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Gender-biased technological change: Milking machines and the exodus of women from farming.*

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Abstract

This paper studies the link between gender-biased technological change in the agricultural sector and structural transformation in Norway. After WWII, Norwegian farms began widely adopting milking machines to replace the hand milking of cows, a task typically performed by women. Combining population-wide panel data from the Norwegian registry with municipality-level data from the Census of Agriculture, we show that the adoption of milking machines triggered a process of structural transformation by displacing young rural women from their traditional jobs on farms in dairy-intensive municipalities. The displaced women moved to urban areas where they acquired a higher level of education and found better-paid employment. These findings are consistent with the predictions of a Roy model of comparative advantage, extended to account for task automation and the gender division of labor in the agricultural sector. We also quantify significant inter-generational effects of this gender-biased technology adoption. Our results imply that the mechanization of farming has broken deeply rooted gender norms, transformed women's work, and improved their long-term educational and earning opportunities, relative to men.

JEL Codes: J16, J24, J43, J61, N34, O14, O33

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1 Introduction

Between 1950 and 2000, agricultural employment fell by 75% in Europe, mostly due to the adoption of labor-saving technologies that automated traditional farming tasks and increased capital intensity on farms. Despite the massive displacement of farm labor with potentially large economic and social costs, labor-saving technologies in agriculture are regarded as the key drivers of structural change and increased welfare. The automation of farming tasks reduces the demand for farm workers and, as a result, displaced workers have moved to cities and have found jobs in the expanding manufacturing and service sectors (e.g., Nurkse, 1953; Schultz, 1953; Rostow, 1960; Gollin et al., 2002).

This well-established narrative ignores the fact that traditional farming is subject to strong gender norms, and the resulting gender division of labor: women have mostly specialized in dairying, livestock, and indoor work, while men have worked outdoors cultivating field crops, amongst other things (e.g., Kussmaul, 1981; Alesina et al., 2013; Voigtländer and Voth, 2013). Because of the traditional division of labor in agriculture, different labor-saving technologies are expected to displace men and women at different rates, depending on which tasks are automated. This, in turn, can influence both genders' decisions to work outside of the farming sector, ultimately affecting both the pace of structural change and their own welfare. Despite the significance of these life-altering decisions, the gender effects of labor-saving agricultural technologies on structural change and the long-term earning opportunities of men and women are not yet well understood.

This paper analyzes the relationship between gender-biased technological change in the agricultural sector, structural transformation, and the long-term earning opportunities of displaced workers. We focus on one of the largest gender-biased automation shocks in modern agriculture: the adoption of milking machines. European dairy farmers widely adopted milking machines from the 1950s onwards, in order to replace the hand milking of cows—the most common job for hundreds of thousands of young rural women. Our study focuses on Norway, which provides an ideal setting in which to evaluate the economic consequences of the introduction of milking machines, as dairying is described as the cornerstone of Norwegian agriculture. Like other European dairy regions, Norway experienced a sharp and widespread increase in the use of milking machines after WWII, which coincided with an exodus of women from farming and a spike in urbanization (Almås, 1983). The number of milking machines increased from 6,357 to 39,924 in the 1950s, while female employment in agriculture fell by

80% between 1948 and 1961.[1] Our goal is to understand how this gender-biased technology shock affected the pace of structural transformation and the fortunes of young rural women and their children.

The detailed Norwegian registry data and official agricultural statistics provide a rare opportunity to study the short- and long-run effects of gender-biased technological change at the individual level. In contrast to studies linking historical records, the Norwegian registry data allows us to systematically follow *men and women* over time.[2] Hence, we can show that the automation of hand milking differentially displaced men and women out of agriculture, and document the extent to which this displacement pushed them out of rural areas and into cities. With this data at hand, we can also assess the effect of the adoption of milking machines on occupational upgrading, as well as on human capital investment and income by gender. One further advantage of the Norwegian registry data is that we can analyze the spillover effect of the mothers' displacements on their children's outcomes.

Our research design is an intensity of treatment framework, where the roll-out of milking machines affects rural female workers differentially, depending on the local farming conditions prior to their adoption. The idea is that municipalities that were better suited to dairy farming prior to the diffusion of milking machines are expected to be more affected by the adoption process.[3] This technology shock, used as a quasi-experiment in our estimation approach, had differential effects for women and men and for different age groups in exposed areas. We develop a simple theoretical model in order to better understand who was affected by the adoption of milking machines, and, especially, who *complied* to leave farming, move into cities, and invest in human capital. Our model combines the key ideas of comparative advantage (Roy, 1951) to explain rural-to-urban migration, with a task-based production function (Zeira, 1998; Autor et al., 2003; Acemoglu and Autor, 2011) to allow for labor-saving technological change and the gender division of labor in traditional farming tasks.[4] Based on this theoretical framework, we are in a better position to identify the compliers of

[1] This figure is based on the number of female hired workers (see Appendix Figure 3, columns 7 and 8; Central Bureau of Statistics of Norway (1968, Table 78)). Other dairy regions, such as Denmark, France, Switzerland, West Germany, and the Netherlands, experienced similar processes. For example, in the Netherlands, the number of milking machines increased from 4,000 to 39,000 in the 1950s, while female employment fell by 75%; from 169,000 to 41,000 in levels (Bieleman, 2005; Mitchell, 1998).

[2] Researchers using automated linking methods to create historical panel data without unique identifiers cannot systematically link women over time since, in most cases, their last name changes after marriage.

[3] We use the number of dairy cows per farm prior to the introduction of milking machines to proxy for conditions favoring the adoption of this new technology. A similar intensity of treatment approach is used by Nunn and Qian (2011) to evaluate how the potato contributed to population growth and urbanization.

[4] Nakamura et al. (2021) highlight the importance of comparative advantage for understanding the costs and benefits of moving.

our quasi-experiment of gender-biased technological change.

We derive four predictions from the model that we bring to the data. First, the adoption of milking machines is expected to push young women out of agriculture and from rural areas into cities. Second, this gender-specific technology shock is expected to increase women's earning opportunities in the long run. Since moving to a city is economically and socially costly, a large share of the women displaced by milking machines were misallocated workers who had their comparative advantage outside of the rural sector.[5] Hence, women pushed out of agriculture and into cities will remove this allocative inefficiency and end up with better-paid jobs. Third, the effect of the milking machines will be stronger in municipalities with farming conditions better suited to dairy production in the pre-milking machines era. Fourth, since rural tasks performed by men and women are relative complements in the rural production process, men are not immediately displaced by the arrival of this technology.

These predictions are consistent with the historical narrative. In the past, dairying and milking the cows were common jobs for young, unmarried women in rural Norway, as in other parts of Europe (Snell, 1981; Schultz, 1985; Osterud, 2014; Lampe and Sharp, 2019). Norwegian sociologists have argued that the rapid mechanization of agriculture after WWII pushed labor off the farms and that women were generally more affected by this process than men. In particular, young women aged between 16 to 25, before marrying and having children, were displaced by milking machines. This led to a gradual masculinization of Norwegian agriculture (Almås, 1983; Almås and Haugen, 1991; Brandth, 2002).[6]

Why were women more likely to move to urban areas after being displaced? As outlined in our model, the answer depends on three factors: first, the comparative advantage of young men and women; second, the occupational structure in rural areas that favored men; and third, job opportunities in urban areas. Norway's farming sector consisted of farmers who owned enough land to feed a family, crofters, and hired male and female workers.[7] For young men, the mechanization of agriculture reduced the available work on farms, however, the rural labor market still offered work opportunities. For example, they were in high

[5]Historically, women faced a variety of costs and barriers in moving out of rural areas, ranging from pure economic costs to social norms, such as losing access to extended family networks, or informal insurance networks. Recent work has emphasized the importance of such moving costs for the misallocation of workers in rural settings (Munshi and Rosenzweig, 2016; Nakamura et al., 2021).

[6]Notably, Almås (2002) stresses that young hired female workers were the first to be displaced as farming became more mechanized, followed by extended family—mostly unmarried sisters, aunts, and cousins. See also Historical Statistics from Statistics Norway (1968, Diagram 17).

[7]Hired male workers typically performed seasonal work on farms and, in addition, worked in other occupations outside of farming. Similarly, male crofters—a large group in rural Norway who rented land for cultivation—also performed seasonal work on other farms in order to complement their income; for example, in construction, and in the fisheries or timber industries.

demand for construction work or in fisheries, especially in the post-WWII boom years. Young women, however, had few job opportunities outside of agriculture in rural areas. After being displaced from farming, they had a comparative advantage in cities by finding employment, for example, in the expanding social services sector, in teaching, child care, or clerical work (Almås, 1983; Almås and Haugen, 1991; Brandth, 2002). Importantly, accessing these jobs required human capital investment, however, most higher education institutions were located in large towns not accessible to rural municipalities. Hence, young rural women displaced by milking machines could re-optimize by moving to urban areas and invest in human capital, and therefore find better-paid employment. In contrast, displaced young men, for the most part, had alternative job opportunities in rural areas with high returns for the skills they had already acquired while working on farms.

Our main finding is that the large-scale adoption of milking machines after WWII triggered a process of structural change in Norway that, despite its short-run costs, increased the return to education and long-term earning opportunities for young women who grew up in dairy-intensive municipalities. This result is based on approximately 380,000 women who lived in rural municipalities at the ages of 16 to 25 and are registered in the Norwegian censuses between 1930 and 1970. We first show that, consistent with the predictions of our theoretical model, the adoption of milking machines pushed young women in affected areas out of traditional jobs in agriculture. In the short run, this displacement effect entailed substantial income losses for affected women.[8] In the long run, however, we document that the automation of hand milking brought prosperity to affected women. We also show that displaced women from dairy-intensive municipalities migrated to urban areas after the adoption of milking machines, where they ended up in higher-skilled and better-paid jobs. Consistent with this result, we also find that affected women were more likely to invest in higher education, which is a requirement for many white-collar jobs. Indeed, the migration decisions were partly determined by local access to higher education institutions, indicating that the long-run effects of task automation on displaced workers are not institution independent. Overall, these results suggest that task reinstatement into the expanding manufacturing and, especially, the service sector improved women's earning opportunities in the long run (Acemoglu and Restrepo, 2018). The long-run income gains were considerable and compensated for the short-run costs: for a one-standard-deviation increase in our treatment

[8] This finding is consistent with workers' fears that labor-saving technological progress curtails employment and lowers wages (Mokyr et al., 2015). For example, Caprettini and Voth (2020) document that the diffusion of threshing machines, a labor-saving technology in agriculture, promoted social unrest in early 19th century England. In modern settings, Acemoglu and Autor (2011) and Acemoglu and Restrepo (2020) show that labor-saving technological change leads to worker displacement and wage depression in the short run.

intensity measure, women climbed up their birth-year specific income distribution by one percentile. Importantly, our results are not driven by pre-trends, and they are robust to: (i) a permutation exercise; (ii) alternative definitions of treatment; (iii) including potential confounders, such as education reforms, hydroelectric power diffusion, and differences in farm sizes; (iv) spatial correlation (see Section 6.4 for details).

Our second set of findings shows that, because of the traditional gender division of labor in agriculture, introducing labor-saving technologies can have major and long-lasting *gender-specific* effects. We find that while displaced women migrated to urban areas, invested in their human capital, and found higher-skilled employment in the expanding service sector, most young men found work in the same rural areas, which offered high returns on the skill sets they had already acquired. This result is consistent with the historical narrative and with the predictions of a comparative advantage framework (Roy, 1951), as outlined in our theoretical model. Overall, our findings show that the adoption of milking machines increased the long-term earning opportunities for young women relative to young men in dairy-intensive municipalities, reducing gender differences in income and in the skill-content of occupations in the long term. We also show that the gender-specific effects of milking machines differ from those of the general mechanization of agriculture after WWII. Specifically, we perform a "horse race" between the adoption of milking machines and tractors (a general-purpose technology) showing that our results are not simply capturing a general mechanization effect of agriculture that affected both genders.[9]

Finally, our third set of findings show that the adoption of milking machines had positive consequences for the children of affected women. The rich Norwegian registry data allows us to link women, who grew up in rural municipalities when milking machines were adopted, to their children. Specifically, we compare the educational attainment and income of children as adults, whose mothers had different exposure to milking machines. Our inter-generational estimates reveal that children from affected mothers have higher educational attainment and a higher income rank as adults. These findings provide an interesting contrast to the generally negative inter-generational effects of worker displacement documented in the literature (e.g., Oreopoulos et al., 2008; Stevens and Schaller, 2011; Rege et al., 2011). Despite the fact that the adoption of milking machines reduced young women's employment opportunities on farms in the short run, this displacement did not worsen the economic situation for

[9]The adoption of tractors is expected to affect both young male and female hired farm workers, as tractors automatized tasks that were typically done by men (e.g., plowing), as well as tasks in which women specialized (e.g., haymaking and grain harvest) (Almås, 2002). We refer readers to Section 6.5 for further details on the diffusion of tractors in Norway.

them or their children in the long run. Our results strongly suggest that the introduction of gender-biased labor-saving technologies in agriculture can trigger a structural transformation process that improves the economic position of affected women and their descendants.

We contribute to a growing literature on the effects of automation on labor markets. Recent examples are Atack et al. (2019) on the automation of US manufacturing in the late 19th century, Feigenbaum and Gross (2022) on telephone operation from 1920 to 1940, and Acemoglu and Restrepo (2019) on robotization in a more modern setting.[10] More generally, economic historians have vividly described how the mechanization of agriculture has transformed farms and displaced workers throughout the 20th century (e.g., Schmitz and Seckler, 1970; Rasmussen, 1982; Binswanger, 1986; Olmstead and Rhode, 2001; Grove and Heinicke, 2003). Our contribution to this literature is twofold. First, while previous empirical literature has focused on the short-run effects of automation, we document empirically its long-term effects, providing evidence that migration and task reinstatement can lead to long-term welfare gains for affected workers. Second, we show that the mechanization of farming broke up deeply rooted gender norms within labor markets (Alesina et al., 2013, 2018; Giuliano, 2015, 2018). In traditional farming, most tasks are strictly divided according to gender. The adoption of milking machines broke up this strict division of labor, as it pushed women (not men) out of rural areas, reduced gender differences in incomes, and contributed to the transformation of women's work in the second half of the 20th century (Goldin, 1990, 2006; Olivetti, 2014).

Our findings of gender-biased technological change in agriculture contribute to a copious literature studying the drivers of structural change.[11] The focus of recent empirical studies has been on evaluating the consequences of increases in agricultural productivity for economic development (e.g., Nunn and Qian, 2011; Hornbeck and Keskin, 2015; Bustos et al., 2016; Carillo, 2021; Gollin et al., 2021). One important insight from this literature is that the factor bias of technological change is a key determinant of the relationship between agricultural productivity and structural change.[12] We show that after the adoption of milking machines,

[10] Feigenbaum and Gross (2022) show that the automation of telephone operation—a job previously carried out by young women—in the US adversely affected incumbent telephone operators, but did not reduce the employment opportunities of future generations. Our study differs in three fundamental respects: (i) we investigate how the automation of tasks *in agriculture* affected the fortune of rural women and their children; (ii) we show how it can trigger structural change and break up deeply rooted gender norms; and (iii) our evidence is based on administrative data from the Norwegian registry, which do not suffer from potential selection bias arising from linking females across historical census records.

[11] See, e.g., Matsuyama (1992); Gollin et al. (2002); Foster and Rosenzweig (2007); Gollin (2010); Alvarez-Cuadrado and Poschke (2011); Herrendorf et al. (2014).

[12] Negative productivity shocks in agriculture unrelated to technological change (e.g., insect plagues or flooding) can also trigger structural change (e.g., Hornbeck and Naidu, 2014; Ager et al., 2020).

affected workers were pushed out of agriculture, they moved to cities, and found higher-skilled employment in the non-agricultural sector.[13] While existing empirical studies mainly focus on evaluating the effect of changes in agricultural productivity on local or national economies, our study provides new insights into how technological change in agriculture affected the economic fortunes of individuals; that is, of displaced rural women and their children. By doing so, we shed light on how changes in women's work has contributed to the process of structural transformation, and how it affected gender gaps in income and occupational choices.

Our results also speak to a large body of literature that considers barriers to migration and the selection of workers into specific locations as the main reasons behind rural-urban wage gaps (e.g. Lagakos and Waugh, 2013; Gollin et al., 2014; Munshi and Rosenzweig, 2016). While other studies rely on forced migration or natural disasters to study the misallocation of labor across sectors and places (Nakamura et al., 2021; Sarvimäki et al., 2022), we consider the large-scale adoption of a gender-biased labor-saving technology (such as milking machines) as a quasi-natural experiment that substantially reduced the barriers to moving by eliminating the job opportunities for women in agriculture. Our finding that displaced rural women moved to cities to find better-paid employment is consistent with the view that women were, on average, less productive in agricultural work than men (e.g., Foster and Rosenzweig, 1996; Pitt et al., 2012; Alesina et al., 2013). It also suggests that moving to cities was traditionally associated with substantial economic and social costs. Indeed, young rural women were often disadvantaged in their birthplace, as our results indicate that there were large long-term benefits associated with moving to cities. The adoption of milking machines broke up allocative inefficiencies in rural areas by reinstating rural women into better-paid employment in the non-agricultural sector. Overall, our evidence supports the view of development economists that the reallocation of workers from unproductive agricultural activities to the modern sector is essential for promoting structural transformation and economic growth (e.g. Lewis, 1955; Rostow, 1960; McMillan et al., 2014).

Finally, we add to the literature on inter-generational mobility. Although this literature is vast,[14] few papers document changes in inter-generational mobility patterns over time. Clark (2014) argues that such changes do not exist and that inter-generational mobility has remained low across historical periods. This persistence is illustrated, for example, by the

[13] This finding is consistent with the predictions of Bustos et al. (2016) that labor-saving technological change in agriculture spurs the reallocation of workers toward the non-agricultural sector. Our results also shed new light on the link between structural transformation and urbanization (Michaels et al., 2012).

[14] See overviews in Black and Devereux (2011) and Björklund and Salvanes (2011).

economic recovery of descendants of slaveholders after the US Civil War (Ager et al., 2021). Others have documented breaks in inter-generational links as a result of economic shocks (Feigenbaum, 2015), policy reforms, the entry of new industries that demand new skills (Bütikofer et al., 2018), and changes in nepotism (De la Croix and Goñi, 2021). We show that technological change can also break inter-generational links: the adoption of milking machines pushed young women to move to cities and to invest in their human capital. This process improved not only their economic opportunities but also that of their children (compared to the children of mothers who stayed behind in rural areas).[15] Consistent with these results, descriptive studies on the same cohorts that we analyze find increased inter-generational mobility in both Norway and Sweden (e.g., Björklund et al., 2009; Pekkarinen et al., 2017).

