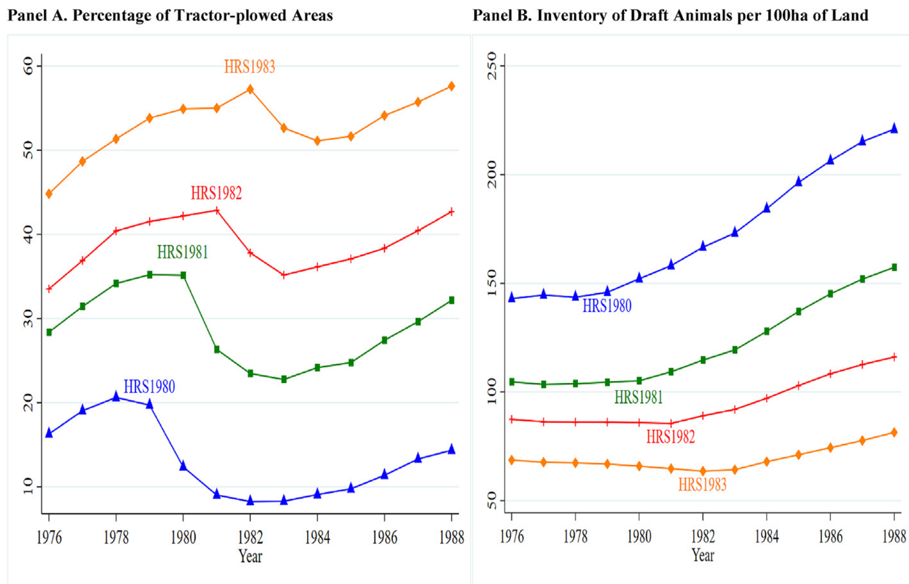
This nonparametric approach allows us to visually assess the dynamic change in the outcomes before and after the reform. To interpret $\mu_{k>-1}$s as the causal effects of the reform, however, would require that the outcome does not follow an upward or downward trend prior to the re-

[13] National Bureau of Statistics (1989) contains a list of 199 "pastoral counties" in the 1980s.

[14] This is the standard definition used by the National Bureau of Statistics (1989). Some local governments sometimes report the total workload of tractors. These statistics could be larger than the total area of arable land since the same patch of land could be plowed multiple times in a given year.

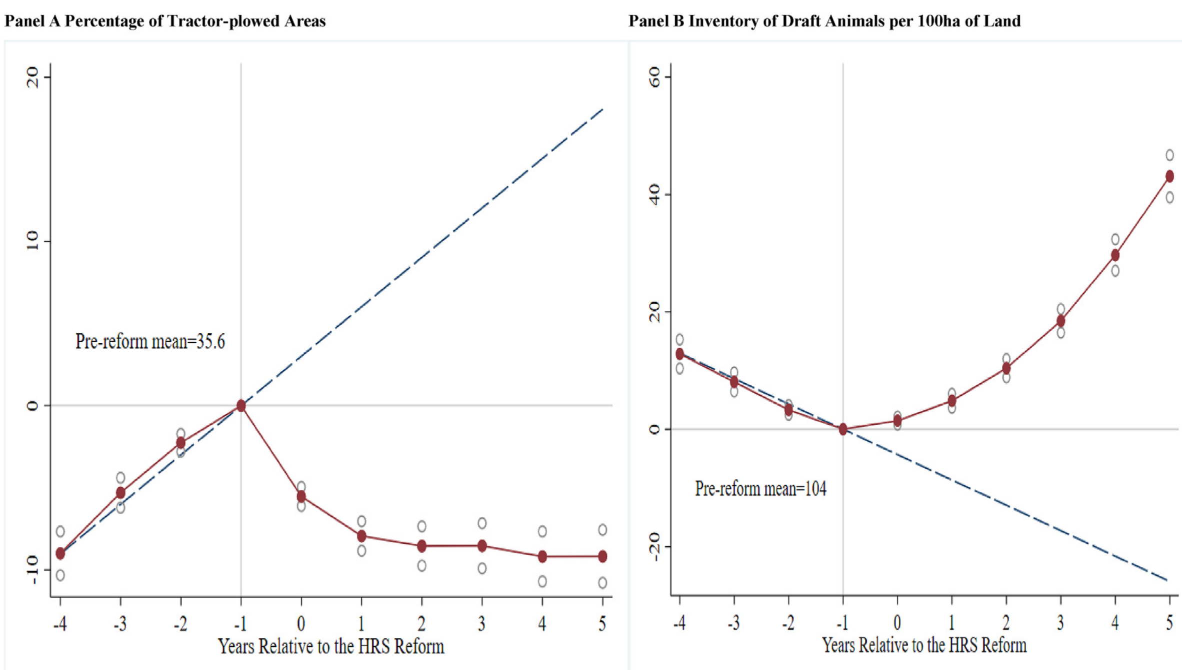
[15] A typical gazetteer records the progress of the HRS reform and the year it was completed. For example, an establishment year of 1982 would indicate one of the following situations: 1) For 1982, the gazetteer records that over 50 percent of the production teams had adopted the HRS; 2) For 1982, the gazetteer does not report a percentage, but it includes some statements such as "most teams had adopted" or "the HRS had become the dominant form of all types of contracts"; or 3) The gazetteer does not record any detail but simply states that the HRS had been established by 1982.