2 Historical background

This section provides a brief overview of Norway's modernization process since the early 19th century, followed by a detailed discussion of the diffusion of milking machines after WWII.

2.1 Structural transformation in Norway

Norway's modernization process began in the 1820s, more than a century before our period of study (1930-1970).[16] By 1820, 90 percent of the population lived in rural areas and worked in agriculture. Over the next 100 years, the urban share had increased up to 30 percent, concentrating economic activity in cities (Statistics Norway, Various Years, 1980, Table 5).[17] This urbanization process was the result of two forces: first, the large-scale emigration from rural areas to North America, which peaked in the late 19th century but had mostly subsided by 1920 (e.g., Semmingsen, 1960; Gjerde, 1989), and second, the expansion of the manufacturing sector, which attracted people to urban areas. Industrialization accelerated with the adoption of hydroelectric power in the 1890s (Venneslan, 2009; Leknes and Modalsli, 2020). By the outbreak of WWI, Norway was among Europe's the 10 leading economies in per-capita manufacturing output (Cameron, 1985), and in 1920 almost every fourth employed person worked in manufacturing.

[15] Our finding is in line with recent evidence that children of households who moved to areas of increased opportunity benefited in the long term (Chetty et al., 2016; Chyn, 2018).

[16] Compared to other Scandinavian countries, Norway's economic performance was between those of Sweden and Denmark, from 1800 to the start of WWII (Grytten, 2020, 2022).

[17] Despite this urbanization process, by 1900, Norway (along with Sweden and Finland) was still a rural society compared to the UK and other industrial countries in Western Europe (Bairoch and Goertz, 1986).

That said, at the beginning of our study period, the agricultural sector was still predominant: about 40 percent of the population was engaged in the primary sector during the 1920s. Most of the rural population owned small farms or were hired as part-time farm workers. Overall, the interwar years were a period of macroeconomic instability in Norway and, as a result, urbanization and industrialization stagnated. Nonetheless, the primary sector weathered the interwar turmoil and remained the largest employer, with relatively stable employment during the 1920s and 1930s (Grytten, 1995, 2022; Statistics Norway, Various Years).[18]

Agricultural employment decreased substantially between WWII and 1970, when Norway experienced a Golden Era of unprecedented economic growth.[19] This period saw an acceleration in the mechanization of agriculture similar to that in other parts of Scandinavia, Western Europe, and the United States. Concomitantly, primary-sector employment declined by 60 percent, from 900,000 workers in 1950 to 365,000 in 1970 (Statistics Norway, Various Years, 1980, Table 17).[20] The manufacturing sector absorbed part of the newly-available labor, while the remainder found employment in the service sector. At the same time, the urbanization process saw a revival, while rural areas faced substantial population losses from the 1950s onward (Hansen, 1989). Internal (rural-to-urban) migration fueled the urbanization process after WWII: immigration to Norway from other countries remained negligible throughout our sample period. By 1970, approximately two-thirds of Norway's population lived in urban areas.[21]

[18] As a small open economy, Norway suffered from the international post-WWI recession (Galenson and Zellner, 1957; Grytten, 1995, 2022), the contraction of its major trading partners (Sweden and the UK), and from a devastating deflationary monetary policy. In 1921, GDP per capita dropped by 11 percentage points, a fall only exceeded by the UK (Grytten, 2020). Grytten's revised series show that GDP per capita grew by 1.1 percent in 1920-1940, which is less than Sweden (2.4) and Denmark (1.2). Except in primary industry, unemployment was high in the 1920s and most of the 1930s (Broadberry, 1984; Grytten, 2020).

[19] After WWII, Norway joined Bretton Woods, the General Agreement on Tariffs and Trade (GATT), the IMF, the World Bank, NATO, and the United Nations. The annual compound growth rate was approximately 4 percent (Grytten, 2020, Table 1). Norway's economic success has been partly attributed to the "Nordic model," which involves a strong public sector role via market intervention, regulation, and central government planning (Lie, 1995; Acemoglu et al., 2021; Grytten, 2020).

[20] The mechanization process was the result of rising labor costs and the removal of trade barriers. In particular, tractors made agricultural production more capital-intensive (see Appendix Figure 1).

[21] After our study period, Norway experienced a massive oil and gas boom. From the 1970s, Norway's economy outperformed its Scandinavian neighbors and major trading partners, becoming one of the world's wealthiest countries (Grytten, 2020, 2022; Bennett et al., 2022).

2.2 Traditional farming and milking machines, 1930-1970

The widespread adoption of milking machines after WWII constituted one of the most profound technological changes on dairy farms. To better understand the gender-specific effects of this technological shock, this section first describes traditional farming in Norway, in which most tasks were divided along gender lines. We then portray the adoption of milking machines from a historical perspective, as well as the types of farms that could afford them. Finally, we document the different employment opportunities for both male and female displaced workers, which determined who took up employment in rural areas and who moved to cities to work in the expanding service and industry sectors.

The cornerstones of traditional farming in Norway were family farms and milk production. Family farms were, and still are, the most common type of farm.[22] Typically, parents, their children, and extended family members worked on the farm, together with seasonal and permanently hired workers. In the early 20th century, dairying was the largest activity in Norway's agricultural sector. Dairies consisted mainly of local co-ops of farmers who produced milk and processed it into cheese and butter (Furre, 2000; Espeli et al., 2006).[23] The most important farm products were milk, products derived from milk (i.e., butter and cheese), and meat associated with milk production (i.e., beef) (Espeli et al., 2006). Grain production was less important due to the soil quality, a short growing season, and low temperatures. In contrast, weather and geographical conditions were well suited for the production of grass and hay for fodder.

Importantly, farm tasks were mainly divided along gender lines. Women predominantly performed indoor tasks—such as housework, child rearing, and looking after the chickens, pigsty, and cowshed—while men worked outdoors—such as cultivating the fields. This traditional division of farm tasks is well documented in Norway and the other Nordic countries (e.g., Almås et al., 1983; Almås and Haugen, 1991; Sommestad, 1994; Osterud, 2014; Kaarlenkaski, 2018). On dairy farms, the main task for women was milking cows. This division of labor was deeply rooted in farming communities: "Dairying was defined as women's work, to the point that the very idea of men performing it was regarded as laughable, or even heretical" (Osterud, 2014, p.667). Besides milking cows and other indoor work, women also worked on the fields alongside men during haymaking and other seasonal harvesting activities. Traditionally, men cut "the hay or grain while the women gathered it together on racks

[22] Family farms were the most common method of organizing food production in Europe and the United States. In fact, today three-quarters of farms in the European Union and the United States are family farms (Graeub et al., 2016; Calus and Huylenbroeck, 2010; Almås, 2020).

[23] Dairies were influential in adopting and developing milk production at the farm level.

or in sheaves" (Osterud, 2014, p.667). Finally, men typically complemented their farming employment with other seasonal work in the rural sector; for example, in fisheries, timber industries, or in the construction sector (Hodne and Grytten, 2000; Almås, 2020).

Milking cows remained women's main chore on farms until the adoption of milking machines.[24] The first milking machines were patented in the United States in the late 19th century (Erf, 1906; Bateman, 1969), yet widespread adoption across Europe and the United States only took place after WWII (e.g., Bateman, 1969; Bieleman, 2005; Settele, 2018).[25] Norway was no exception to this pattern, as Figure 1 illustrates. Although there was a slow uptake in the 1930s, the adoption of milking machines on Norwegian farms only widely took place after WWII. The most important factor behind this take-off is that in 1951, Norway lifted all import restrictions on agricultural equipment (Espeli, 1990).

The adoption of milking machines had a profound impact on dairy farming (Bieleman, 2005). Compared to hand milking, a milking machine could milk a substantially larger number of cows. For example, in 1964, a single person in a milking parlor with eight workstations could milk 30 cows per hour with a milking machine. Without such a machine, one person could hand-milk only seven or eight cows per hour, with decreasing productivity as fatigue accumulated (Settele, 2018). With the adoption of milking machines, milk yield per cow increased in Norway from around 2,000 kilograms in 1950 to more than 4,000 kilograms in 1969 (see Appendix Figure 2). A similar pattern is also observed in other Scandinavian countries and the Netherlands (Bieleman, 2005). Throughout the second half of the 20th century, the dairy industry adopted complementary innovations together with the milking machines. Innovations in breeding technology, milking systems, feeding, and herd management also allowed farms to reduce the pressure from increasingly costly labor (Bieleman, 2005; Gallardo and Sauer, 2018). Altogether, these changes transformed the dairy industry in Norway, as well as in other Western countries (Espeli et al., 2006).

In contrast to other farm equipment and machinery, milking machines were profitable for small farms as soon as the 1950s. As Settele emphasizes (2018, p.855):

[24] During Norway's economic boom in the early 1900s, farmers adopted labor-saving technologies related to the use of horses, such as plows and harvesters, to replace the increasingly costly farmhands. At the same time, professional dairies gradually took over the processing of milk, cheese, and butter in other Western countries; for example, Denmark, Ireland, and the United States (Sommestad, 1994). These two factors reduced the role of women in dairying. That said, however, milking remained the most important source of female employment on farms in Norway until the 1950s (Almås et al., 1983).

[25] In 1910, only 10,000 milking machines were in use in the United States. The reasons for this delayed adoption are manifold. Bateman (1969, p.211), for example, describes how early 20th century farmers hesitated to adopt milking machines because the models were fire hazards and often irritated or injured cows. Whetham (1970) describes similar issues in the United Kingdom before WWII.

> The general consensus of the early 1950s held that the use of a machine reaped benefits when used with four or more cows. It should be noted that the call from the outset to use milking machines not only on large-scale but also small-scale farms, represented an important exception in the patterns of the history of mechanization.

Milking machines were affordable for small farms because they were used indoors in cowsheds, without requiring expansion or further investment, and because the machines themselves were relatively inexpensive. For a farmer in 1950, the price of a milking machine was about the same as half a year's wages for a male servant. In contrast, it was five times more costly to buy a tractor.[26]

Who was displaced by the adoption of milking machines? The traditional division of labor on dairy farms as explained above indicates that milking machines automated the tasks typically performed by women. Specifically, young women aged around 16-25 commonly worked as milkmaids on farms before getting married (see, e.g., Almås (2002) and Historical Statistics from Statistics Norway 1968, Diagram 17). After the widespread adoption of milking machines, the demand for these milking services disappeared. Hence, when dairy farms shifted to milking cows mechanically, this process almost exclusively displaced female workers, in particular milkmaids and servants (Almås et al., 1983; Thorsen, 1986; Brandth, 2002). Almås et al. (1983) describe the adoption of milking machines as "the masculinization of Norwegian agriculture." Hiring female labor for milking cows was no longer needed, and men now took over the milking process using the new technology.[27] In contrast, the adoption of general-purpose technologies in agriculture—most importantly, tractors—replaced the use of draft animals (mostly horses) for the cultivation of fields and automated activities, such as haymaking and other seasonal harvesting tasks. Since haymaking and seasonal harvesting were tasks performed by both men and women, the introduction of general-purpose technologies such as tractors replaced both male and female labor. Importantly, in Section 6.4, we show that the diffusion of tractors in Norway, which took place around the same time as milking machines, does not confound our results.

Following the general mechanization of family farms, displaced workers could find alternative employment in either rural areas or in the expanding industrial and service sectors in

[26] According to Almås (personal communication) the price of a milking machine was NOK 2,000 in 1950, while a standard tractor produced in the United States cost NOK 10,000. To put this in perspective, the price of a milking machine corresponded to a male servant's half-year wage with board—NOK 1,840 in 1952/53 (Statistical Yearbook 1955, Table 250)—and roughly to a female servant's yearly wage.

[27] This process not only affected seasonal servants and milkmaids, but also farmers' wives and daughters, as a large part of the farm work was now taken over by men.

urban areas. The opportunities to remain in rural areas, however, differed according to gender. Men had a comparative advantage for the existing rural jobs. Specifically, a large share of jobs in rural areas consisted of seasonal work on farms, in construction, and in fisheries, which were usually carried out by male crofters.[28] While the mechanization of farms reduced men's opportunities to take on seasonal work on farms, they were still in high demand for these other seasonal jobs in construction or fisheries, especially during the post-WWII boom years. These alternative rural jobs offered high returns to the skills men had already acquired as part-time farm workers. For women, the situation differed as they did not have access to these existing jobs in rural areas. As a consequence, women displaced from farms left the countryside during the late 1940s, 1950s, and 1960s in the hope of finding new jobs in the cities (Almås et al., 1983; Almås and Haugen, 1991). Notably, young hired female workers, typically around ages 16-25, were the first to be displaced. They were followed by the female family members of farm owners—mostly unmarried sisters, aunts, and cousins—and, lastly, the farmers' wives, who all reduced their labor supply on farms (see Almås (2002) and Appendix Figure 3). Facilitated by the expansion of the local welfare services in the 1970s, many women found new jobs outside of agriculture; for example in social services, teaching, child care, or clerical work (Almås, 1983; Brandth, 2002).

Overall, the historical narrative suggests that the rapid mechanization of agriculture after WWII pushed labor off the farms, and that women were generally more affected by the modernization process. Affected men continued to have employment opportunities in rural areas (e.g., in fisheries or construction), while displaced women had a comparative advantage in employment available in the expanding manufacturing and service sectors in urban areas. Hence, we expect different long-term effects from the adoption of milking machines for women and men in relation to the decision to migrate to cities, future income, employment, and corresponding human capital investments. The next section formalizes these predictions.

[28] Crofters comprised a large share of the rural population. They typically rented small landholdings that were not large enough to feed their families. Hence, crofters took up seasonal work on other farms, in construction, or in fisheries to complement their income.

3 Model of labor-saving technological change and rural-urban mobility

We build a simple model that captures gender differences in (a) the division of tasks in agriculture, (b) the displacement effect of automation, and (c) the rural-to-urban mobility patterns that followed the adoption of labor-saving technologies. To do so, we combine the key ideas of comparative advantage (Roy, 1951) to explain rural-to-urban migration, with a task-based production function that allows for the gender division of labor and labor-saving technological change (Zeira, 1998; Autor et al., 2003; Acemoglu and Autor, 2011). The model helps to identify the compliers of our quasi-experiment of gender-biased technology adoption and formulates the hypotheses that we bring to the data.

Consider an economy with a large number of municipalities divided into two areas: rural and urban. Municipalities in rural areas are mostly specialized in the primary sector (R) while urban areas are specialized in the manufacturing and services sectors (U). Men and women inelastically supply one unit of labor. Each individual i is endowed with two skills, $\alpha_R(i)$ and $\alpha_U(i)$. These skills represent efficiency units for labor in the rural and urban sector, respectively. In our setting, $\alpha_R(i)$ are skills suited for occupations in rural areas that often require less general human capital. Conversely, $\alpha_U(i)$ represents skills demanding more general human capital for occupations in the cities. The skill pair $(\alpha_R(i), \alpha_U(i))$ is equally distributed by gender. We define an individual i's comparative advantage in the urban sector as $\alpha_U(i)/\alpha_R(i)$. Individuals maximize their consumption. To do so, they face the choice of supplying their labor to either the urban or rural sector. To gain insights for our empirical analysis, we focus on the decisions of individuals in rural areas, for whom supplying labor to the urban sector requires moving to a city. This entails moving costs c, which we assume to be a fraction of their earnings. This could be thought of as the economic cost of moving to a new locality, the foregone social ties and rural insurance networks (Munshi and Rosenzweig, 2016), but also as the educational investments necessary to secure employment in, for example, the city's service sector. In a similar setting, Nakamura et al. (2021) show that such moving costs can have large effects on lifetime earnings by generating barriers that impede individuals from moving to the locations where they would earn the highest returns.[29]

[29] Although we do not directly observe this moving cost, our empirical analysis provides important insights on it. First, by showing that migration patterns did not differ across more and less dairy-intensive municipalities before the introduction of milking machines, we can rule out substantial differences in moving costs across municipalities, and that moving costs were already declining in the pre-milking machines era. Second,

The rural sector produces one final good Y_R by combining two tasks, y_1 and y_2. For simplicity, we assume a constant returns to scale Cobb-Douglas technology:

$$Y_R = y_1^{1-\beta}\ y_2^{\beta}\ . \tag{1}$$

Two factors of production are used in the rural sector: labor L_R and capital M. To capture the gender division of labor in traditional agriculture, we assume that task y_1 uses female labor, and task y_2 uses male labor. In our setting, task y_1 can be interpreted as indoor activities, such as milking cows, working in the cowshed, looking after the chickens, or housework—activities traditionally performed by women. Conversely, task y_2 consists of outdoor work in agriculture (e.g., work on the fields using horses), but also seasonal work outside of agriculture (e.g., in construction, fisheries)—activities traditionally performed by men.[30] To capture the displacement effects caused by the mechanization of agriculture, we assume that capital M and female labor are perfect substitutes. In our setting, we can interpret M as milking machines, which automates the tasks of milkmaids. Formally, the production function of each task is:

$$y_1 = A_R L_R^f + M \quad \text{and} \quad y_2 = A_R L_R^m\ , \tag{2}$$

where

$$L_R^f = \int_{i \in \mathcal{F}_\mathcal{R}} \alpha_R(i) di \quad \text{and} \quad L_R^m = \int_{i \in \mathcal{M}_\mathcal{R}} \alpha_R(i) di$$

are, respectively, female and male labor in rural areas, and $\mathcal{F}_\mathcal{R}$ and $\mathcal{M}_\mathcal{R}$ denote the set of female and male workers employed in the rural sector.

This task-based production function encompasses two types of technological change. First, A_R represents the canonical labor-augmenting technological change. Second, we allow for labor-saving technological change. Specifically, the machines used in the first task, M, are supplied perfectly elastically at market price $\mu > 1$, which falls exogenously due to technological advances. Hence, the declining price of the machines is the labor-saving technological change in our model.

The urban sector produces one final good Y_U using labor L_U as the only factor of pro-

by using municipality fixed-effects, we control for *municipality-specific* moving costs that may have affected women's decisions to migrate to the cities and their long-run income gains that are driven exclusively by *municipality-specific* moving costs.

[30] The division of farming tasks along gender lines is well-documented in the historical literature (Section 2). Although tracing the origins of this division is beyond the scope of this article, we note that it is consistent with men having a comparative advantage on physically-intensive outdoor work in agriculture, and women on less brawn-intensive indoor work; for example, hand milking (Galor and Weil, 1996).

duction, irrespective of gender. Formally, the production function is:

$$Y_U = A_U L_U \ , \text{ where } \ L_U = \int_{i \in \mathcal{S}_\mathcal{U}} \alpha_U(i) di \tag{3}$$

and $\mathcal{S}_\mathcal{U}$ denotes the set of female and male workers employed in the urban sector.

Labor markets are perfectly competitive and the economy is small, so the prices of the rural (P_R) and urban (P_U) goods are taken as given. This implies that the wage per efficiency unit of labor in the urban sector is given by:

$$W_U = A_U \ P_U \ . \tag{4}$$

Three main conditions govern the remainder of the equilibrium. The first condition is the perfect substitutability of female labor and machines in the rural sector. This implies that the wage per efficiency unit of female labor in the rural sector is pinned down by both the labor-augmenting technological change, A_R, and by the labor-saving technological change, which is captured by the price of machines μ:

$$W_R^f = A_R \ \mu \tag{5}$$

The second condition is the production technology in the rural sector. The Cobb-Douglas form implies that the machines used in task y_1 and the male labor used in task y_2 are relative complements (specifically, they are q-complements). Hence, the wage per efficiency unit of male labor in the rural sector is negatively associated with the price of machines:

$$W_R^m = A_R \ P_R^{\frac{1}{\beta}} \ \beta \left(\frac{1-\beta}{\mu} \right)^{\frac{1-\beta}{\beta}} \ . \tag{6}$$

The third condition is worker self-selection among rural and urban areas. The labor earnings for worker i are $W_R^f \cdot \alpha_R(i)$ for women in the rural sector, $W_R^m \cdot \alpha_R(i)$ for men in the rural sector, and $W_U \cdot \alpha_U(i)$ for women and men in the urban sector. Taking into account the cost of moving from rural to urban areas, this implies that the marginal female worker, $\imath^*$, is indifferent between remaining in a rural area and moving to an urban area if $W_R^f \cdot \alpha_R(\imath^*) \ = \ (1-c) \cdot W_U \cdot \alpha_U(\imath^*)$ and the marginal male worker $\jmath^*$ is indifferent if $W_R^m \cdot \alpha_R(\jmath^*) \ = \ (1-c) \cdot W_U \cdot \alpha_U(\jmath^*)$. It is useful to re-define these indifference conditions as a function of the relative earnings in

the urban vs. rural sector. Let

$$\eta_i^f := \frac{W_U}{W_R^f} \cdot \frac{\alpha_U(i)}{\alpha_R(i)} \quad \text{and} \quad \eta_i^m := \frac{W_U}{W_R^m} \cdot \frac{\alpha_U(i)}{\alpha_R(i)}$$

be the relative earnings of female and male workers, respectively. The indifference condition is then $\eta_{\imath^*}^f = \eta_{\jmath^*}^m = \frac{1}{1-c}$. Note that this differs from the optimal allocation of workers, which is achieved when the marginal female worker is $\tilde{\imath}$ and the marginal male worker is $\tilde{\jmath}$ with $\eta_{\tilde{\imath}}^f = \eta_{\tilde{\jmath}}^m = 1$.

The model's equilibrium is illustrated in Figure 2, Panel A. Female workers with a higher comparative advantage in the urban sector have higher relative earnings in that sector.[31] All women with a comparative advantage above $\tilde{\imath}$ would earn a higher salary in the urban sector. However, the moving cost implies that all women with a comparative advantage below $\imath^*$ will remain and be employed in the rural sector, and that only women with a comparative advantage above $\imath^*$ will relocate to the cities and be employed in the urban sector. Hence, all women between $\tilde{\imath}$ and $\imath^*$ will be "misallocated" and their earnings would increase if they moved to a city. An analogous argument applies for men.

Let us now consider the situation at the time of the mechanization of agriculture and derive predictions for our empirical exercise. As explained above, the adoption of milking machines automated tasks typically performed by women in rural areas. In our model, this labor-saving technological change is captured by a decline in the price of the machines, M, from μ to μ'. This quasi-experiment is illustrated in Figure 2, Panels B and C.

The first prediction is that the adoption of milking machines will displace women from agricultural jobs in the rural sector and push them out of the countryside to find employment in the urban sector. It is immediately clear from equation (5) that a decline in the price of machines reduces the female wage in rural areas, $\partial W_R^f/\partial\mu = A_R > 0$, and hence, increases their relative earnings in the urban sector, $\partial\eta^f/\partial\mu = -(A_U P_U/A_R\mu^2) \cdot (\alpha_U(i)/\alpha_R(i)) < 0$. Visually, this is illustrated by the relative earnings curve shifting up (red line). Since female and male workers are bound to a task in the rural sector, this does not generate any re-sorting of female workers across tasks in the rural sector. Instead, the Roy framework with respect to rural and urban skills, implies that female workers' decisions to migrate to urban areas will respond elastically to relative wage levels in the rural and urban sectors. Specifically, all women with a comparative advantage between $\imath^{*\prime}$ and $\imath^*$ will be displaced by milking

[31] For simplicity, the figure η_i^f takes a linear form by assuming that $\alpha_U(i)$ and $\alpha_R(i)$ are uniformly distributed, but that different skill distributions can lead to different shapes. The only necessary assumption is that η_i^f is upward-sloping, i.e., that $\frac{\alpha_U(i)}{\alpha_R(i)}$ reflects a comparative advantage in the urban sector.

machines from agricultural jobs in the rural sector and migrate to find employment in the urban sector.

The model also allows us to identify the compliers of our natural experiment of gender-biased technological change. Based on the terminology of Angrist (2004), female workers to the left of $\imath^{*\prime}$ in Figure 2, Panel B are "never-takers." They have such a strong comparative advantage in the rural sector that they will not migrate to urban areas, even after the adoption of milking machines. Female workers between $\imath^{*\prime}$ and $\imath^{*}$ are "compliers." They will migrate to urban areas if and only if their municipality adopts milking machines. Finally, female workers to the right of $\imath^{*}$ are "always-takers". They have such a strong comparative advantage in the urban sector that they will move, even if their municipality does not adopt milking machines.

The second prediction of the model is that, on average, displaced women will experience long-run income gains. This prediction emanates from the fact that the first women displaced by milking machines are those with the highest comparative advantage in the urban sector. These women are misallocated workers, in the sense that their earnings would be higher in the urban sector to begin with, but they remain in rural areas only due to the moving cost. In Figure 2, this is illustrated by the fact that the displaced women (between $\imath^{*\prime}$ and $\imath^{*}$) are in the region of misallocated workers (between $\tilde{\imath}$ and $\imath^{*}$). A depression in female rural wages, such as the one induced by the automation of milking tasks, can break up this allocative inefficiency and induce long-run income gains to the displaced female workers who relocate to cities. This result hinges on the assumption that the cost of moving is large enough such that a substantial share of the compliers are misallocated in rural areas prior to the technology shock. Recent evidence supports this assumption, showing that barriers to migration and moving costs are substantial in rural settings similar to our case study Nakamura et al. (2021), and that social ties and rural insurance networks can result in a large misallocation of workers in rural areas (Munshi and Rosenzweig, 2016). In addition, young women historically faced additional social costs of moving out of rural areas, such as losing access to extended family networks. Under these additional constraints, female emigration only occurred under a large urban-rural wage premium—such as that generated by the adoption of milking machines.

The third prediction of the model is that rural municipalities with farming conditions better suited for dairy production will adopt milking machines to a greater extent, and hence, will experience more drastic displacement effects. To see this, we interpret this economy as a collection of rural municipalities $j \in J$. Each municipality operates with

the production functions in equations (1) and (2), but municipalities are heterogeneous with respect to $\beta(j)$, the factor share of different farming tasks. A small $\beta(j)$ represents a task-y_1-intensive municipality—in our setting, municipalities better suited for dairy production. Note that although all municipalities face the same price of milking machines, μ, the degree to which municipalities adopt this technology, as the price declines, depends on $\beta(j)$. To see this, it is useful to define the input demand in rural municipalities as $\theta(j) = (A_R L_R^f(j) + M(j))/(A_R L_R^m(j))$. In other words, $\theta(j)$ captures how much a rural municipality j demands milking machines and/or female labor (i.e., task-y_1 input) relative to male labor (i.e., task-y_2 input). Assuming that each municipality satisfies productive efficiency,

$$\partial Y_R(j)/\partial L_R^f(j) = W_R^f(j),\ \partial Y_R(j)/\partial M(j) = \mu, \text{ and } \partial Y_R(j)/\partial L_R^m(j) = W_R^m(j),$$

implies that the the input demand in rural municipalities is $\theta(j) = [P_R(1-\beta(j))/\mu]^{\frac{1}{\beta(j)}}$. The partial derivative of $ln\theta(j)$ with respect to μ and $\beta(j)$ is:

$$\frac{\partial ln\theta(j)}{\partial \mu} = \frac{-1}{\mu\beta(j)} < 0 \ \text{ and } \ \frac{\partial^2 ln\ \theta(j)}{\partial\mu\partial\beta(j)} = \frac{1}{\mu\beta(j)^2} > 0\ . \tag{7}$$

Equation (7) shows that as the price of milking machines declines, the demand for milking machines and/or female labor (i.e., for task-y_1 input) increases. As shown above, this increased input demand will be met entirely by an influx of milking machines, as female wages in the rural sector will fall and marginal female workers will reallocate their labor input to the urban sector. In addition, the cross-partial derivative shows that the aforementioned influx of milking machines, and hence, the first-order displacement effect of milking machines on female labor, will be relatively larger in municipalities with a large $1 - \beta(j)$ (i.e., those more suited for dairy production). In our empirical analysis, we confirm this prediction by showing that rural municipalities that were historically (i.e., in the pre-milking machine era) more suited for dairy production adopted milking machines to a greater extent (see, e.g., Figure 4). We also adopt this theoretical insight into our intensity of treatment framework. We capture municipality-level heterogeneity in $1 - \beta(j)$ prior to the diffusion of milking machines using two measures: first, the number of dairy cows per farm in 1929 for our main specification; and second, women's employment shares in activities related to milking in 1930 for the robustness analysis.[32]

[32] In our model, the factor shares for female labor, milking machines, and male labor in rural areas are, respectively, $(1-\beta)\frac{AL^f}{AL^f+M}$, $(1-\beta)\frac{M}{AL^f+M}$, and β. In the pre-milking machines era, i.e., with $M = 0$, the factor share for female labor in rural municipalities is equal to $1-\beta$. In other words, there is a one-to-one

Finally, the fourth prediction of the model concerns male labor. As explained above, the Cobb-Douglas production function in equation (1) implies that the machines used in task y_1 and male labor used in task y_2 are q-complements. In other words, the adoption of milking machines after a fall in their price from μ to μ' will increase the wage per efficiency unit of male labor in the rural sector. Formally, from equation (6), we see that $\partial W_R^m/\partial\mu = -P_R\ A_R\ [(1-\beta)/\mu]^{\frac{1}{\beta}}$. This is consistent with the historical evidence in Section 2 that the rapid mechanization of farming led to the masculinization of agriculture in Norway. It is also consistent with the historical observation that men found more employment opportunities in rural areas outside of agriculture (in construction, fisheries, etc.). That said, the effect on men is expected to be smaller in magnitude than the effect on women, since $\partial W_R^f/\partial\mu$ is larger in magnitude than $\partial W_R^m/\partial\mu$, as long as $\mu > P_R(1-\beta)$,[33] This implies that labor-saving technological change has a larger impact on women's earnings than on men's.

This different effect for men is illustrated in Figure 2, Panel C. Note that the effect of the decline in the price of milking machines on men's relative earnings η_i^m is smaller in magnitude than the effect on women's relative earnings η_i^f and goes in the opposite direction. Hence, this labor-saving technological change in relation to men triggers neither a displacement effect nor migration to urban areas, and as a result, the potential long-run income gains from moving to a city are not realized. Visually, men with a comparative advantage between $\tilde{\jmath}$ and $\jmath^*$ (those whose potential wage in urban areas is higher than their wage in rural areas) remain where they are.

In the remaining part of the paper, we bring these predictions to the data and evaluate how women who were born in rural areas when Norwegian farms introduced milking machines performed later in life.

4 Data

Our empirical analysis draws on individual-level administrative data and municipality-level data on the adoption of milking machines over time. The primary source is Norwegian Registry Data maintained by Statistics Norway, which consists of a linked individual-level administrative dataset that covers the complete Norwegian population from 1960 up to 2019. These data cover different administrative registers, such as the central population register,

correspondence between our model's β and the pre-milking machine women's employment shares used for the robustness analysis.

[33] This condition is satisfied by construction when milking machines are first introduced. The pre-adoption price of new technologies, here μ_0, is typically modeled as a price that tends to infinity, hence satisfying $\mu_0 > P_R(1-\beta)$.

the full count population censuses of 1960, 1970, and 1980, the education register, and the tax and earnings register. These registers provide information on place of birth and residence, occupation, earnings, educational attainment, and personal identifiers that make it possible to follow men and women over time and to establish parent-child links. The other source is municipality-level data on the adoption of milking machines from the census statistics on Norwegian farms in 1930, 1946, 1950, 1960, and 1970. These agricultural censuses report farm equipment (e.g., milking machines and tractors), the number of farms and dairy cows, as well as other measures of agricultural intensity for each municipality. In our analysis, we focus on adult outcomes of women from rural areas who, at ages 16-25, would have traditionally been hired by farms to perform hand milking (see Section 2). Our main sample includes circa 380,000 women born in rural municipalities with at least one farm in 1929, who were aged 16-25 in 1930, 1940, 1950, 1960, or 1970 (agricultural census years).[34] In extended specifications, we also consider the corresponding cohorts of men and the children of the women in our main sample. We refer readers to Appendix Table 1 for detailed summary statistics.

4.1 Registry data

Our individual-level data draw on the administrative registries provided by Statistics Norway. For our analysis, we use the linked central population register, the full count population censuses, the education register, and the tax and earnings register. The central population register covers the full Norwegian population from 1960 to 2019. An updated part of the population file contains the municipality of birth.[35] We use the municipality of birth to build our sample of young women born in rural municipalities and to measure women's exposure to the adoption of milking machines at the age of 16-25 when they would have traditionally been hired by farms to perform hand milking.[36] The central population registry includes personal identifiers, which we use to follow women over time and to establish links to their children. Importantly, these unique identifiers allow us to link all women, notwithstanding changes in their last name after marriage. This adds to the credibility of our data over other historical studies using automated linking methods to create historical panel data without unique identifiers. In addition, the unique personal identifier enables matching to registers

[34]Specifically, we consider women turning 16 to 25 in each agricultural census year, who might have been 15 at the start of the year. For the 1946 agricultural census, we consider women aged 16-25 in 1940 instead of in 1946 in order to avoid overlapping cohorts in 1946 and 1950.

[35]Municipality borders have changed over time, however, we use the 1980 borders throughout our analysis.

[36]In other words, we use the municipality of birth as a proxy for the municipality of residence at age 16-25. This assignment also avoids capturing the effect of endogenous migration decisions.

on tax and earnings, education, and full count censuses.

We supplement this data with full count population censuses from 1960, 1970, and 1980. The censuses are used to identify each individual's occupation and to evaluate the displacement effect of milking machines out of agriculture for young women later in life. To do this, we classify occupations into farming and non-farming activities and evaluate how the diffusion of milking machines when a woman was aged 16-25 affected her occupation after age 25, as reported in the subsequent census.[37] The occupations registered in the censuses are self-reported and cover almost the entire population. On average, 9 percent of the women in our sample worked in agriculture after the age of 25. We also use the decennial occupation data to examine effects on the occupations' skill content. More specifically, we use the classification of occupations matched with skill content from O*Net to group occupations outside agriculture into high-, medium-, and low-skilled jobs (Autor, 2019). Around 12 and 18 percent of the women in our sample who were not employed in farming performed high- and medium-skill jobs after the age of 25. The full count population censuses also report the municipality of residence of each individual. This, together with the municipality of birth, allows us to examine rural-to-urban migration patterns. We evaluate the extent to which the diffusion of milking machines when a woman was aged 16-25 affected her decision to migrate to an urban area. We also use this information to construct measures of rural-to-rural migration and migration outside and within an individual's county of birth. Forty-percent of the women in our sample emigrated from their rural municipality of birth into an urban area and out-of-county.

Finally, we link this data to information on individual earnings and educational attainment. Earnings are measured from the tax registry maintained by Statistics Norway, which has been available since 1967. We use gross earnings to evaluate both the short- and long-term effects of the adoption of milking machines on women's income. For short-term effects, we follow the year-by-year income trajectory of women turning 16 in 1970—the first cohort in our sample for which yearly income data is available from the start of their working life. For long-term effects, we consider our main sample, measure their income later in life, and construct income percentile ranks based on all individuals (i.e., men and women) born in the same year. Specifically, we construct income percentile ranks based on gross earnings at the age of 45. Because the tax registry only starts in 1967, we use gross earnings at age 52

[37]Specifically, for women aged 16-25 in 1930, 1940, and 1950, we look at their occupation in the 1960 Census; for women aged 16-25 in 1960, we look at their occupation in the 1970 Census; and for women aged 16-25 in 1970, we look at their occupation in the 1980 Census. When a woman's occupation is missing in a given census, we look at their reported occupation in a later census.

for women aged 16-25 in 1940 and pre-tax earnings at age 62 for women aged 16-25 in 1930. Appendix Figure 4 shows that there is a high correlation between income percentile ranks at ages 45, 52, and 62. In addition, several studies show that income rank is less sensitive to the age at which income is measured than the income in levels (Nybom and Stuhler, 2017; Chetty and Hendren, 2018). The average adult earnings are approximately 65,000 Norwegian kroner (NOK) for women in our sample. Educational attainment is measured using the educational database provided by Statistics Norway. This data is based on educational attainment reports submitted directly by the educational institutions to Statistics Norway every year since 1970. This minimizes any measurement error from misreporting. From these data, we construct three measures of educational attainment: whether individuals attained upper-secondary education or higher; post-secondary education or higher; or undergraduate education or higher. On average, 10 percent of the women in our sample attained undergraduate education or higher, although this percentage has increased substantially over time (see Appendix Figure 5).

To evaluate spillover effects on the next generation, we construct analogous income and educational measures for the children of the women in our main sample. These variables are described in detail in Section 6.6.