[16] Our sample contains 13 years of data from 1976 to 1988, divided into four groups of counties that adopted the HRS from 1980 to 1983. To ensure that the event study includes every county in each event year, we only have ten event years spanning from four years before to six years after the reform.



Notes: Counties are grouped by the establishment year of the HRS. The points represent within-group means.

Fig. 2. Tractor-plowed Areas and Draft Animals, by County.



Notes: The points represent the effect of event time, estimated in equation (1), and the hollow circles are the 95 percent confidence intervals. The establishment year of the HRS is *t=0*, and the base year in the estimation is *t=-1*. The dashed line represents the pre-reform trend of the outcome, estimated in equation (2), with the level adjusted to match the non-parametric estimates, i.e. to cross the point (-1,0).

Fig. 3. Event Study: Full Sample.

form. Otherwise, an increase or decrease in $\mu_{k>-1}$s would simply represent a continuation of the pre-trend. The estimates of equation (1) allow us to inspect whether such a pre-trend exists in the years leading up to the HRS reform. In the 1970s, rapid agricultural mechanization and the replacement of draft animals with tractors indeed generated a rising pre-trend in tractor use and a falling pre-trend in the number of draft animals. These estimates motivate and guide our formulation of the following parametric event study.

$$Y_{it} = \alpha_i^{'} + \lambda_t^{'} + \delta t + \sum_{k=0}^{5} \mu_k^{'} + \varepsilon_i^{'} \tag{2}$$

We add a linear pre-trend term t in equation (2). This choice of the functional form is guided by the estimates of equation (1). In the event study figures below, we superimpose the estimated linear trend t onto the coefficients estimated from equation (1). The results show that t captures any secular pre-trends very well. After controlling for county fixed effects

Table 2
Event-study estimates: Full sample.

	Percentage of tractor-plowed area		Draft animals per 100ha of land	
	non-parametric	parametric	non-parametric	parametric
	(1)	(2)	(3)	(4)
1-year effect	−5.541***	−8.764***	1.470***	6.082***
	(0.294)	(0.345)	(0.364)	(0.377)
2-year effect	−7.943***	−14.119***	4.866***	13.745***
	(0.456)	(0.601)	(0.604)	(0.791)
3-year effect	−8.550***	−17.711***	10.405***	23.585***
	(0.608)	(0.904)	(0.796)	(1.343)
4-year effect	−8.536***	−20.688***	18.486***	35.978***
	(0.698)	(1.222)	(1.017)	(2.043)
5-year effect	−9.184***	−24.322***	29.693***	51.490***
	(0.772)	(1.558)	(1.363)	(2.912)
6-year effect	−9.177***	−27.300***	43.113***	69.215***
	(0.819)	(1.900)	(1.828)	(3.900)
Pre-HRS trend		3.006***		−4.322***
		(0.225)		(0.422)
Observations	12,730	12,730	15,500	15,500

Notes: All regressions include a set of county dummies and calendar year dummies. Columns 1 and 3 include event year dummies before the HRS reform, while columns 2 and 4 replace these dummies with a linear trend. Standard errors are clustered at the county level.

and a pre-trend, the timing of the HRS reform appears to be uncorrelated with deviations of the outcome from the pre-trend (Fig. 2). Thus we can interpret μ's as the causal effect of the reform. Had the outcome continued moving along its pre-reform trend without disruption, it would have been, say, x_k in the kth year after the reform. The estimated $\mu_k^{'}$ in equation (2) measures the difference between this counterfactual x_k and the realized u_k in equation (1).