4.2 Agriculture censuses

We combine our individual-level data with aggregated municipality-level census statistics on Norwegian farms. These agricultural censuses were collected on a decennial basis, cover our entire study period from 1930 to 1970, and report detailed statistics on the number of farms, agricultural machinery, equipment, crops, and livestock in each municipality. For our analysis, we use the number of milking machines per farm in each municipality in each census year. Over our study period, an average rural municipality had seven milking machines per 100 farms, although as discussed above, there is a considerable heterogeneity across time and space (see Figure 1 and Appendix Figure 6). In addition, we use information on the number of dairy cows per farm in each municipality in 1929 to capture conditions favoring dairy farming prior to the introduction of milking machines. Figure 3 shows that there was substantial cross-sectional variation in the share of cows per farm before milking machines were introduced in Norway. In extended specifications, we also use municipality-level information on the number of tractors per farm in each census year and on the number of horses per farm in 1929 to capture pre-conditions favoring the adoption of this technology.

The agricultural censuses also report information that is useful to construct control vari-

ables that capture initial municipality-specific characteristics that could also have affected the diffusion of milking machines over time. Specifically, we construct two measures of agricultural intensity for 1929, the start of our study period: the share of improved farmland and the number of farms per capita in each municipality. In contrast, no information on agricultural output is reported. We also use the ratio of large to small farms in each census year to show that the farm size distribution remained relatively stable during our study period (see Appendix Figure 13) and that our results are not confounded by local changes in the farm-size distribution.

5 Empirical strategy

The aim of this study is to estimate the causal effect of the adoption of milking machines on various outcomes of interest Y_{ijt}, including displacement from farming, moving out of rural areas, investing in education, occupation upgrading, as well as income and other adult labor market outcomes. Our baseline econometric model is outlined by the following equation:

$$Y_{ijc} = \alpha_j + \beta_c + \gamma(C_j^{1929} \times M_{jc}) + \epsilon_{ijc} \tag{8}$$

where Y_{ijc} denotes the outcome of interest for a woman i born in year c in municipality j. Our baseline estimating equation (8) includes fixed effects for municipalities, α_j, and birth cohort, β_c. The main variable of interest, $C_j^{1929} \times M_{jc}$, is the interaction between the number of milking machines per farm, M, in municipality j at the time when birth cohort c was aged 16-25—i.e., the age cohort that would have traditionally been employed in hand milking; and the number of (dairy) cows per farm, C, in municipality j in 1929.[38] This interaction is our measure of treatment intensity, and is based on the idea that the roll out of milking machines across municipalities affects young women differently, depending on the farming conditions prior to their adoption. To proxy for local conditions favoring dairy farming, we use the number of cows per farm in 1929, which captures cross-sectional differences in the intensity of (hired but also unpaid) female labor engaged in dairy farming. Since cows per farm in 1929 measures the intensity of dairy farming before the uptake of milking machines, it ensures that the interaction term is exogenous to outcome changes during periods of rapid technological change. Our results are robust to different forms of treatment intensity, such as replacing the number of milking machines per farm at the municipality level with the

[38] It is not necessary to add the number of cows per farm in municipality j in 1929 to equation (8), as the municipality fixed effects capture the direct effect.

nationwide numbers, or replacing the number of dairy cows per farm—our proxy for the intensity of dairy farming—with the pre-treatment municipality-level employment shares of women working in agriculture or of female agricultural servants.

As Figure 3 illustrates, there was substantial cross-sectional variation in the share of cows per farm before milking machines were introduced in Norway. Figure 4 shows that rural municipalities that specialized in dairy production in the pre-milking machines era had a higher uptake of milking machines per farm.[39] The estimated coefficients in Figure 4 are the result of regressing milking machines-per-farm on cows-per-farm in 1929 interacted by census year fixed effects (and controlling for municipality and census year fixed effects). Importantly, this regression can be interpreted as the first stage of our analysis showing the take-up of milking machines as a function of the treatment. The estimated coefficients reveal that farmers in more dairy-intensive municipalities made substantial investments in milking machines after WWII, which is consistent with the timing of the diffusion observed at the national level. Overall, this finding validates the model's third prediction and supports the notion that our estimation strategy captures the effect of the diffusion of milking machines on agricultural workers in dairy-intensive municipalities.

Under the hypothesis that the diffusion of milking machines was gender-biased and triggered a structural change, and that most of the (hired) women engaged in dairying and milk processing were young and unmarried, we would expect to find the largest effects on women aged 16-25. As explained in detail in Section 3, these young rural women contain the group of *compliers* that we can identify with our estimation strategy; that is, they would leave agriculture and move to cities if their home town was affected by the uptake of milking machines, but remain and continue to work on the farm otherwise. Hence, our main empirical analysis in the next section focuses on the adult outcomes of women who lived in *rural* municipalities at the age of 16-25 in 1930, 1950, 1950, 1960, and 1970, but we will also contrast the results with young rural men, who were less affected by the diffusion of milking machines.

The estimate of γ measures the impact of the introduction of milking machines under the standard parallel trend assumption that municipalities more (or less) affected by the adoption of milking machines would have evolved similarly without their adoption. As a first check, we present the baseline municipality characteristics at pre-treatment (1930) by treatment intensity (constructed as the average over the sample period) in Appendix Table 2. We focus on important characteristics, such as the share of women in agriculture, the share of women in other industries, the female labor force participation rate, net migration of women, farms

[39] We classify municipalities as rural if they report no urban population and at least one farm in the Census of Agriculture 1929.

per capita, the share of improved farmland, average farm size, and the share of females aged 15-19 and 20-39. We conduct a balancing test reporting the estimated coefficient of regressing the municipality characteristics in 1929/1930 (or the differences in the indicated municipality characteristics between 1919 and 1929) on treatment intensity in our sample period (average 1929-1969). Column (2) reports the results for the level differences. The average treatment intensity in the sample period was only correlated with a few pre-reform characteristics of municipalities. Municipality fixed effects capture the time-invariant differences between municipalities in our econometric model. However, it is possible, for instance, that in more affected municipalities, women's participation in agriculture could have evolved differently even had milking machines not been adopted. The results in column (3) looking at the pre-1930 *changes* mitigate this concern, since there are no significant differences by treatment status in the share of women in agriculture or other important municipality characteristics. On top of this, we present additional strategies to substantiate that our empirical analysis does not violate the parallel trends assumption.

First, we examine different specifications of flexible trends by sequentially adding a stricter set of controls to estimating equation (8), such as county-by-birth cohort fixed effects, and initial municipality-specific differences in agricultural intensity. We proxy a municipality's agricultural intensity by the share of improved farmland and farms per capita in 1929, interacted by birth cohort fixed effects. The inclusion of county-by-birth cohort fixed effects flexibly account for county-specific cohort trends. Our proxies for a municipality's initial farming intensity interacted with birth cohort fixed effects are intended to capture the possibility that cohorts in more agricultural municipalities were on a different trajectory of structural transformation. After adding these controls, our estimation strategy should effectively identify the local labor push effect as a result of the diffusion of milking machines. Second, we use digitized census records from 1900 and 1910 and undertake a placebo experiment for this period. The placebo experiment tests whether the parallel trends assumption is violated by evaluating whether young women in more dairy-intensive municipalities were already less likely to be engaged in agriculture before the uptake of milking machines, and whether they already moved out of their birthplace at a higher rate in the pre-milking machines era.[40] Third, we conduct a permutation exercise for our main results on women who were exposed to milking machines (and subsequently left agriculture and migrated to cities)

[40]Since we control for municipality fixed effects, our empirical analysis accounts for time-invariant *municipality-specific* moving costs. The placebo experiment further allows us to test whether outmigration rates were already different, for example, due to declining moving costs, in dairy-intensive municipalities before the roll-out of milking machines.

by reshuffling our treatment-intensity measure randomly throughout the rural municipalities within age cohorts. We discuss these robustness checks in more detail in Section 6.4.

Standard errors in estimating equation (8) are clustered at the municipality level to account for correlations within a municipality in a given year and over time, however, we also show that our results are robust when accounting for different degrees of spatial correlation using Conley standard errors (Conley, 1999) with different distance cutoffs. Throughout our analysis, we keep municipality borders constant based on the "kommuner" classification of 1980, since the boundaries of several municipalities were changed during our study period due to administrative reforms.

6 Empirical results

This section presents the results of our empirical analysis. We show that the adoption of milking machines in Norway substantially changed the career path of young rural women and their children. Section 6.1 examines the effects for young women in the *short run*. Our main results on how the adoption of milking machines affected young women *later in life* are outlined in Sections 6.2 and 6.3. We show that affected women were displaced from farming, moved to cities, invested more in their education, and ended up in higher-paid employment, and in more high-skill occupations later in life. Section 6.4 presents a series of robustness checks. Section 6.5 compares the effects on women and men of the same age and presents a "horse race" between the adoption of milking machines and tractors, thus accounting for the general mechanization of agriculture in Norway during our sample period. Finally, Section 6.6 assesses the spillover effects on the next generation.

6.1 Contemporaneous income effects

Our first goal is to evaluate whether the adoption of milking machines had any contemporaneous income effect on young women. It has been documented elsewhere that in the short run, labor automation brings economic hardship to displaced workers (Acemoglu and Autor, 2011; Acemoglu and Restrepo, 2020). The historical evidence outlined in Section 2 suggests that the adoption of milking machines in Norway had similar short-term negative effects, particularly among young women aged 16-25 when milking machines were adopted and who, as a result, lost their jobs as servants and milkmaids ("cow tenders"). The displacement costs were substantial. For example, during the 1950s, the foregone income of not working as a cow tender was around NOK 3,100 per year for women. This would cover around one-

quarter of the expenditure of a working-class household with two children in a Norwegian city (Statistical Yearbook of Norway 1955, Tables 237 and 250).

To capture the short-term effects of the adoption of milking machines, we use yearly income data from Norway's tax registry. This data allows us to examine short-term income responses for young women by comparing the evolution of their incomes over time in municipalities with a high and low treatment exposure. Since the earliest tax registry data is from 1967, the short-term analysis is restricted by construction to the group of compliers in 1970. More specifically, we focus on women who turned 16 in 1970. This allows us to evaluate the short-term income responses from the start of their working life. Importantly, the Census of Agriculture 1970 reports a large-scale uptake of milking machines.[41] Hence, the evolution of the incomes of these young women in the years following 1970 provides a good illustration of the short-run effects of the adoption of this new technology. If the adoption of milking machines triggered negative short-term effects, we would expect young women's incomes to evolve differently in municipalities with a high and low treatment intensity. We estimate the differential evolution of young women's incomes as follows:

$$Y_{ijt} = \alpha_j + \delta_t + \sum_{t=1971}^{2000} \gamma_t \, \mathbf{1}[t - 1970] \times T_j^{high} + u_{ijt}, \tag{9}$$

where Y_{ijt} is the income in year $t \in \{1970, ..., 2000\}$ of a woman i who turned 16 in 1970 and who was born in rural municipality j. We measure income in logarithmic units as log(1+income). The parameters α_j and δ_t are fixed effects for municipality and year. The variable of interest, $\mathbf{1}[t-1970] \times T_j^{high}$, is the interaction of an indicator variable equal to one if municipality j had a treatment above the 1970 median[42] with a set of dummy variables for the number of years since 1970, when the relevant milking machine uptake took place for the women in this sample. Hence, the γ_t coefficients capture the differential evolution of incomes for young women in municipalities with a treatment above vs. below the median in the 1970s.

Figure 5 displays the estimated γ_t coefficients from equation (9) using a panel of 8,935 women over 30 years (1970-2000). In the short run, the adoption of milking machines entails substantial negative effects on young women's incomes. In the first three years, women from municipalities with above-median treatment suffered an income decline of 26-

[41] In Norway, the number of milking machines increased from 40,000 in 1960 to 50,000 in 1970 (Figure 1).

[42] That is, T_j^{high} is equal to one if the number of dairy cows per farm in 1929 times the number of milking machines per farm in 1970, $C_j^{1929} \times M_{jc}^{1970}$, is above the 1970 median across all rural municipalities.

36% relative to women from municipalities with low adoption rates.[43] This is consistent with an adverse income effect of being displaced from milkmaid and servant jobs, which were typically performed by young women in dairy-intensive municipalities. Appendix Figure 7 shows that the estimated negative short-term effects of the adoption of milking machines are robust to alternative measures of women's incomes. We find that the probability of reporting a zero income (i.e., of being unemployed or at school) after three years increased by 3 percentage points for women from municipalities with above-median treatment exposure, relative to women from municipalities with low adoption rates of milking machines. Similarly, the negative short-term effects are robust to using the inverse hyperbolic transformation for women's incomes and to including individual fixed effects in equation (9).

In Appendix Table 3, we also use the 1960 Census to show similar negative effects for earlier households. We document a negative association between the diffusion of milking machines in 1960 and the share of household members who are employed in 1960.[44] That said, there is also a positive association with contemporaneous student activity by young women in affected municipalities. This suggests that they stayed longer at school as a result of reduced earning opportunities when milking machines replaced milkmaid and servant work.

Finally, Figure 5 further shows that the negative short-term effects on young women's incomes are short-lived. Ten years after the 1970s roll-out, we observe no significant income differences between women who, in 1970, resided in municipalities with different treatment intensities. Twenty years later, the negative income effects are reversed, and women originally from municipalities with a high treatment intensity consistently receive around 25% higher incomes. Altogether, this provides some initial evidence that the diffusion of milking machines, despite its initial negative income effects, increased the long-term earning opportunities for young women who grew up in dairy-intensive municipalities. In the next sections, we study these long-term effects in detail and show that they are associated with a structural change process that transformed women's work.

[43] The omitted category is 1970, so Figure 5 shows the differential evolution of incomes in high vs. low treatment municipalities relative to the 1970 differences. The difference is statistically significant at the 10% and 1% level in the first and third year, respectively.

[44] We look at the share of household members who are employed to measure negative short-term effects at the household level. This complements the estimates of equation (9), which capture negative short-term effects at the individual level for affected women (individual income data are only available since 1967).

6.2 Main results: long-term effects

We begin our long-term analysis by assessing whether the diffusion of milking machines pushed young female workers out of agriculture and from rural into urban areas. Both processes are crucial elements of structural change. The econometric model is based on equation (8), which exploits temporal variations in the uptake of milking machines across municipalities and shows that the diffusion of milking machines had a stronger impact in municipalities specialized in dairy production. Hence, the estimates should be interpreted as an intention-to-treat.

Table 1 presents compelling evidence that women who were affected by the diffusion of milking machines at the age of 16-25 are less likely to be engaged in agriculture as middle-aged adults.[45] The estimated coefficients show a clear pattern across all specifications: young women in municipalities more affected by the diffusion of milking machines are substantially less likely to work in agriculture later in their careers. This effect is statistically significant at the 1-percent level and remains almost unchanged when including a stricter set of controls that account for flexible trends across municipalities in women's propensity to remain in agriculture. Column (1) includes only municipality and birth cohort fixed effects. Column (2) additionally incorporates county-by-birth cohort fixed effects. Columns (3) and (4) further include, respectively, the share of improved farmland and the number of farms per capita in each municipality in 1929, both interacted with birth cohort fixed effects. These flexible trends allow for different trajectories of structural transformation in municipalities that were more agricultural intensive prior to the introduction of milking machines. Using the specification presented in column (1) as an example, we estimate that a one-standard-deviation increase in our treatment-intensity measure, $C_j^{1929} \times M_{jc}$, decreases a woman's likelihood of working in agriculture after the adoption of milking machines by around 2 percentage points, or 20 percent of the sample mean, which is an economically sizable effect. Taken together, these results suggest that our estimates effectively capture a local displacement effect as a result of the adoption of milking machines.[46]

After showing that the uptake of milking machines reduced women's long-term employment in the agricultural sector in dairy-dependent municipalities, we investigate whether

[45] As explained above, we classify occupations in the 1960, 1970, and 1980 census into farming and non-farming activities and evaluate how the adoption of milking machines when a woman was aged 16-25 affected her occupation after age 25, as reported in the following census. About 30 percent of the women in our sample do not report any occupation in the following census. Results are robust to excluding them from the analysis (see Appendix Table 4).

[46] In addition, Appendix Table 4 shows a similar pattern if we only include middle-aged women who are working. Excluding the information on occupations reported in the 1960 Census does not affect the results.

these areas also experienced a substantial out-migration of young female workers. To do so, we construct variables indicating whether a woman ever migrated based on her birthplace and place of residence in 1960, 1970, 1980, and 1990, as reported in the registry data. As before, the migration analysis is based on equation (8), estimated with the full set of controls of column (4) of Table 1: fixed effects for municipalities and birth cohort, county-by-birth cohort fixed effects, and our two measures of initial farming intensity interacted by birth cohort fixed effects.

Table 2 presents the results. Column (1) shows that the diffusion of milking machines significantly increased the likelihood of young women moving out of dairy-intensive municipalities. This result is largely driven by rural-to-urban migration (columns 2-3). A one-standard-deviation increase in our treatment measure, $C_j^{1929} \times M_{jc}$, increased the likelihood of a potentially displaced woman moving to a city by 0.8 percentage points, or about 2 percent of the sample mean. This effect is statistically significant at the 1-percent level. We find no evidence of significant rural-to-rural movements after milking machines were introduced. In addition, the estimates reported in columns (4)-(5) reveal that the automation of milking tasks triggered the long-distance migration of young women. We find that women who decided to migrate left their county of birth. A one-standard-deviation increase in treatment intensity increased out-of-county migration by 1.1 percentage points, or about 3 percent of the sample mean. This effect is also statistically significant at the 1-percent level. Instead, we find no evidence that the adoption of milking machines affected short-distance migration within one's county of birth. Altogether, our results suggest that the diffusion of milking machines contributed to the structural transformation of the Norwegian economy after WWII: it reduced female employment in agriculture and accelerated the urbanization process by pushing young affected women out of their rural homes and into cities.

Next, we examine the effect of the adoption of milking machines on women's long-term earning opportunities. Did the automation of hand milking bring economic hardship to displaced women in the long term? Or, on the contrary, did they find better-paid employment in the expanding manufacturing and service sectors? First, we evaluate whether the uptake of milking machines resulted in *relative* income losses or gains in the long term for women who resided in more dairy-intensive municipalities at the age of 16-25. To do so, we construct income percentile ranks based on the income at age 45 of all individuals (i.e., women and men) born in the same year.[47] Table 3 presents the results based on women's income rank

[47]The results remain unchanged if we construct income percentile ranks based on women only or when excluding the earlier cohorts from the sample since their adult income is measured at ages 52 and 62 respectively (see Section 4.1 for details).

as middle-aged adults. We follow the same structure as in Table 1 by subsequently adding a stricter set of controls. In line with the evidence presented in Section 6.1, we find that in the longer-term, women from municipalities with a higher dairy farming intensity ended up at a higher echelon of the income distribution. The point estimates range between 0.72 and 0.8, depending on the set of controls included—all of them are statistically significant at the 1-percent level. In other words, we find that for a one-standard-deviation increase in treatment intensity, $C_j^{1929} \times M_{jc}$, women climbed up the income distribution by almost one percentile. Importantly, women exposed to milking machines at the age of 16-25 improved their income rank as middle-aged adults, not only because they were more likely to report a positive income (extensive margin) but also because they had a higher income (measured in logs) at the age of 40-45 (Appendix Table 5). These results are most likely driven by women who left their birthplace and moved to cities (Appendix Table 6).[48]

Second, we analyze the effects of the adoption of milking machines on task reinstatement and occupational upgrading. Specifically, we investigate whether women exposed to milking machines at the age of 16-25, and who were displaced from jobs in the agricultural sector, were reinstated into high-skill occupations as middle-aged adults. For this analysis, we group occupations into high-, medium- and low-skill occupations following the classification of Autor (2019). The sample only consists of women who *did not work* in the agricultural sector as middle-aged adults. Table 4 presents the results. In column (1), we observe that women who were more exposed to milking machines at the age of 16-25 were significantly more likely to work in high-skill occupations later in life. This effect is statistically significant at the 1-percent level. A one-standard-deviation increase in treatment intensity, $C_j^{1929} \times M_{jc}$, resulted in a 0.4 percentage point higher likelihood of working as a middle-aged adult in a high-skill occupation, or about 3 percent of the sample mean. While there is no detectable effect on medium-skill occupations (column 2), we find a highly statistically significant negative effect for low-skill occupations (column 3). A one-standard-deviation increase in treatment intensity resulted in a 0.6 percentage point lower likelihood of working as a middle-aged adult in a low-skilled job, or about 2 percent of the sample mean. Overall, our results indicate that the diffusion of milking machines, and the associated process of structural transformation, led to the occupational upgrading of displaced women and, consequently, increased the earning opportunities of young rural women from affected municipalities in the long term.[49]

[48] Because of data limitations (income for the tax registry is only available from 1967), the results in Appendix Tables 5 and 6 are only based on women aged 16-25 in 1950, 1960, and 1970.

[49] Our findings imply that a general increase in the rural-urban wage gap after WWII alone cannot explain these patterns. The reason is that a general increase in the rural-urban wage gap would have affected the migration decisions and long-term outcomes of rural young women in more and less dairy-intensive

6.3 Long-term mechanisms: educational investments

We now turn our attention to the underlying mechanisms behind these results. We examine educational investments as a possible channel through which the automation of hand milking, despite its negative income effects in the short term, resulted in occupational upgrading and income gains in the long term for affected young women. In detail, the reallocation of displaced young women from agricultural jobs in rural areas into more lucrative, and more highly-skilled employment in urban areas required them to acquire new skills and to invest in higher education—a prerequisite for most white collar jobs. We test this hypothesis by using data on educational attainment from the education registry, which is available for all individuals in our sample, except those who died before 1960.[50] Specifically, we examine whether potentially displaced young women invested more in their education using the highest level of completed education as the outcome variable.

Table 5 presents the results based on estimating equation (8). The estimates confirm our hypothesis that potentially displaced young women invested more in human capital. The specification with the full set of controls in column (4) reveals that women exposed to milking machines at the age of 16-25 were more likely to have at least (i) upper secondary education; (ii) post-secondary education; and (iii) an undergraduate degree. For example, a one-standard-deviation increase in our treatment measure, $C_j^{1929} \times M_{jc}$, increased the likelihood of women completing at least upper secondary education by 0.5 percentage points, or 3 percent of the sample mean. These findings are consistent with the historical narrative that, after WWII, better-educated young rural women took up white-collar jobs in the cities. They also suggest that human capital investments played a major role in the occupational upgrading experienced by women after the automation of hand milking.

Next, we delve deeper into this mechanism by examining the relationship between local (above primary) schooling infrastructure and the decision of young women to move out from rural areas affected by the diffusion of milking machines. Because the reinstatement of displaced women into high-skill jobs in urban areas required further investment in formal education, there are two ways in which we expect migration decisions to depend on the local schooling infrastructure. On the one hand, potentially displaced women would be more

municipalities in the same manner. Since we also do not observe any negative income effects for affected women in the long term (on average), it is unlikely that the rural-urban wage gap was generally so small that, in the absence of the milking machines, nobody would have moved.

[50] Appendix Figure 5 displays a general upward trend of educational attainment for women in our baseline sample. Over time, not only did more women complete at least basic upper secondary education; circa 15-20 percent of the later cohorts also obtained an undergraduate degree.

likely to emigrate from rural to urban areas with higher-education institutions, where they could pursue their formal education. On the other hand, we expect less out-migration from affected rural areas with existing (above primary) schooling infrastructure.

We examine these hypotheses using data from Machin et al. (2012) on the schooling infrastructure of 421 municipalities from 1963 to 1992.[51] The data lists whether a municipality had at least one vocational high-school (*Yrkesskole*), a gymnasium, or higher-education institution (*Høyskole* or university). Using this information, we assess whether young women migrated to a town with a higher-education institution in Norway, as well as whether the existing local schooling infrastructure reduced the incentives to migrate out of the municipality.

Column (1) of Table 6 shows that the diffusion of milking machines positively affected the probability of migrating to a town with a higher-education institution. This effect is statistically significant at the 1-percent level. A one-standard-deviation increase in our treatment measure, $C_j^{1929} \times M_{jc}$, increased the likelihood of a potentially displaced woman moving to an urban area with a university or a *Høyskole* by 0.8 percentage points, or about 4 percent of the sample mean.[52] Columns (2)-(6) examine the differential effect of the diffusion of milking machines by the existing local schooling infrastructure. We do so by extending the specification in equation (8), which now also includes interactions between our treatment-intensity measure and indicator variables equal to one, if a woman's municipality of birth had a vocational high-school, a gymnasium, or a higher-education institution in 1963. As before, our estimates reveal that the diffusion of milking machines pushed women out of rural areas into towns with higher-education institutions, cities, and long-distance migration outside of their county of birth, but had no effect on short-distance migration within a county or on rural-to-rural migration. In addition, we find that these effects are stronger in municipalities lacking schooling infrastructure (reference group) than in municipalities with a gymnasium and, especially, with a higher-education institution (*Høyskole*). These results reveal that the migration flows resulting from the diffusion of milking machines were partly driven by the desire to acquire the formal education required to access high-skill employment in urban areas. Furthermore, they suggest that the long-term effects of automation are not institution independent, as the lack of local schooling seems to exacerbate the out-migration of potentially displaced workers.

[51] The data is for 435 municipalities in 1960, which correspond to 421 municipalities using 1980 borders.

[52] This effect is not only explained by migration to a few cities. Although, from 1970, only five towns had a university (Oslo, Bergen, Trondheim, Tromsø, and Ås), *Høyskole* higher-education institutions were disseminated across the country. For example, in 1963 there were 28 different municipalities with a *Høyskole*.

6.4 Robustness checks

In this section, we deal with potential threats to identification. We present (i) a placebo test showing that our results are not driven by pre-trends in modernization across municipalities that eventually adopted milking machines at different rates; (ii) the results of two permutation tests; (iii) evidence that our estimates are not confounded by major social-democratic education reforms; and a series of robustness checks (iv) using employment shares and (v) the national roll-out of milking machines in our treatment-intensity measure; (vi) accounting for heterogeneous treatment effects; (vii) controlling for a municipality's initial farm size distribution and for its evolution over time; (viii) controlling for access to hydroelectric power—Norway's main mode of electricity production; and (ix) adjusting standard errors to account for spatial correlation (Conley, 1999).

We first address the potential concern that our estimation approach is capturing pre-existing differences in modernization between more and less dairy-dependent municipalities before the large-scale introduction of milking machines. To address this issue, we use the digital collection of the historical complete count census records of Norway in 1900 and 1910 from the Norwegian Historical Data Centre (University of Tromsø) and the Minnesota Population Center (2020).[53] The data contain detailed information about individuals' occupations, their municipality of birth and residence. Based on the 1900 and 1910 censuses, we conduct a placebo experiment by considering what would have happened in dairy-intensive municipalities if the substantial increase in milking machines between 1950 and 1960 had occurred instead at the beginning of the 20th century. If municipalities with a large uptake of milking machines between 1950 and 1960 had already undergone a substantial modernization process in the early 1900s, that affected the misallocation of young rural women, our placebo exercise would detect significant effects. If there are no pre-existing trends in modernization by municipalities that adopted more (or less) milking machines between 1950 and 1960, our placebo estimates will be close to zero.

Reassuringly, the placebo exercise shows no signs of pre-trends in the relevant outcomes. Table 7 presents the regression results of the placebo exercise using estimating equation (8). The estimated coefficients reveal that women born in dairy-intensive municipalities were not less (or more) likely to work in agriculture (column 1), in husbandry (column 2), or as a servant (column 3) as middle-aged adults. They also did not leave their birthplace (column 4) or move to cities (column 5) at different rates, indicating that moving costs were not already declining in dairy-intensive municipalities in the pre-milking machines era.

[53] At the time of writing, the data for the 1920 and 1930 censuses have not been made publicly available.

The point estimates are all very small, close to zero, and statistically insignificant. This suggests that our main results are not capturing any substantial pre-trends in dairy-intensive municipalities before the widespread adoption of milking machines after WWII.

Next, we conduct a permutation exercise for our main findings, that women exposed to milking machines left agriculture (Table 1, column 4) and migrated to cities (Table 2, column 2). The permutation exercise reshuffles our treatment-intensity measure randomly (i) among rural municipalities within age cohorts (Panel A of Appendix Figure 8) and (ii) among rural municipalities but keeping the roll-out structure of milking machines fixed (Panel B of Appendix Figure 8). For both exercises, the true coefficient is substantially larger in (absolute) magnitude than almost any other random treatment assignment.

Another threat to identification is that access to basic education increased over the 20th century due to two major social-democratic reforms: the Folk School Law (1936) and the Primary School Reform (1959). Municipalities were given five and 12 years, respectively, to implement the two reforms. Because educational investments were important for migration and occupational upgrading after the automation of milking tasks (see Section 6.2), our estimates may potentially confound the effect of milking machines with that of the staggered educational reforms. This would be the case if the municipalities that adopted this new technology early on were also the first to implement the reforms. However, this scenario is unlikely. The Folk School Law aimed to equalize access to primary schooling across rural and urban areas (Rust, 1989) and was fully implemented in every municipality by 1941.[54] Specifically, this occurred before milking machines were introduced in Norway after WWII and became widespread in the 1960s. On the other hand, the Primary School Reform increased compulsory education from 7 to 9 years and was implemented by different municipalities at different points in time from 1960 to 1972 (Black et al., 2005).[55] Although the roll-out of the reform was concomitant with the large scale adoption of milking machines, the two processes were orthogonal. Appendix Figure 9 shows that municipalities with a large-scale adoption of milking machines by 1960 did not implement the Primary School Reform earlier than municipalities with few or no milking machines (Panel A). A local polynomial regression of the first cohort affected by the reform in each municipality on our treatment-intensity measure confirms that the roll-out of the reform was statistically independent from the diffusion of milking machines (Panel B).[56] Furthermore, Appendix Table 7 shows that all our

[54]By 1941, every rural municipality had fully implemented the increase in the number of weeks of instruction (from 15 to 16 and 18 weeks in the first three and last four grades), the reduction of class sizes (from 35 to 30), and the curricula changes embedded in the Folk School Law reform.

[55]In addition, access to schools improved and the curriculum was reformed.

[56]The figure uses data from Black et al. (2005). Panel A plots our treatment-intensity measure in 1960

estimates for the effect of milking machines on women's outcomes are robust to controlling for the roll-out of the Primary Education Reform. To do so, we include a reform indicator in equation (8) equal to one if municipality m had fully implemented the Primary School Reform when cohort c attended school. Section 6.5 further confirms that our results are not driven by the reforms. We find that the automation of female-specific tasks by milking machines only affected women's outcomes, while both men and women were treated by these two education reforms.

In addition, we examine the robustness of our results to various modifications of the treatment-intensity measure. First, we use two alternative measures that proxy for dairy-farming suitability prior to the diffusion of milking machines. Instead of using the number of milking cows per farm in 1929, we use municipality-level employment shares in the the pre-milking machines era in two activities related to milking: first, the share of rural women working as agricultural servants (who were often hired as milkmaids) in 1930; and second, the share of rural women working in agriculture in 1930. Although employment shares are a less exogenous proxy of dairy-farming suitability than our baseline measure and do not capture unpaid labor, their use is also motivated by the predictions of our theoretical model. Our model's third prediction is that the effects of milking automation will be stronger in municipalities with a production technology that is intensive in milking tasks. Specifically, Equation (7) shows that the first-order displacement effect of milking machines on female labor is related to $1 - \beta(j)$. Note that, under our Cobb-Douglas production function, the female employment share in rural municipality j is $(1 - \beta(j))\dfrac{AL^f}{AL^f + M}$ in general, and $(1-\beta(j))$ in the pre-milking machines era. In other words, we can use the two aforementioned female employment shares, measured before the adoption of milking machines, as a one-to-one proxy for $1-\beta(j)$ in rural municipalities. Appendix Tables 8 and 9 show that our results are very similar under this alternative definition of the treatment.

Second, our results remain qualitatively unchanged if we modify our treatment-intensity measure with respect to the roll-out of milking machines. We replace the municipality-specific roll-out of milking machines M_{jc} in estimating equation (8) with the national roll-out M (Appendix Table 12). Using the national roll-out is appealing, as it is orthogonal to local conditions, which may have influenced both the adoption of milking machines and women's outcomes. Despite the fact that using the national roll-out reduces the cross-sectional variation in our treatment-intensity measure, our main results remain almost unchanged.

(right) and the first cohort affected by the reform (left) in each municipality, sorted by the reform implementation date. Panel B displays a Kernel-weighted local polynomial showing that, on average, the 1953-54 cohort was the first affected by the reform independently of a municipality's milking-machine adoption rate.

Furthermore, we consider the issue that the treatment effect might not be constant between municipalities and over time. Recent work discusses how staggered treatment timing and treatment effect heterogeneity complicate the identification of causal effects in difference-in-differences designs (see de Chaisemartin and D'Haultfœuille (2022) for a survey). Milking machines were rolled-out in Norway across municipalities at different points in time and treatment effects might be heterogeneous. Our solution to these potential concerns in our setting is to compare estimates across stratified samples. In Appendix Table 13, we compare the estimates for women aged 16-25 who lived in municipalities with no milking machines in 1940, 1950, or 1960, to those who lived in municipalities that already had a positive number of milking machines in the corresponding year. That is, we compare the estimated effects for switchers and non-switchers at different points in time. Reassuringly, the estimates across these samples are quantitatively very similar.

Finally, our main results are robust to controlling for differences in the initial farm size distribution at the municipality level interacted by birth cohort fixed effects (Appendix Tables 14 and 15). Although, on average, the farm size distribution remains fairly stable during our sample period (see Appendix Figure 13), the tables also report specifications that control for its evolution over time at the municipality level.[57] Next, we show that our main results are not confounded by local access to hydroelectric power (Appendix Table 16). Hydroelectric power was the main mode of electricity production in Norway during our study period. To account for it, we consider either the year of initial hydropower production, hydropower status in the period 1900–1910 (i.e., a proxy for early adopters), or hydroelectric potential measured as in Leknes and Modalsli (2020), and interacted by birth cohort fixed effects.[58] Lastly, we account for spatial dependence in the error term using Conley standard errors with different distance cutoffs (Appendix Figure 10).

6.5 Men and the diffusion of tractors

This section shows that the introduction of milking machines had opposite effects on men and women, narrowing the long-term gender gap in income and in the skill levels of occupations.

[57] Appendix Tables 14 and 15 capture variation in farm size distribution across municipalities using the pre-treatment or the contemporaneous share of farms below 5 decares (omitted category), 5–50, 50–100, 100–200, 200–500, and above 500 decares; the pre-treatment or the contemporaneous ratio of large (above 200 decares) to small farms (below 5 decares); and the pre-treatment share of non-separately liable farms. Non-separately liable farms include agricultural farms as well as other farm uses, such as the remains of old homesteads and housing on built-up land. Pre-treatment measures are from the Census of Agriculture 1930 and are interacted with birth year FE.

[58] Most hydroelectric power plants were built in the period 1900–1920. By 1920, plants were distributed all over Norway; see Leknes and Modalsli (2020, Figures 1 and 2).

We also show that the gender-specific effects of milking machines are distinct from, and not confounded by, the effects of general-purpose labor-saving technologies on male and female farm workers.

To do so, we extend our analysis along two dimensions: First, we extend our sample with the corresponding cohorts of men born in rural municipalities aged 16-25 in the census years 1930-1970. Second, we modify our specification to account for the gender-specific effects of both milking machines and tractors. Tractors are a general-purpose labor-saving technology that fundamentally contributed to the mechanization of farms after WWII throughout Europe and the United States. In Norway, tractors automated haymaking and seasonal harvesting; two tasks that employed both men and women. Hence, in contrast to milking machines, we expect tractors to replace both male and female workers. While studying the effect of "tractorization" is interesting in itself, accounting for it will also remove a potential omitted variable bias from the estimated treatment effect. In other words, by incorporating tractors into the analysis, we also address the concern that our results simply reflect the adoption of general-purpose technologies during the mechanization of the agricultural sector after WWII. Before presenting the extended estimating equation and the results, we provide a brief overview of the adoption and use of tractors in Norway.

Tractors and milking machines were introduced on a large scale around the same time. Although Henry Ford introduced the first mass-produced gasoline tractor, the *Fordson*, in 1917, tractors were not broadly adopted before the 1940s in Norway or in the rest of Europe and the United States.[59] The reasons for this delayed adoption are partly technical: The first tractors were heavy and cumbersome, and not well suited for cultivating fields. Over time, tractors became smaller, incorporated rubber wheels, and were adjusted to serve multiple tasks—particularly after WWII, when flexible hydraulic systems for attaching equipment were introduced.[60] These smaller multipurpose tractors were also more suitable for Norway's hilly terrain. Aside from technical reasons, the severe economic situation in Norway in the 1920s and early 1930s, and the German occupation during WWII, also contributed to the slow uptake prior to 1945. Appendix Figure 11 shows a rapid uptake of tractors on Norwegian farms in the 1950s.[61] Between 1950 and 1970, the number of tractors increased

[59] In the United States, for example, the percentage of farms that reported owning a tractor increased from 23.1 in 1940 to 80.8 in 1969 (Binswanger, 1986; Olmstead and Rhode, 2001; Manuelli and Seshadri, 2014).

[60] Olmstead and Rhode (2001), Manuelli and Seshadri (2014) and Gross (2018) consider the continuous development of the tractor as the main reason for its relatively slow adoption in the US and other countries.