4.3. Estimates with the full sample

Fig. 3 shows the effects of the HRS reform on the percentage of tractor-plowed areas and the inventory of draft animals. For each outcome, we plot the estimated coefficients on event time (μ_ks) from the nonparametric event study regression in equation (1). We superimpose the pre-reform linear trend t estimated from the parametric event study regression in equation (2). The linear trends in both figures capture the pre-reform variations quite well. For each year k after the reform, the causal effect of the HRS on the outcome is the gap between μ_k and the linear trend. These gaps are estimated by $\mu_k^{'}$ in equation (2).

Table 2 reports estimated μ_k for $k \geq 0$ (the full set of estimates is reported in Appendix Table A1) and $\mu_k^{'}$. In the first year after the reform, the percentage of tractor-plowed areas immediately fell by 5.5 percentage points (column 1) from the year prior to the reform and by 8.8 percentage points (column 2) from the pre-reform trend. The decline was driven by tractor-plowed areas (the numerator), not by the area of arable land (the denominator), as shown in Appendix Figure A3. The decline stabilized after three years into the reform, but the causal effects implied by the linear counterfactual continued to increase. The three-year causal effect of the reform was a decline of 18 percentage points and the six-year effect was 27 percentage points. We note that the linear pre-trend could not continue in the long run because the outcome has an upper bound. Over a period of six years, however, the counterfactual 18-percentage-point increase implied by the linear trend was not implausible. Prior to the reform, tractor-plowed areas had increased by 18 percentage points to 39 percent from 1971 to 1977 (Panel A of Fig. 1). The original official goal, before it was abandoned, was to push this to over 60 percent in three years. While achieving a seven-percentage-point increase per year was criticized as infeasible, a less ambitious target of an 18-percentage-point increase over six years, or three percentage points per year, might have been achieved had the reform not been initiated.

Farmland not plowed by tractors had to be plowed by draft animals; no alternative was available. The inventory of draft animals increased modestly in the first year after the reform, by 1.5 head per 100 ha of land (column 3) from the year prior to the reform and by 6.1 head (column 4) from the pre-reform trend. The inventory did not surge instantly because it was restricted by the animals' birth rates. After six years, the gradual buildup accumulated into a large causal effect: an increase of 69 head or 66 percent of the pre-reform mean. This increase seems larger than the necessary replacement predicted by the pre-reform ratio of tractor use to animal use.[17] There are two possible explanations. First, the small independent households created by the reform each had to own their means of production after the old sharing arrangements collapsed with the collectives, which greatly increased the demand for draft animals. Second, the reform increased labor inputs, which raised complementary factor inputs such as draft animals (Lin, 1988).

4.4. Heterogeneity and the timing of the HRS reform

A salient feature of the HRS reform is that it began as a bottom-up reform by individual communes in the late 1970s. It only became national policy after it was officially recognized and approved by the central government on January 1, 1982, in its famous "No. 1 Document" for the year. Thus, for the counties that established the HRS in 1980 and 1981, the timing of the reform was probably more endogenous to local conditions, while for the counties that established the HRS in 1982 and 1983, the timing was likely more exogenous.