[61] Tractors were mostly imported from the US and subsidized through the Marshall Plan. In particular, quota restrictions on agricultural equipment and machinery were lifted in the fall of 1951, contributing to the rapid spread of milking machines and tractors in Norway (Espeli, 1990).

from less than 20,000 to over 100,000. The large-scale adoption of tractors contributed to the general mechanization of Norwegian farms and led to a more capital-intensive production (see Appendix Figure 1).[62] Tractors replaced the use of draft animals (mostly horses and mules), resulting in significant labor savings and contributing to the decline in the farming population in the United States and Europe throughout the 20th century (Olmstead and Rhode, 2001, Table 7).

In contrast to milking machines, tractors are a general-purpose labor-saving technology. In the case of Norway, tractors facilitated the cultivation of fields, automated haymaking, and simplified other seasonal harvesting activities. As explained in Section 2, haymaking and harvesting activities were performed by both men and women, where men cut the hay or grain and women gathered it up (Osterud, 2014, p.667). Hence, the introduction of a general-purpose technology such as the tractor was expected to displace both male and female labor, although probably at different rates.

To estimate the gender-specific effects of the adoption of milking machines and to contrast it with the adoption of tractors, we modify our baseline estimating equation (8). We estimate it on a sample of both women and men born in rural municipalities who were aged 16-25 in the census years 1930-1970, and we interact our treatment-intensity measure for the adoption of milking machines, $C_j^{1929} \times M_{jc}$, with an indicator for men. This interaction term captures the differential effect of the adoption of milking machines on men and women. To distinguish these gender effects from those of the adoption of general-purpose mechanization technologies in agriculture, we estimate the impact of tractorization by using a similar intensity-of-treatment research design, as for milking machines. Specifically, we add the interaction between the number of tractors per farm, T_{jc}, in each municipality j at each census year when birth cohort c was aged 16-25, with pre-conditions favoring the adoption of tractors. We capture these pre-conditions with the municipality's share of horses per farm in 1929, H_j^{1929}. Before tractors took over the cultivation of fields, farmers used horses and other draft animals for this purpose. Consequently, we expect larger effects of the adoption of tractors in municipalities that relied more on horsepower before their adoption. Appendix Figure 12 shows that there was substantial variation in horses per farm before tractors were introduced in Norway. Hence, our measure of tractorization, $H_j^{1929} \times T_{jc}$, effectively captures the differential effect of the diffusion of tractors in municipalities with a greater reliance on horses in the pre-adoption period. As before, we interact this treatment-intensity measure with indicators for men to capture the differential effect of the tractorization of agriculture

[62] A similar increase in the capital-labor ratio has been observed in other European countries after WWII (Martín-Retortillo and Pinilla, 2015, Table 6).

on men and women. Finally, the modified specification includes the strictest set of controls. To further account for different responses by gender, we interact the set of municipality and county-by-birth-cohort fixed effects with a gender dummy.

Table 8 summarizes the results by gender when accounting for the diffusion of milking machines, $C_j^{1929} \times M_{jc}$, and tractors, $H_j^{1929} \times T_{jc}$. Three important patterns emerge. First, our previous estimates for the long-term effect of the diffusion of milking machines on young rural women are robust to include men in the analysis and to account for the adoption of tractors after WWII. Specifically, the estimates on $C_j^{1929} \times M_{jc}$ in this extended specification also show that, after the adoption of milking machines, young women in dairy intensive municipalities were displaced from farming (column 1), migrated to urban areas (column 2), climbed the income distribution (column 3), were reinstated away from low-skilled jobs (columns 4-6), and invested more in higher education (column 7). The magnitude of all estimates is similar to that in our baseline specification (Tables 1-5).

Second, we find that the adoption of milking machines had opposing effects on men and women, reducing long-term gender differences in income and in the skill content of occupations. All the estimates on the triple interaction $C_j^{1929} \times M_{jc} \times man$ have opposite signs to the effect of milking machines on young rural women. Relative to women in the same cohort, men were more likely to remain in farming after the diffusion of milking machines (column 1) and were less likely to emigrate from rural areas (column 2). Importantly, income differences between these young men and women were reduced by about 0.6 percentile ranks later in life (column 3), and the occupational distribution shifted so that young rural men were relatively less likely than their female counterparts to take on higher-skilled jobs later in life (columns 4-6). Although not statistically significant, we also find that the adoption of milking machines led to differential educational investments for men and women (column 7).

Third, our results suggest that the effects of adopting milking machines on male and female rural workers differed from the effects of the adoption of tractors. The estimates in column (1) reveal that women were pushed out of agriculture in municipalities with a higher reliance on dairy farming and horses as draft animals after the widespread adoption of milking machines and tractors, respectively. In contrast, men strongly responded to the uptake of tractors but they did not leave agriculture at a higher rate in dairy-intensive municipalities. Column (2) shows that women moved out of dairy-intensive municipalities into cities after the diffusion of milking machines, whereas the adoption of general-purpose technologies such as tractors did not trigger women's emigration to cities. For men, we

do not find any substantial out-migration triggered by the adoption of milking machines or tractors.[63] Both results mirror the historical narrative described in Section 2.2 and the predictions of our model. Interestingly, both the diffusion of milking machines and tractors resulted in detectable income gains for women but not for men (column 3). A one-standard-deviation increase in the treatment-intensity measure for the diffusion of milking machines (tractors) moved affected women up by 0.5 (0.4) percentile ranks, while displaced men, if anything, experienced small but not statistically significant income losses. We observe some skill upgrading of displaced women from dairy-intensive municipalities in columns (4)-(6)—although only the point estimate of not working in low-skilled occupations is statistically significant at the 5-percent level—and no skill upgrading for displaced women as a result of the adoption of tractors. For men, we find a worsening of their position relative to women from the adoption of milking machines, but no significant gender patterns emerge from the adoption of tractors. Finally, in terms of educational attainment, the estimates in column (7) reveal that only women from dairy-intensive municipalities invested more in their education after the diffusion of milking machines. There are no effects for men.[64]

Overall, our results provide compelling evidence that labor-saving technological change in the agricultural sector had fundamentally different consequences for young rural men and women. The adoption of milking machines improved women's economic opportunities relative to men and reduced gender differences in income in the long term, over and above the transformations brought about by the adoption of general-purpose technologies during the mechanization of agriculture after WWII.

6.6 Spillover effects to the next generation

We conclude our empirical analysis by asking whether the adoption of milking machines also left a mark on the next generation. The Norwegian registry data can be used to link mothers to their children, thus allowing us to track shocks across generations. The sample includes the children of women who lived in rural municipalities at age 16-25 in the census years 1930-1970 (i.e., our main sample). We focus on two outcomes to capture the key inter-generational effects of mothers moving out of agriculture and rural areas: educational attainment and income. Our reduced form estimates are based on a modified version of estimating equation (8), including fixed effects for each child's gender and year of birth alongside the same set of

[63] Although the estimate on men from dairy-intensive municipalities is statistically significant (p-value 0.055), this result is not robust to modifying our treatment-intensity measure (Appendix Tables 10 and 11).

[64] Results for women are similar when we modify our treatment measure (Appendix Tables 10 and 11) or when we evaluate the effect of tractors on a sample of women only (Appendix Table 17).

control variables as in Tables 1-5.

Table 9 shows that children attended school longer if their mothers grew up in a municipality with higher exposure to the adoption of milking machines. While the estimated coefficient on our treatment-intensity measure, $C_j^{1929} \times M_{jc}$, decreases in size when including a stricter set of controls, we find that children from more affected mothers had a significantly higher likelihood of completing upper secondary school (Panel A). There is also a higher likelihood that these children received post-secondary education (Panel B) and an undergraduate degree (Panel C), but the estimated coefficients are no longer statistically significant in the strictest specification (column 4). Taking the point estimate in column 4 (Panel A) at face value, a one-standard-deviation increase in treatment intensity increases the likelihood that the child completed at least upper secondary school by 0.3 percentage points, or 0.5 percent of the sample mean. The effect size is roughly between one-sixth to one-fifth of the effect size on the mothers (see Table 5 and Table 8), indicating that the effects of milking machines diminished over time.

Table 10 presents the results for income. As in Table 3, we construct income percentile ranks based on all individuals (i.e., women and men) born in the same year as the children of women in our main sample. Because the Norwegian tax registry starts in 1967, we consider income at age 40 for children born before 1970 and income at age 30 for children born in the 1970s.[65] The estimated coefficient ranges between 0.17 and 0.24, depending on the set of controls included, and is statistically significant at least at the 5-percent level. The point estimates imply that for a one-standard-deviation increase in treatment intensity, $C_j^{1929} \times M_{jc}$, the children of affected women climbed up the income distribution by about one-fifth of a percentile: a quantitatively small but detectable effect. Overall, our results indicate that the diffusion of milking machines triggered a structural change in Norway that affected young rural women and also carried over to their children.

7 Conclusion

The rapid mechanization of agriculture in Europe and North America after WWII led to a substantial decline in farm employment. Displaced workers left rural areas in large numbers and contributed to the growth of the manufacturing and service sectors in urban areas. This well-known structural transformation process included a reallocation of workers, both

[65] This excludes 21.8 percent of the children of women aged 16-35 in 1970 due to data restrictions (i.e. these children are too young and appear in the tax registry only before age 30). The results in the full specification remain unaffected when excluding all the children of women aged 16-35 in 1970.

within rural areas and into cities, based on their comparative advantage, employment available in cities, and alternative employment opportunities in the rural areas at that time. Because tasks on farms were typically divided along gender lines, the technological change in agriculture during this period affected the earning opportunities of displaced men and women differently. Hence, the mechanization of tasks in agriculture entailed gender-specific consequences with important implications for rural women's career paths and for gender differences in labor markets.

We focused on one of the most important automation processes in agriculture, the mechanization of milking cows—a task that provided jobs for hundreds of thousands of rural women—to study the economic consequences of gender-biased technological change. Our focus was on Norway, which provides an ideal setting in which to evaluate the economic impact of the adoption of milking machines. Norway had a dairy-intensive farming sector and experienced the rapid adoption of milking machines after WWII, similar to other dairy-intensive countries in Western Europe. Yet more so than in other countries, the location of dairy farms in Norway is likely determined by its unique geography, thereby facilitating the identification of the diffusion of milking machines at the local level. Moreover, the Norwegian registry data and agricultural census statistics contain detailed information on individuals, farms, and farm equipment, allowing us to evaluate the short-term and long-term effects of the roll-out of milking machines for young rural women and their children.

Our results show that the introduction of milking machines had different consequences for men and women. This gender-specific technology shock shifted misallocated young women out of agriculture and into the urban sector, where they invested more in their education and ended up at a higher echelon of the income distribution as adults. On the other hand, the corresponding cohort of affected men were not displaced by the adoption of milking machines and remained in rural areas. The effects of adopting milking machines differed from those of adopting general-purpose technologies, such as tractors, and also carried over to the next generation. In contrast to the negative inter-generational effects of worker displacement documented in the literature, our results suggest that the children of affected mothers attended school longer and enjoyed some small income gains as adults compared to their peers whose mothers grew up in less affected rural areas. This is perhaps because they benefited from their mothers' decision to move to opportunity at a young age.

There are also some parallels to today's debate about the economic consequences of labor competing against more and more sophisticated technologies, such as industrial robots and artificial intelligence. The net effect of automating tasks depends on whether the dis-

placement effect outweighs productivity gains and the reinstatement effect of creating new labor-intensive tasks (e.g., Acemoglu and Restrepo, 2018, 2019). In our case, the creation of new jobs in the manufacturing and service sectors appears to be the dominant force. As in other European countries after WWII, Norway's economy was in a transition phase with remarkable growth rates, especially in the manufacturing and service industries. Despite the fact that milking machines immediately displaced young female agricultural workers, in the long run they benefited (on average) from being pushed off the farms because the Norwegian economy provided new job opportunities for women in urban areas. However, it should be clear from this discussion that the effects of automation are not institution independent, and that the introduction of gender-biased labor-saving technologies in agriculture might not always result in being beneficial for displaced workers. The effects will likely depend on their comparative advantage and gender-specific job opportunities in rural and urban areas.

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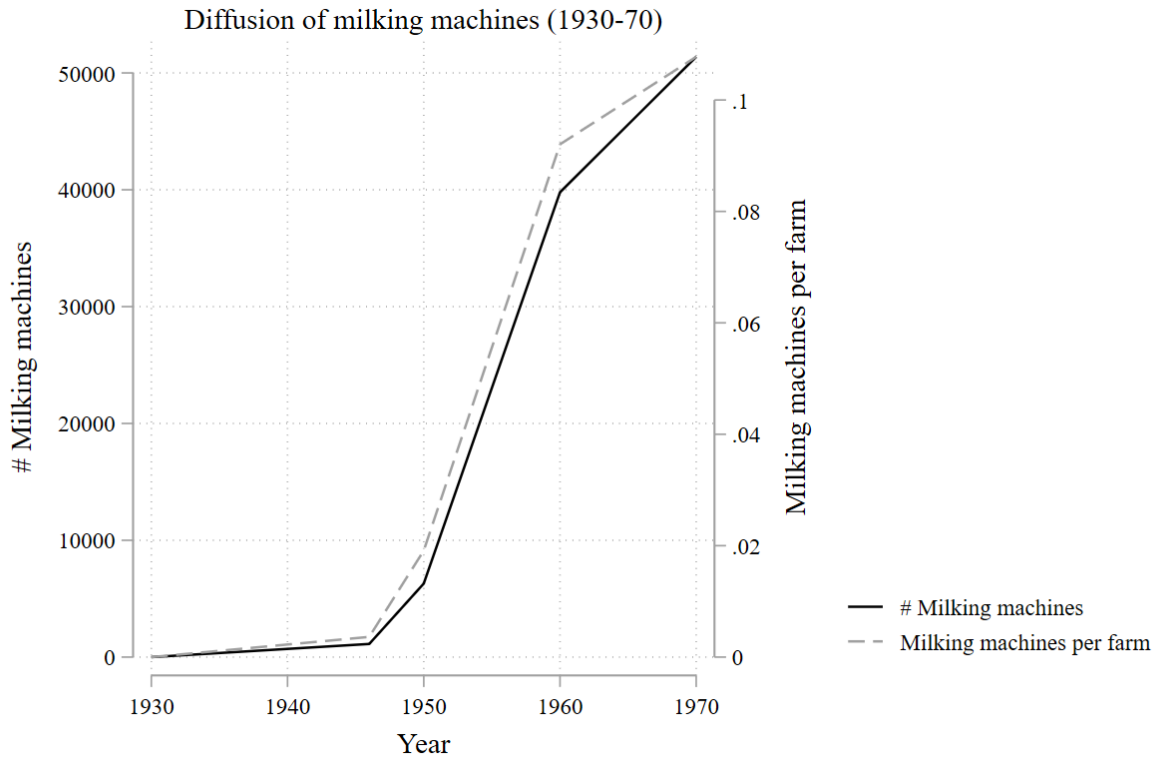
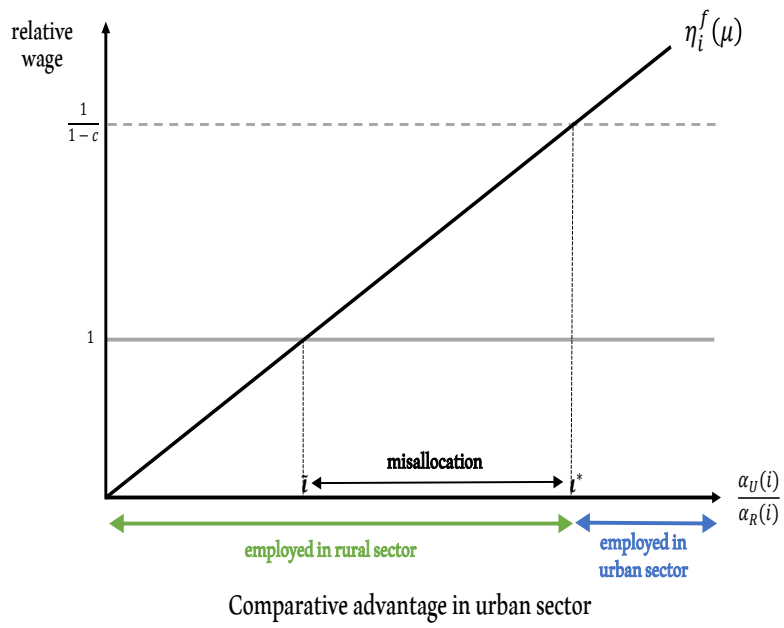
Tables and figures

Figure 1

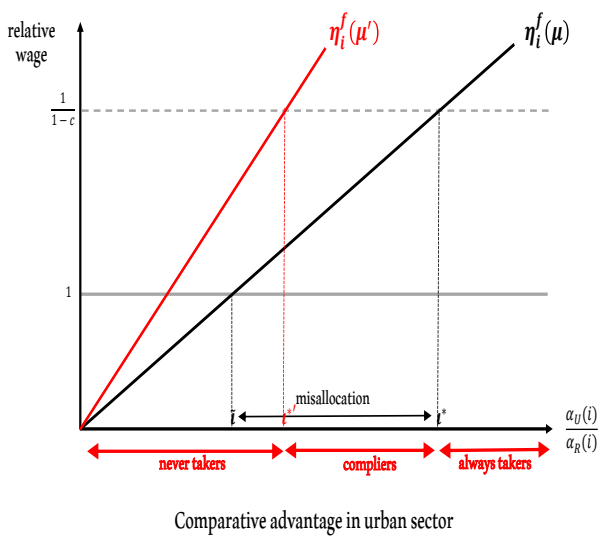


NOTE.— This figure shows the evolution of milking machines (left vertical axis) and milking machines per farm (right vertical axis) in Norway between 1930 and 1970. Source: Census of Agriculture (own calculations).