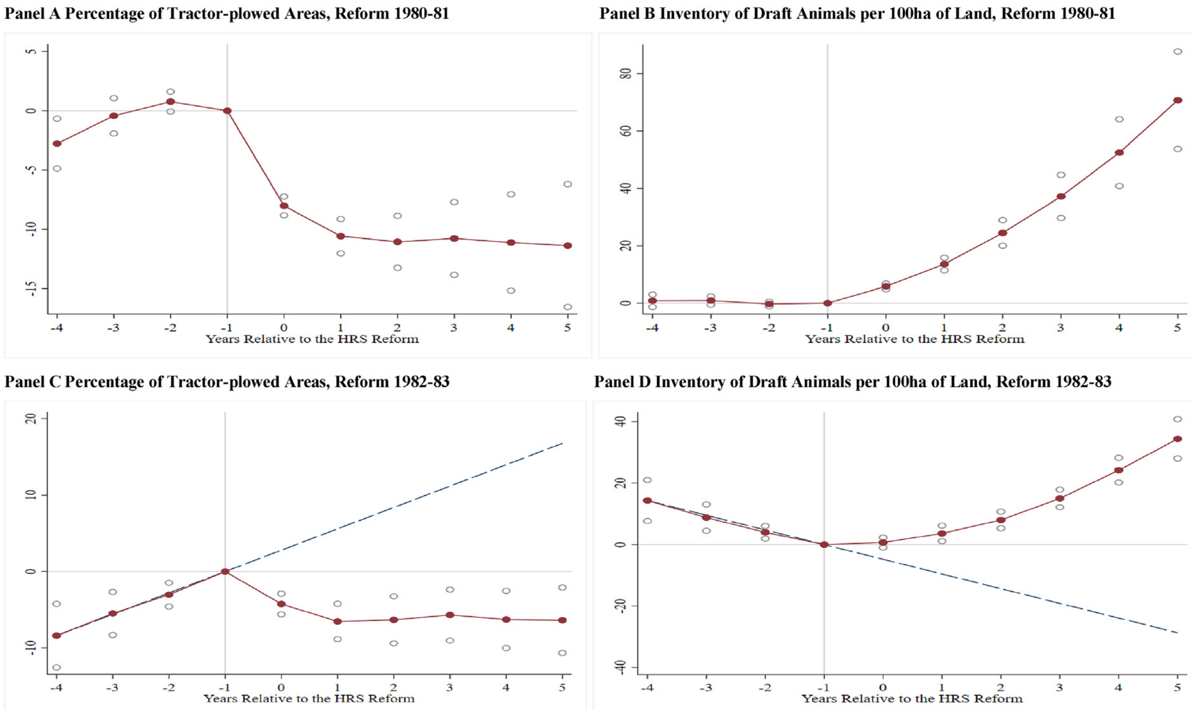
We split the counties into two subsamples according to their HRS establishment year: 1980–81 and 1982–83. We then repeat our estimates of equations (1) and (2) for each sub-sample. For the earlier group, panels A and B in Fig. 4 show no clear trend prior to the reform. Thus the causal effects of the reform should be estimated with μ_k for $k \geq 0$ in equation (1), reported in columns (1) and (2) in Table 3. For the counties that established the HRS only after the national endorsement, panels C and D in Fig. 4 show a pattern similar to that in Fig. 3. The salient pre-trends are captured fairly well by linear trend terms, and the estimated causal effects $\mu_k^{'}$ in equation (2) are reported in columns (3) and (4) in Table 3.

These estimates with sub-samples are in line with the estimates using the full sample. For tractor use, the non-parametric estimates are similar across all samples: it declined by 8–10 percentage points after 3 years of the reform and stabilized afterwards. The parametric estimates of causal effects in the 1982-83 sub-sample are also similar to those with the full sample: the three-year effect was a decline of about 15–18 percentage points and the six-year effect was of 23–27 percentage points. For the number of draft animals, the estimates are almost the same across all samples: the three-year effect of the reform was an increase of 24 head and the six-year effect was an increase of about 70 head per 100 ha of land.

Moreover, within each subsample, we could test the common trend hypothesis. Since each subsample only includes two groups of counties, it is straightforward to test whether the two groups were similar prior to the reform. If they were, the reform timing within each subsample be more likely to be exogenous. We use the following model:

$$Y_{it} = \alpha_i + G_i \sum_{k \geq -4}^{-1} \mu_k + \varepsilon_{it}, \tag{3}$$

[17] Before the reform, tractors plowed 35 percent of the land and draft animals plowed the remaining 65 percent. Our estimates show that, compared to the last year prior to the reform, the percentage of tractor-plowed areas fell by 9 percentage points in the first five years after the reform. This would have led to a 14 percent increase in the workload of draft animals (9 over 65). Had the intensity of animal use remained the same as in the period prior to the reform, a 14 percent increase in the workload would have led to an increase of 15 animals per 100 ha of land (14%*104, the pre-reform mean). Instead, our estimates show that, compared to the last year prior to the reform, the number of draft animals increased by 30.



Notes: The points represent the effect of event time, estimated in equation (1), and the hollow circles are the 95 percent confidence intervals. The establishment year of the HRS is *t=0*, and the base year in the estimation is *t=-1*. The dashed line represents the pre-reform trend of the outcome, estimated in equation (2), with the level adjusted to match the non-parametric estimates.

Fig. 4. Event Study: Split Samples.

Table 3
Event-study estimates: Split sample.

	reform year 1980-1981; non-parametric estimates		reform year 1982-1983; parametric estimates	
	tractor-plowed area	draft animals per unit of land	tractor-plowed area	draft animals per unit of land
	(1)	(2)	(3)	(4)
1-year effect	−8.018***	5.849***	−7.048***	5.465***
	(0.403)	(0.497)	(0.763)	(0.762)
2-year effect	−10.576***	13.627***	−12.133***	13.201***
	(0.737)	(1.102)	(1.665)	(1.787)
3-year effect	−11.046***	24.478***	−14.723***	22.355***
	(1.118)	(2.263)	(2.772)	(3.174)
4-year effect	−10.767***	37.193***	−16.895***	34.139***
	(1.560)	(3.834)	(3.920)	(4.992)
5-year effect	−11.104***	52.496***	−20.276***	48.124***
	(2.071)	(5.933)	(5.105)	(7.242)
6-year effect	−11.364***	70.742***	−23.168***	63.082***
	(2.636)	(8.645)	(6.276)	(9.796)
Pre-HRS trend	N	N	2.799***	−4.781***
			(0.706)	(1.133)
Observations	7620	9420	5110	6080

Notes: All regressions include county dummies and calendar year dummies. Columns 1 and 2 also include event year dummies before the HRS reform, while columns 3 and 4 replace these dummies with a linear trend, as shown in Fig. 4. Standard errors are clustered at the county level.

where α_i are county fixed effects and μ_ks are dummies for event years prior to the reform. Within each subsample, G_i is an indicator for counties that established the HRS later. For example, within the 1980-81 subsample, G_i is an indicator for the counties that established the HRS in 1981. The interaction terms between G_i and μ_k capture the changes of "counties of 1981" over time, relative to "counties of 1980". If these

Table 4
Common trend within each subsample.

	reform year 1980-1981		reform year 1982-1983	
	tractor-plowed area	draft animals per unit of land	tractor-plowed area	draft animals per unit of land
	(1)	(2)	(3)	(4)
Later group*three years before reform	−0.002	−1.348**	−0.035	−0.936**
	(0.460)	(0.547)	(0.753)	(0.376)
Later group*two years before reform	−0.540	0.361	−0.579	−1.886***
	(0.623)	(0.557)	(0.924)	(0.658)
Later group*one year before reform	0.296	−1.210	0.988	−2.656***
	(0.721)	(0.823)	(1.014)	(0.935)
Observations	3048	3768	2044	2432

Notes: All regressions include county dummies and event year dummies prior to the reform. Standard errors are clustered at the county level.

terms are close to 0, we cannot reject the common trend hypothesis prior to the reform. Since each subsample only includes two groups, the interactions between G_i and μ_k would absorb all the changes over time, and a separate set of calendar year dummies would not be identified. Standard errors are clustered at the county level.

Table 4 reports these interaction terms for the three years prior to the reform, compared to the base year $k = -4$. For tractor use, within each subsample, the pre-reform yearly differences between the two groups of counties are neither economically nor statistically significant from 0. For draft animals, the pre-trend of "counties of 1981" is very close to the pre-trend of "counties of 1980", except for the earliest event year. But that difference of 1.3 is not economically significant, compared to 120, the sample mean of the dependent variable. In the 1982-83 sample, the "counties of 1983" experienced a slightly steeper decline in draft animals prior to the reform relative to the "counties of 1982". This does not necessarily imply that the two groups were not comparable or the reform timing was endogenous. After all, their tractor use followed a common trend prior to the reform. In Appendix Table A2, we further show that rural population and arable land area in these two groups of counties also followed a common trend prior to the reform. That said, we should adjust our estimates in column (4) of Table 3 by allowing for group-specific trends prior to the reform. Appendix Table A3 shows that this adjustment reduces the estimated effects by about a third.

5. Tractor use and factor endowments

The overall decline in tractor use does not imply a drop in tractor *efficiency*. Private investment and technology adoption are presumably more efficient than government or collectives, perhaps because government is less efficient at using local information (Hayek, 1945). Prior to the reform, private ownership of tractors was forbidden. By 1989, however, more than 92 percent of tractors were privately owned (China Agriculture Yearbook, 1981–1990).[18] Section 5.1 shows that post-reform tractor use was more responsive to local factor endowments. Section 5.2 shows that tractor use was more prevalent in counties in which household farms were larger after the reform. Since household farms were much smaller than collective farms, the number of small tractors increased significantly after the reform, while the number of large tractors declined.