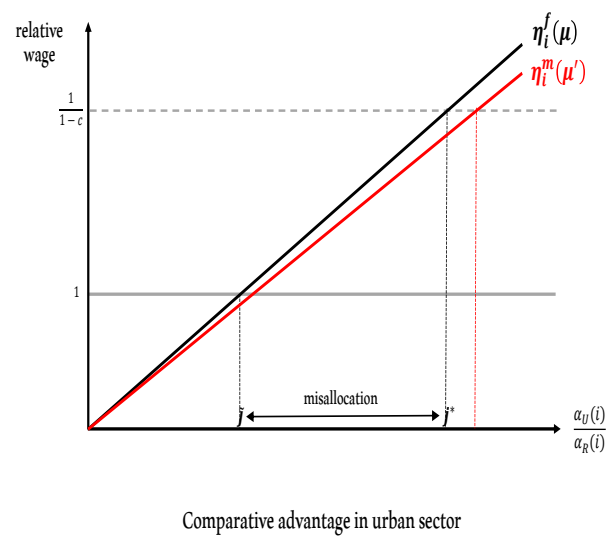
Figure 2



A. Sorting by comparative advantage (women)



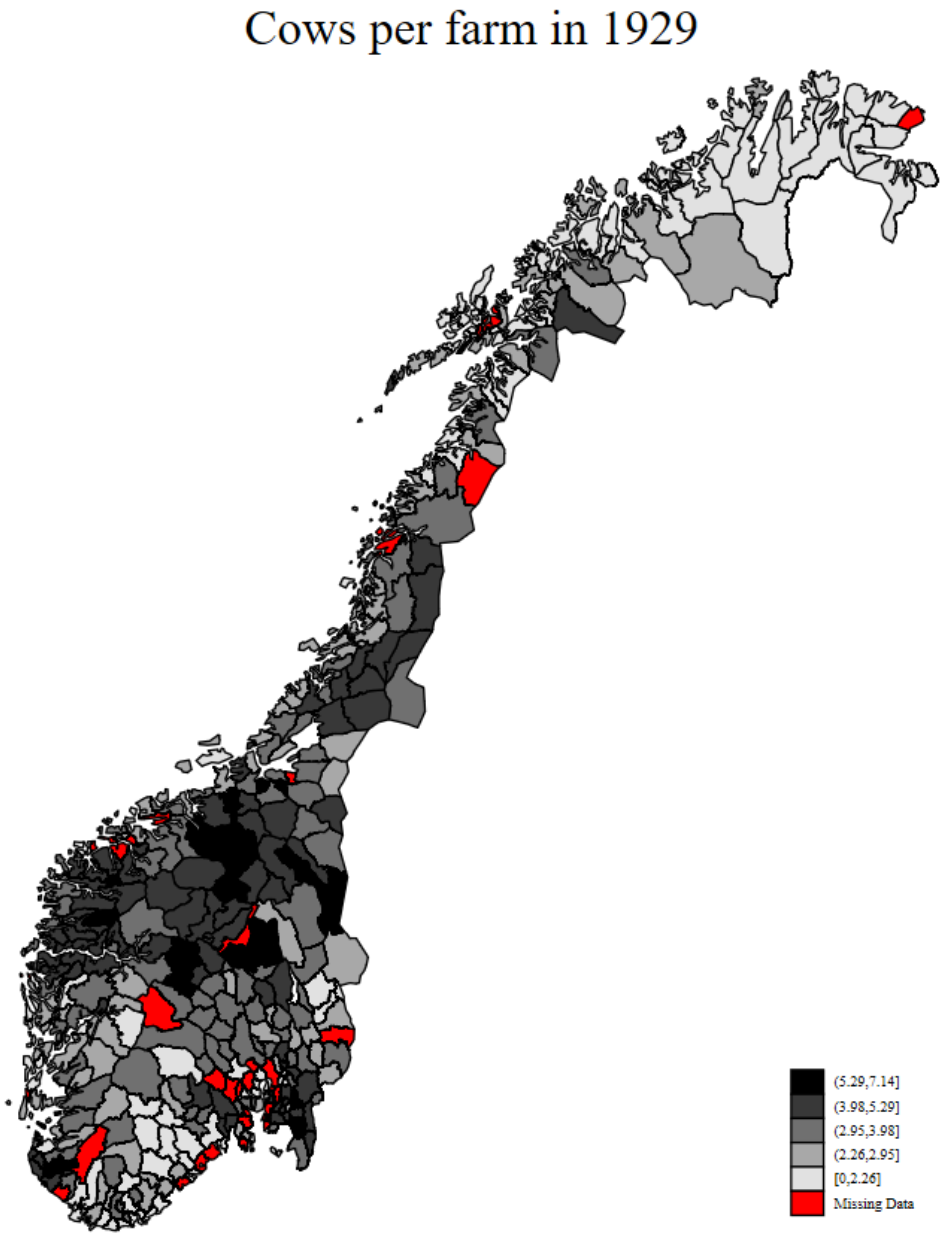
B. Milking machines' impact on women



C. Milking machines' impact on men

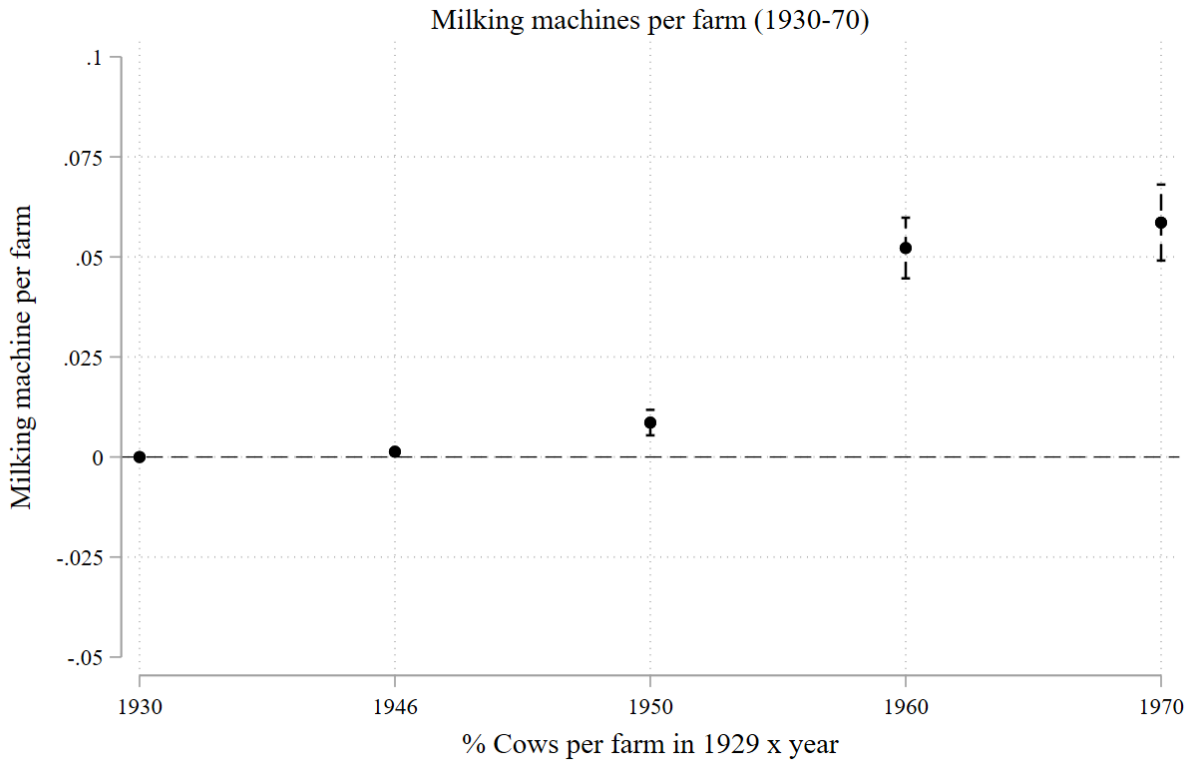
NOTE.— This figure shows the model's equilibrium (Panel A) and comparative statics for the effects of the adoption of milking machines on women (Panel B) and men (Panel C). For illustrative purposes, it is assumed that $\alpha_U(i)$ and $\alpha_R(i)$ are uniformly distributed.

Figure 3



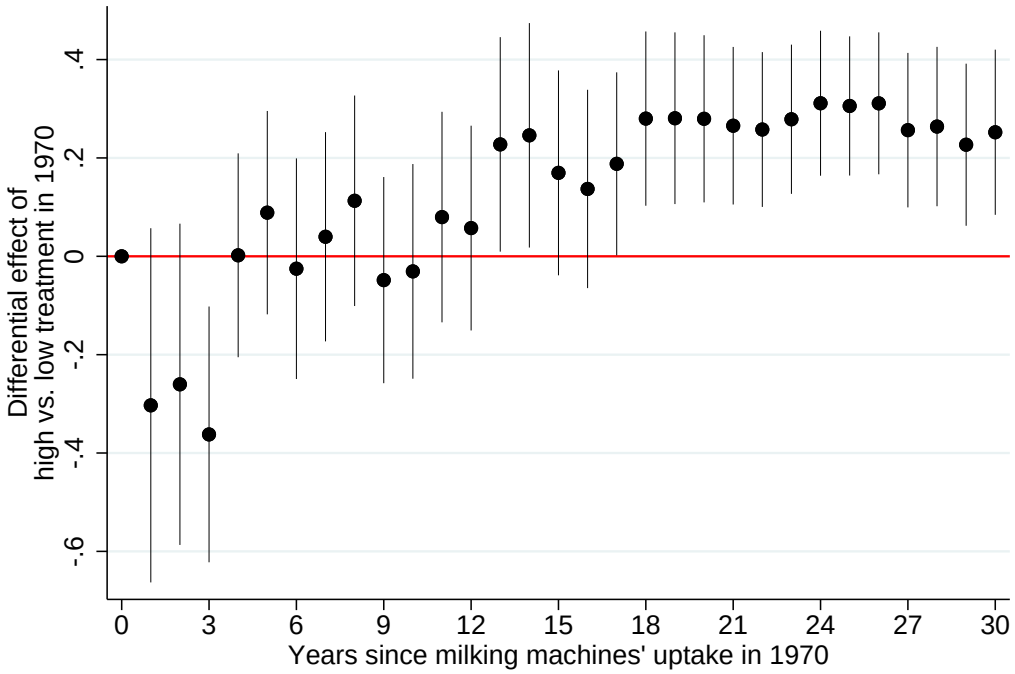
NOTE.— This figure shows the distribution of cows per farm in 1929 across Norwegian municipalities. A darker color refers to higher values of cows per farm. Red polygons denote missing observations. Source: Census of Agriculture (own calculations).

Figure 4



NOTE.— This figure displays the estimated coefficients of regressing milking machines per farm on cows per farm in 1929 interacted by census year fixed effects and controlling for municipality and census year fixed effects. The omitted reference year is 1930. Estimates are reported with their corresponding 95-percent level confidence intervals.

Figure 5: Year-by-year evolution of young women's incomes, by treatment intensity in 1970



NOTE.— This figure plots estimates of γ_t from Equation (9) and 95% confidence intervals. The sample is a panel of 8,935 women in rural municipalities who turned 16 in 1970 and their incomes over 30 years, from 1970 to 2000. Standard errors are clustered by municipality.

Table 1: The diffusion of milking machines and women's employment in agriculture

	(1) works in agriculture	(2) works in agriculture	(3) works in agriculture	(4) works in agriculture
$C_j^{1929} \times M_{jc}$	-1.84***	-1.85***	-1.90***	-1.62***
	(0.28)	(0.23)	(0.24)	(0.23)
Observations	381,002	381,002	381,002	381,002
R-squared	0.06	0.06	0.06	0.06
Municipality FE	yes	yes	yes	yes
Birth year FE	yes	yes	yes	yes
County-by-byear FE	no	yes	yes	yes
Impr. farmland^{1929} $\times$ byear FE	no	no	yes	yes
Farms p.c.^{1929} $\times$ byear FE	no	no	no	yes
Mean dep. variable	9.13	9.13	9.13	9.13
Effect size %	-20.20	-20.20	-20.80	-17.80

NOTE.— This table shows the effect of the diffusion of milking machines on whether women worked in agriculture after the treatment. The sample includes women born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1930, 1940, 1950, 1960, or 1970. The dependent variable is a dummy variable equal to 100 if a woman is employed in the agricultural sector after the age of 25. The variable C_j^{1929} is the number of cows per farm in 1929 in a woman's municipality of birth (j). The variable M_{jc} is the number of milking machines per farm in a woman's municipality of birth j when she was aged 16–25 (c). The interaction between these two variables, $C_j^{1929} \times M_{jc}$, is our treatment-intensity measure and is normalized to have a mean of zero and an SD of one. All regressions include fixed effects for a woman's municipality of birth and birth year. We further include county-by-birth year fixed effects (Columns 2-4), the share of improved farmland in 1929 (Columns 3-4), and the number of farms per capita in 1929 (Column 4) in each municipality interacted with the women's birth year indicators. Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 2: The diffusion of milking machines and women's migration decisions

	(1) migrates anywhere	(2) migrates to city	(3) migrates to rural area	(4) migrates outside county	(5) migrates inside county
$C_j^{1929} \times M_{jc}$	0.98***	0.81***	0.17	1.13***	-0.15
	(0.28)	(0.28)	(0.23)	(0.33)	(0.26)
Observations	381,002	381,002	381,002	381,002	381,002
R-squared	0.06	0.04	0.04	0.08	0.08
Municipality FE	yes	yes	yes	yes	yes
Birth year FE	yes	yes	yes	yes	yes
County-by-byear FE	yes	yes	yes	yes	yes
Imp. farmland^{1929} × byear FE	yes	yes	yes	yes	yes
Farms p.c.^{1929} × byear FE	yes	yes	yes	yes	yes
Mean dep. variable	68.90	37.80	31.09	39.89	29.00
Effect size %	1.40	2.10	0.60	2.80	-0.50

Note.— This table shows the effect of the diffusion of milking machines on women's decisions to migrate. The sample includes women born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1930, 1940, 1950, 1960, or 1970. The dependent variable is a dummy variable equal to 100 if a woman moved out of her birthplace anywhere (Column 1), to a city (Column 2), to another rural municipality (Column 3), outside (Column 4), and inside (Column 5) their county of birth. The variable $C_j^{1929} \times M_{jc}$ is the interaction between the number of cows per farm in a woman's municipality of birth (j) in 1929 and the number of milking machines per farm in municipality j when she was aged 16–25 (c). This variable is normalized to have a mean of zero and an SD of one. Control variables are defined as in Table 1. Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 3: The diffusion of milking machines and women's incomes

	(1) income rank	(2) income rank	(3) income rank	(4) income rank
$C_j^{1929} \times M_{jc}$	0.79***	0.76***	0.80***	0.72***
	(0.13)	(0.12)	(0.12)	(0.12)
Observations	344,459	344,459	344,459	344,459
R-squared	0.10	0.11	0.11	0.11
Municipality FE	yes	yes	yes	yes
Birth year FE	yes	yes	yes	yes
County FE	no	no	no	no
County-by-byear FE	no	yes	yes	yes
Imp. farmland^{1929} $\times$ byear FE	no	no	yes	yes
Farms p.c.^{1929} $\times$ byear FE	no	no	no	yes

Note.— This table shows the effect of the diffusion of milking machines on women's percentile income rank after the treatment. The sample includes women born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1930–1970. The dependent variable is the percentile income rank of a woman relative to all individuals born in the same year. Income is measured at age 45 for cohorts aged 16–25 in 1950, 1960, and 1970, and at age 52 and 62 for the cohorts aged 16-25 in 1940 and 1930, respectively. The variable $C_j^{1929} \times M_{jc}$ is the interaction between cows per farm in a woman's municipality of birth (j) in 1929 and milking machines per farm in municipality j when she was aged 16–25 (c). This variable is normalized to have a mean of zero and an SD of one. Control variables are defined as in Table 1. Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 4: The diffusion of milking machines and women's employment skills

	(1) high skill	(2) med skill	(3) low skill
$C_j^{1929} \times M_{jc}$	0.37***	-0.10	-0.62***
	(0.14)	(0.19)	(0.21)
Observations	346,215	346,215	346,215
R-squared	0.03	0.02	0.03
Municipality FE	yes	yes	yes
Birth year FE	yes	yes	yes
County-by-byear FE	yes	yes	yes
Improved farmland^{1929} $\times$ byear FE	yes	yes	yes
Farms p.c.^{1929} $\times$ byear FE	yes	yes	yes
Mean dep. variable	12.46	18.34	34.30
Effect size %	2.90	-0.60	-1.80

NOTE.— This table shows the effect of the diffusion of milking machines on whether women in non-agricultural occupations worked in a high-, middle- or low-skill occupation after treatment. The sample includes women who were born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1930–1970, and who worked in non-agricultural occupations after treatment. The variable $C_j^{1929} \times M_{jc}$ is the interaction between the number of cows per farm in a woman's municipality of birth (j) in 1929 and the number of milking machines per farm in municipality j when she was aged 16–25 (c). This variable is normalized to have a mean of zero and an SD of one. Control variables are defined as in Table 1. Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 5: The diffusion of milking machines and women's education

	(1)	(2)	(3)	(4)
	Upper secondary, final edu. or higher			
$C_j^{1929} \times M_{jc}$	0.49***	0.54**	0.53**	0.50**
	(0.18)	(0.22)	(0.22)	(0.22)
Effect size %	2.90	3.20	3.20	3.00
	Post-secondary education or higher			
$C_j^{1929} \times M_{jc}$	0.27*	0.37**	0.35*	0.42**
	(0.16)	(0.18)	(0.18)	(0.18)
Effect size %	2.30	3.20	3.00	3.60
	Undergraduate or higher			
$C_j^{1929} \times M_{jc}$	0.33**	0.45***	0.44***	0.49***
	(0.15)	(0.17)	(0.17)	(0.17)
Effect size %	3.10	4.10	4.00	4.60
Observations	378,317	378,317	378,317	378,317
Municipality FE	yes	yes	yes	yes
Birth year FE	yes	yes	yes	yes
County-by-byear FE	no	yes	yes	yes
Improved farmland^{1929} $\times$ byear FE	no	no	yes	yes
Farms p.c.^{1929} $\times$ byear FE	no	no	no	yes

Note.— This table shows the effect of the diffusion of milking machines on women's education. The sample includes women born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1930–1970. The dependent variable is a dummy variable equal to 100 if a woman achieved the education level indicated in each panel, or higher. The variable $C_j^{1929} \times M_{jc}$ is the interaction between the number of cows per farm in a woman's municipality of birth (j) in 1929 and the number of milking machines per farm in municipality j when she was aged 16–25 (c). This variable is normalized to have a mean of zero and an SD of one. Control variables are defined as in Table 1. Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 6: The diffusion of milking machines, educational investments, and migration decisions