5.1. Factor endowments

Since it is a labor-saving technology, tractor use in tillage should decrease when more labor is available. Meanwhile, tractors should be more efficient on larger and flatter land. Thus we evaluate the effects of three types of factor endowments on tractor use: rural labor, land area, and land topography. The heterogeneous effects of land and labor could not be equalized across counties. During the reform period, land sale was forbidden and domestic migration was essentially zero due to the severe restrictions imposed by the *hukou* (population registration) system.[19] In addition, Appendix Figure A3 shows that both the rural population and the amount of arable land change smoothly over time, and are not affected by the HRS reform.

We use the following model to examine whether the reform enhanced the effects of these factor endowments, i.e. whether post-reform tractor use became more suitable to local conditions.

$$Y_{it} = \mathbf{X}_{it} + T_{it} + \mathbf{X}_{it}T_{it} + \lambda_t + \varepsilon_{it}, \tag{4}$$

Y_{it} is the logarithm of the percentage of tractor-plowed areas in all arable land in county i and year t, which measures the extent of tractor use in tillage. The factor endowment vector $\mathbf{X}_{it}$ includes (*the log of rural population, the log of area of arable land, flatness of land*). T_{it} is a dummy variable for post-reform years, which captures the mean shift of Y_{it}. The interaction terms $\mathbf{X}_{it}T_{it}$ examine whether the effects of the factor endowments changed after the reform. λ_t is a set of calendar year fixed effects.

Since we want to compare the difference between counties, we first estimate this model without including county fixed effects. Variations of factor endowments are mainly *between*-rather than *within-counties*. Land topography is time-invariant within a county. For rural population and land area, over 99 percent of the overall-variance is from between-county-variance. As for the percentage of tractor-plowed areas, about 86 percent of the overall-variance is from between-county-variance.

Table 5
Factor Endowments and Tractor Use, Y = log(percentage of tractor-plowed area).

	full sample		HRS 80-81	HRS 82-83
	(1)	(2)	(3)	(4)
Log (rural population)[a]	−0.112***	−0.114	0.265	−0.012
	(0.029)	(0.219)	(0.406)	(0.230)
Log (arable land)[a]	0.192***	0.096	0.431	−0.049
	(0.042)	(0.195)	(0.334)	(0.175)
Flatness of land[a]	0.604***			
	(0.029)			
Post-HRS*Log (rural population)	−0.118***	−0.097***	−0.109***	−0.047*
	(0.024)	(0.023)	(0.036)	(0.026)
Post-HRS*Log (arable land)	0.132***	0.114***	0.117**	0.080**
	(0.035)	(0.031)	(0.045)	(0.033)
Post-HRS*Flatness of land	0.176***	0.159***	0.170***	0.096***
	(0.023)	(0.021)	(0.030)	(0.024)
Post-HRS	−1.080***	−0.235***	−0.278***	−0.157***
	(0.045)	(0.017)	(0.028)	(0.026)
County FE	N	Y	Y	Y
Observations	12,730	12,730	7620	5110

Notes: All regressions include a set of calendar year dummies. Standard errors are clustered at the county level.
[a] These three variables are demeaned from their sample mean. This transformation does not affect the coefficients of these variables or their interaction terms. The effect of "post-HRS" should be interpreted as the effect at the mean value of the three variables.

Column 1 of Table 5 reports the results. All the factor endowments had large and significant effects with the expected signs. The reform enhanced these effects: the effects of rural population and land size almost doubled after the reform. These results merit discussion. First, labor-saving tractor use declined more in counties with larger rural populations. Though we lack data on the effective labor supply, it is reasonable to assume that its post-reform increase, due to incentivized peasants who work harder, was larger in counties with larger rural population. Second, the post-reform decline in tractor use was *less* severe in counties with more arable land. Third, the enhanced effects of all three factors suggest that peasants' choice of technology was more responsive to local conditions than the government and collectives. However, even before the reform, the relationships between tractor use and local endowments were still sensible. After all, local conditions also restricted the actions of the government and collectives.

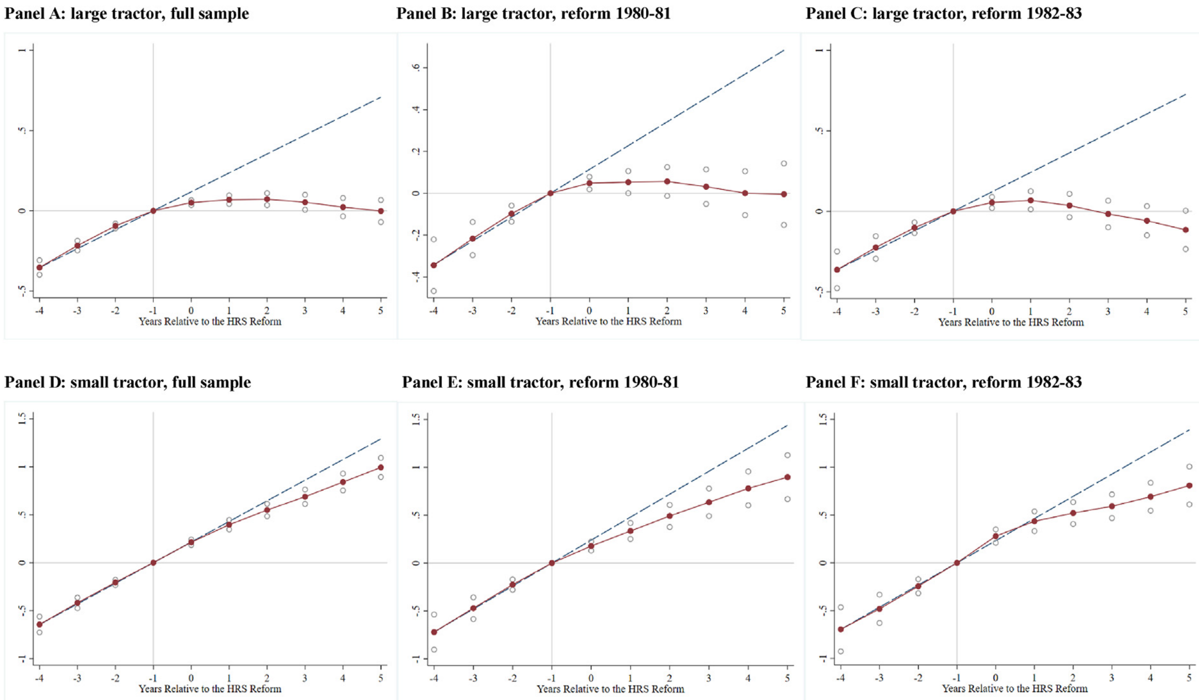
Column 2 estimates equation (4) including county fixed effects, which is driven by much smaller within-variations. On average, tractor use fell by 24 percent after the reform. This mean shift should *not* be interpreted as the causal average treatment effect since there is a pre-reform trend. We estimated the dynamic causal effects in the previous section; our focus here is the interaction terms $\mathbf{X}_{it}T_{it}$. As in column 1, the *within-county* post-reform decline in tractor use was greater among counties with larger populations, and smaller among those with more or flatter land. The coefficients of rural population and land size have the expected signs but are not accurately estimated. This low efficiency is due to small *within-variations* in both variables, which account for only 0.2 percent of overall-variation. The coefficient of time-invariant land topography is not identified while county fixed effects are included.

Columns 3 and 4 repeat the estimation of column 2 for two subsamples, and the results are similar. Taken together, the results reported in Table 4 could explain the salient divergence in tractor use between the south and north, as shown with macro-level data in Fig. 1. Tractors were more popular in the north because it has 70 percent of the country's arable land but only 52 percent of its rural population. The north is also much flatter: it contains 78 percent of the country's "flat counties."

5.2. Farm size and tractor size

Tractor use is more likely on larger farms (Olmstead and Rhode,

[18] Appendix Figure A4 illustrates the ownership change over time.
[19] According to the 1982 census, migrants accounted for 0.8 percent of the adult population (14 years and older) in 1981. This increased to 2 percent in 1989, according to the 1990 census.



Notes: The engine of a small tractor is less than 20 horsepower, or 14.7 kilowatt. The points represent the effect of event time, estimated in equation (1), and the hollow circles are the 95 percent confidence intervals. The establishment year of the HRS is *t=0*, and the base year in the estimation is *t=-1*. The dashed line represents the pre-reform trend of the outcome, estimated in equation (2).

Fig. 5. Event Study: Tractor Type; Y = log (number of tractors).

2001; Hornbeck and Naidu, 2014; Foster and Rosenzweig, 2011). The HRS reform divided the arable land equally among its rural residents, so the arable land per capita is a good proxy for the average size of household farms in a county. Moreover, as we argued in Section 5.1, the HRS reform did not change either the land size or the population size, at least for the first couple of years. Hence household farm size was exogenously determined. Given the log of the rural population, the coefficients of "post-HRS*log (arable land)" in Table 5 also measure the elasticity between household farm size and tractor use after the reform: a 10 percent increase in the size of household farms would increase tractor use by about 1 percent after the reform.[20]

Smaller household farms and lower household budgets also generated a large demand for smaller and cheaper tractors. Pre-reform tillage mechanization was characterized by the popularity of large tractors in collective farms. The Massey Ferguson 35 (made in Canada), the ДТ-54 (made in the Soviet Union), and particularly the domestic *Dongfanghong*-54 were once household names of large tractors and were perceived as a symbol of modern agriculture. Since these large machines cannot be operated efficiently on small household farms, they were soon replaced by cheaper small tractors.

For about 950 counties, we collect data on the year-end inventory of large/medium-sized tractors and small or walking tractors. These variables are measured by physical numbers, not mechanical power capacity. The engine of a small tractor is usually less than 20 horsepower, or 14.7 kW. Fig. 5 plots the event study estimates of the reform effects on the number of different tractors. Across all samples, the number of large tractors stops growing and declines after the reform. The number of small tractors, however, continues to increase, at a somewhat slower rate than in the pre-reform years. Across all samples, the number of small tractors increased by about 0.9 log point, or 150 percent, in the six years after the reform compared to the year prior to the reform.

The large increase in small tractors and the relatively stable number of large tractors suggests an increase in the total number of tractors after the reform. However, this increase was accompanied by a decrease in tractor use in tillage. This implies that many large tractors, though exists in books, were abandoned in practice since they were too expensive to use on small farms. The collective production system that centered on them, including the supply chain of parts and diesel, the operators' training schools and the management organizations, and the maintenance service, became obsolete.

The increase in the use of small tractors was not fast enough to compensate for the loss of large tractors. One reason could be that many households were too poor to buy a small tractor, and effective sharing arrangements such as a rental market had not yet been developed. Another reason could be technology. In order to plow a field, tractors need other equipment such as tractor-drawn plows. This equipment is not interchangeable between large and small tractors. The transition from large to small tractors hence created a temporary shortage in the supply of small tractor-drawn equipment. From 1981 to 1985, the number of tractor-drawn equipment per small tractor decreased by 21 percent from 1.12 to 0.89 (Compendium 1988, 1183). This shortage might have restricted the use of small tractors in tillage. Some farmers also bought small tractors for transportation in the countryside, a profitable operation in the late 1980s since the economic reform created better market access. In 1985, transportation accounted for about 60 percent of the total workload of all general-purpose agricultural machinery, including tractors (Editorial Board of Contemporary China Series, 1991, 65).

6. Conclusions

Better institutions do not always advance technologies; they might

[20] Since we define *log(farm size) = log(arable land)-log(rural population)*, after controlling for *log(rural population)*, whether we estimate the coefficient of *log(farm size)* or the coefficient of *log(arable land)*, the results are the same.

also lead to backward but economically efficient technologies. We use a novel county-by-year dataset to document how China's HRS reform in the early 1980s transformed tillage technology, from using tractors on large collective farms to using draft animals on small household farms. The tractors that were still used after the reform were employed more efficiently, in ways that were more suitable to local conditions and farm size.

This paper focuses on the HRS reform's immediate effects on technology adoption. Since the reform, household farms have remained small for at least three decades. This small-farm system has its difficulties in supporting persistent productivity growth, and its intensive use of chemical fertilizers has produced severe pollution (Wu et al., 2018). Further land reforms have been proposed and implemented, and some recent research has started to evaluate their effects (Chari et al., 2017). Given the country's rapid urbanization and huge rural out-migration, Chinese farms will certainly become larger and more capital-intensive in the future. However, large farms, at least collective ones, are not always more efficient. In the 1980s, it was those small farms equipped with labor-intensive and primitive technology that sparked China's economic takeoff.

Author statement

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jdeveco.2020.102536.

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Further reading

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