	(1)	(2)	(3)	(4)	(5)	(6)
	migrates to: town with higher-edu. institution	town with higher-edu. institution	city	outside county	inside county	rural area
$C_j^{1929} \times M_{jc}$	0.79***	1.05***	1.12***	1.11***	-0.04	-0.05
	(0.30)	(0.36)	(0.36)	(0.35)	(0.29)	(0.29)
$C_j^{1929} \times M_{jc} \times$ municipality has voc. high-school in 1963	.	-0.36	-0.66	0.33	-0.44	0.54
		(0.47)	(0.48)	(0.46)	(0.37)	(0.35)
$C_j^{1929} \times M_{jc} \times$ municipality has gymnasium in 1963	.	-1.05*	-0.75	-1.11*	0.75	0.39
		(0.56)	(0.57)	(0.56)	(0.49)	(0.46)
$C_j^{1929} \times M_{jc} \times$ municipality has higher-education in 1963	.	-4.11*	-3.31*	-2.89	-0.74	-0.32
		(2.18)	(1.86)	(2.77)	(1.61)	(3.07)
Observations	353,239	353,239	369,030	369,030	369,030	369,030
R-squared	0.06	0.06	0.04	0.08	0.08	0.04
Municipality FE	yes	yes	yes	yes	yes	yes
Birth year FE	yes	yes	yes	yes	yes	yes
County-by-byear FE	yes	yes	yes	yes	yes	yes
Impr. farmland^{1929} $\times$ byear FE	yes	yes	yes	yes	yes	yes
Farms p.c.^{1929} $\times$ byear FE	yes	yes	yes	yes	yes	yes
Mean dep. variable	32.90	32.90	37.72	40.41	31.37	28.68
Effect size %	-20.20	-20.20	-20.80	-17.80		

NOTE.— This table shows the effect of the diffusion of milking machines on women's out-migration from rural areas, and the differential effect by a municipality's school infrastructure in 1963. The sample includes women born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1930, 1940, 1950, 1960, or 1970. Women in municipalities with no information on the school structure are excluded. The dependent variable is a dummy variable equal to 100 if a woman moved out of her birthplace into a town with higher-education institution (*Høyskole* or university) (Columns 1–2), to a city (Column 3), outside (Column 4), and inside (Column 5) their county of birth, or to another rural municipality (Column 6). The variable C_j^{1929} is the number of cows per farm in 1929 in a woman's municipality of birth (j). The variable M_{jc} is the number of milking machines per farm in a woman's municipality of birth j when she was aged 16–25 (c). The interaction between these two variables, $C_j^{1929} \times M_{jc}$, is our treatment-intensity measure and is normalized to have a mean of zero and an SD of one. Triple interactions between $C_j^{1929} \times M_{jc}$ and a municipality's school structure in 1963 capture, respectively, the differential effect of the diffusion of milking machines in towns with (a) at least one vocational high-school (*Yrkesskole*) in 1963, (b) at least one gymnasium in 1963, and (c) at least one higher-education institution (*Høyskole* or university) in 1963. Control variables are defined as in Table 1. Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 7: The diffusion of milking machines and women's employment in agriculture and migration decisions—Placebo experiment 1900–1910

	(1) works in agriculture	(2) works in husbandry	(3) works as servant	(4) migrates anywhere	(5) migrates to city
$C_j^{1929} \times M_{jc}$	-0.004	-0.001	-0.004	0.002	0.004
	(0.003)	(0.004)	(0.003)	(0.004)	(0.003)
Observations	279,261	279,261	279,261	279,261	279,261
R-squared	0.056	0.055	0.054	0.077	0.090
Municipality FE	yes	yes	yes	yes	yes
Birth year FE	yes	yes	yes	yes	yes
County-by-byear FE	yes	yes	yes	yes	yes
Mean(Y)	0.107	0.0776	0.227	0.455	0.211
Effect Size (%)	-4.048	-1.317	-1.694	0.395	2.101

NOTE.— This table uses data from the 1900 and 1910 censuses to show the placebo effect of backdating the substantial adoption of milking machines between 1950 and 1960 to the beginning of the 2oth century. It shows the placebo effect on whether a woman has a job related to farming (Columns 1-3) and who left their birthplace (Columns 4-5). The sample includes women at age 16–25 and, as in the main analysis, looks at their outcomes 10 years later (i.e., at the age of 25–35 in the 1900 and 1910 censuses). The variable C_j^{1929} is the number of cows per farm in 1929 in a woman's municipality of birth (j). The variable M_{jc} is the number of (placebo) milking machines per farm in a woman's municipality of birth j when she was aged 16–25 (c). The interaction between these two variables, $C_j^{1929} \times M_{jc}$, is our treatment-intensity measure. The treatment measure in 1900 and 1910 is assigned to their municipality of birth. All regressions include fixed effects for a woman's municipality of birth and birth year, and county-by-birth year fixed effects. Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 8: The diffusion of milking machines and tractors, results for both sexes

	(1) works in agriculture	(2) migrates to city	(3) income rank	(4) high skill	(5) low skill	(6) med skill	(7) edu $\geq$ upper secondary)
$C_j^{1929} \times M_{jc}$	-1.00***	1.25***	0.51***	0.20	-0.66**	-0.22	0.59**
	(0.32)	(0.38)	(0.16)	(0.18)	(0.30)	(0.26)	(0.26)
$C_j^{1929} \times M_{jc} \times man$	1.32***	-0.54	-0.62***	-0.78**	0.62*	1.10**	-0.44
	(0.38)	(0.37)	(0.22)	(0.31)	(0.36)	(0.46)	(0.31)
$H_j^{1929} \times T_{jc}$	-1.17***	-0.68	0.37**	0.31	-0.02	0.17	-0.18
	(0.32)	(0.49)	(0.17)	(0.19)	(0.37)	(0.29)	(0.26)
$H_j^{1929} \times T_{jc} \times man$	-1.23***	0.16	-0.46	-0.11	0.37	-0.25	0.21
	(0.46)	(0.34)	(0.37)	(0.39)	(0.40)	(0.53)	(0.44)
Observations	729,723	729,723	690,989	633,686	633,686	633,686	724,200
R-squared	0.11	0.05	0.34	0.07	0.12	0.18	0.14
Effect $C_j^{1929} \times M_{jc}$ for men	.318	.71	-.114	-.585	-.046	.873	.15
p-value	0.39	0.055*	0.571	0.08*	0.743	0.041**	0.604
Man	yes	yes	yes	yes	yes	yes	yes
Municipality $\times$ man FE	yes	yes	yes	yes	yes	yes	yes
Birth year FE	yes	yes	yes	yes	yes	yes	yes
County $\times$ byear $\times$ man FE	yes	yes	yes	yes	yes	yes	yes
Imp. farmland^{1929} $\times$ byear FE	yes	yes	yes	yes	yes	yes	yes
Farms p.c.^{1929} $\times$ byear FE	yes	yes	yes	yes	yes	yes	yes
Mean dep. variable	13.16	35.11		19.15	22.27	35.51	23.37

NOTE.— This table shows the effect of the diffusion of milking machines on various outcomes for men and women, accounting for the diffusion of tractors. The variable $C_j^{1929} \times M_{jc}$ is the interaction between the cows per farm in an individual's municipality of birth (j) in 1929 and milking machines per farm in the municipality when he/she was aged 16–25 (c). The variable $H_j^{1929} \times T_{jc}$ is the corresponding interaction between the number of horses per farm in 1929 and the number of tractors per farm when he/she was aged 16–25. These two variables are normalized to have a mean of zero and an SD of one. The variable *man* indicates whether the individual under analysis is a man. Control variables are defined as in Table 1. The sample includes men and women born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1930, 1940, 1950, 1960, or 1970. Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 9: The diffusion of milking machines and education for the following generation

	(1)	(2)	(3)	(4)
	Upper secondary, final edu. or higher			
$C_j^{1929} \times M_{jc}$	0.74***	0.37**	0.42***	0.31**
	(0.20)	(0.15)	(0.15)	(0.15)
Effect size %	1.20	0.60	0.70	0.50
	Post-secondary education or higher			
$C_j^{1929} \times M_{jc}$	0.51**	0.29*	0.34**	0.26
	(0.20)	(0.16)	(0.16)	(0.16)
Effect size %	1.50	0.80	1.00	0.80
	Undergraduate or higher			
$C_j^{1929} \times M_{jc}$	0.38**	0.25	0.29*	0.24
	(0.18)	(0.15)	(0.15)	(0.16)
Effect size %	1.30	0.80	1.00	0.80
Observations	770,469	770,469	770,469	770,469
Child's birth year FE	yes	yes	yes	yes
Child's gender FE	yes	yes	yes	yes
Mother: municipality FE	yes	yes	yes	yes
Mother: birth year FE	yes	yes	yes	yes
Mother: county-by-byear FE	no	yes	yes	yes
Mother: imp. farmland^{1929} $\times$ byear FE	no	no	yes	yes
Mother: farms p.c.^{1929} $\times$ byear FE	no	no	no	yes

NOTE.— This table shows the effect of the diffusion of milking machines on the educational outcomes of the next generation (i.e., the children of the women in our baseline sample). The dependent variable is a dummy variable equal to 100 if a child achieved the educational level indicated in each panel, or higher. The variable $C_j^{1929} \times M_{jc}$ is the interaction between the number of cows per farm in the municipality of birth of women in our baseline sample in 1929 and the number of milking machines per farm in the municipality when she was aged 16–25. This variable is normalized to have a mean of zero and an SD of one. Control variables include fixed effects for the children's gender and birth year, as well as all control variables as defined in Table 1. The sample includes all children of the women in our baseline sample (i.e., women born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1930–1970). Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

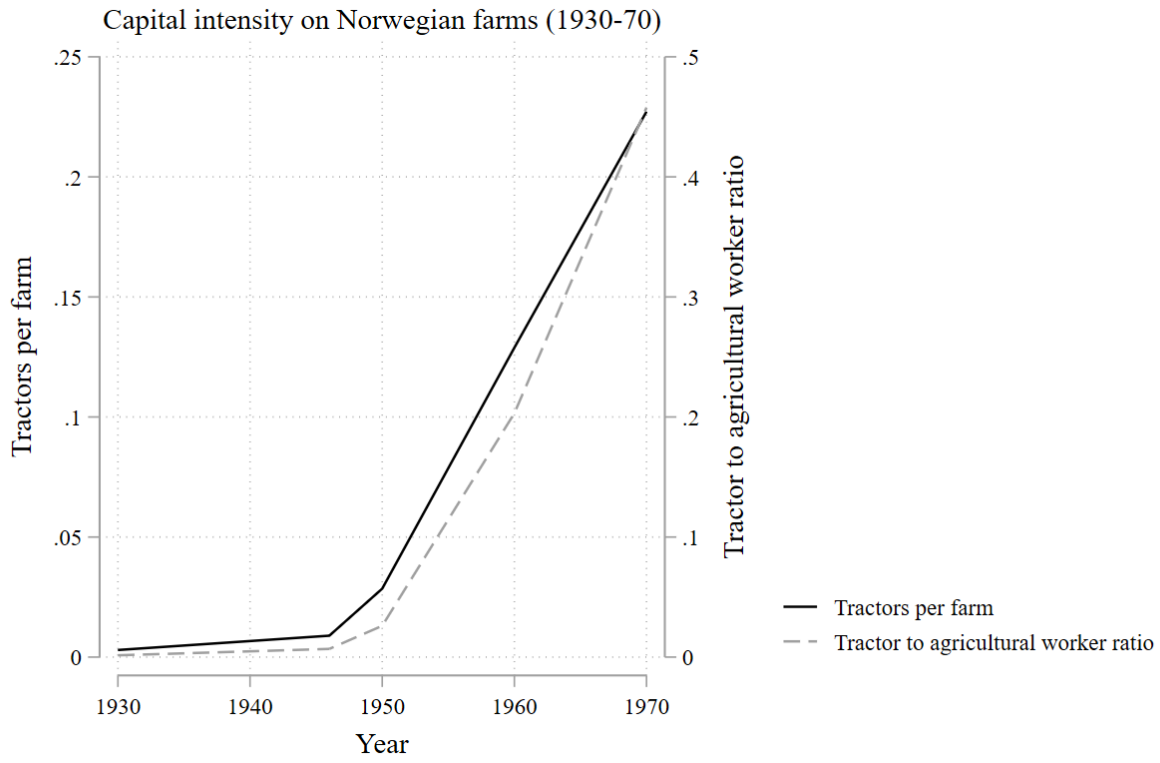
Table 10: The diffusion of milking machines and income for the following generation

	(1) income rank	(2) income rank	(3) income rank	(4) income rank
$C_j^{1929} \times M_{jc}$	0.17**	0.20***	0.24***	0.21***
	(0.08)	(0.07)	(0.07)	(0.07)
Observations	732,406	732,406	732,406	732,406
R-squared	0.14	0.14	0.14	0.14
Child's birth year FE	yes	yes	yes	yes
Child's gender FE	yes	yes	yes	yes
Mother: municipality FE	yes	yes	yes	yes
Mother: birth year FE	yes	yes	yes	yes
Mother: county-by-byear FE	no	yes	yes	yes
Mother: imp. farmland^{1929} $\times$ byear FE	no	no	yes	yes
Mother: farms p.c.^{1929} $\times$ byear FE	no	no	no	yes

NOTE.— This table shows the effect of the diffusion of milking machines on the percentile income rank of the next generation (i.e., the children of the women in our baseline sample). The dependent variable is the percentile income rank relative to all individuals born in the same year. Income is measured at age 40 and at age 30 for individuals born after 1980 (21.8 percent).The variable $C_j^{1929} \times M_{jc}$ is the interaction between the number of cows per farm in the municipality of birth of the women in our baseline sample in 1929 and the number of milking machines per farm in the municipality when she was aged 16–25. This variable is normalized to have a mean of zero and an SD of one. Control variables include fixed effects for the children's gender and birth year, as well as all control variables as defined in Table 1. The sample includes all children of women in our baseline sample (i.e., women born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1930–1970). Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Appendix Figures and tables

Figure 1: Capital intensity in agriculture (1930–1970)



Note.— This figure shows the evolution of tractors per farm (left vertical axis) and the ratio of tractor to agricultural worker (right vertical axis) in Norway between 1930 and 1970. Source: Census of Agriculture (own calculations).

Figure 2: Milk yields per cow (1927/28–1969)

Tabell 8. Mjølkemengd pr. ku og egg pr. høne. Kilo. Heile landet *Milk yield per cow and eggs per hen. Kilos. The whole country*

Husdyrprodukt *Livestock product*	1927-28	1930	1935	1939-40	1949-50	1954-55	1959-60	1964	1969
Mjølk pr. ku *Milk per cow* ..	1 534[1)]	1 620	1 698	1 761	2 092	2 314	2 681	3 139	4 027
Egg pr. høne *Eggs per hen* ..	6,3	..	..	..	7,3	8,1	9,0	9,2	9,9

1) 1925.

NOTE.— This figure shows the evolution of milk yields per cow from 1927-28 to 1969. Source: Central Bureau of Statistics of Norway (1974, Table 8).

Figure 3: Labor input on agricultural holdings (1928–29 to 1965–66)

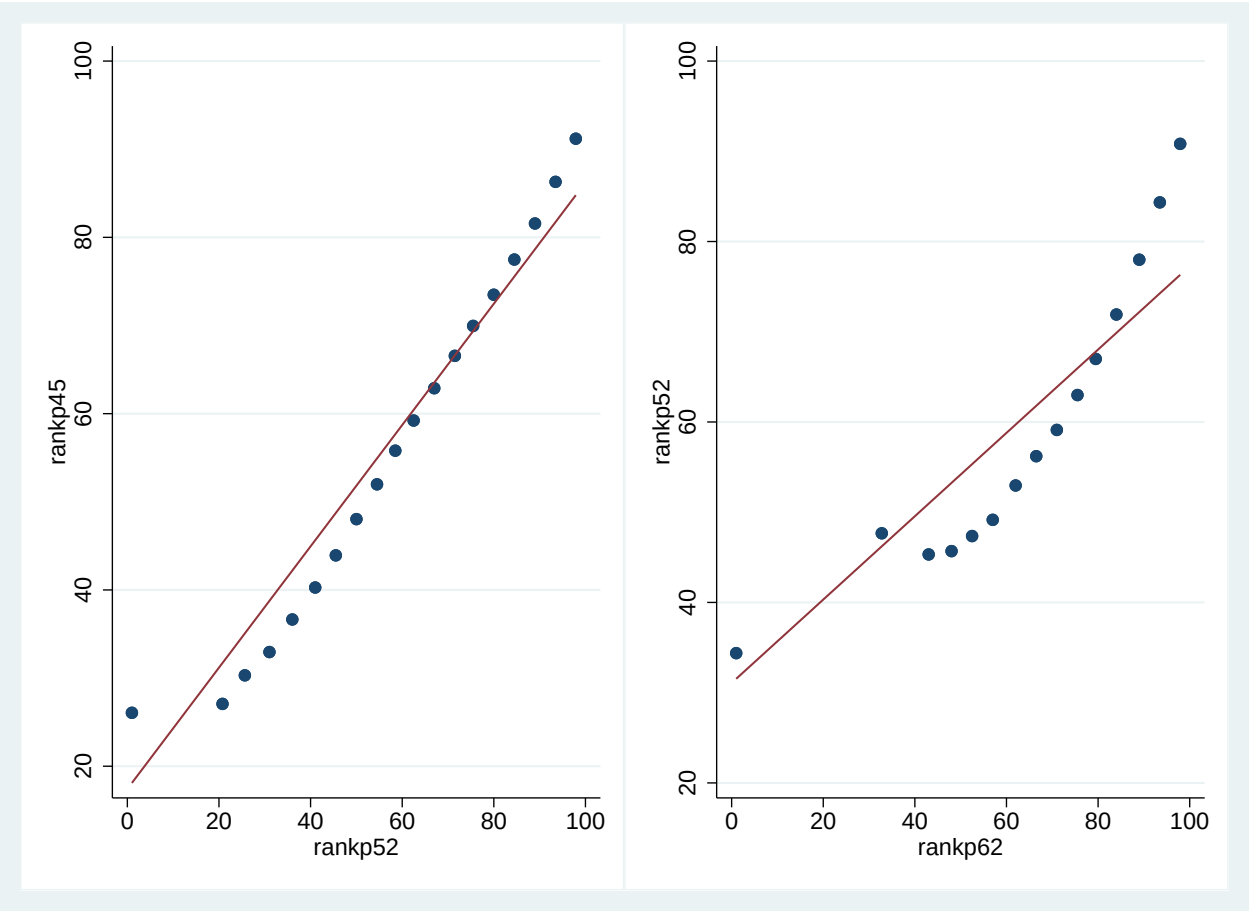
Tabell 78. Arbeidskraft på brukene. Årsverk.
Labour input on holdings. Man-years.

År *Year*	I alt *Total*		Brukere og ektemaker *Holders and their spouses*		Andre familiemedlemmer *Other family members*		Fremmed arbeidshjelp *Hired workers*	
	Menn *Males*	Kvinner *Females*	Menn *Males*	Kvinner *Females*	Menn *Males*	Kvinner *Females*	Menn *Males*	Kvinner *Females*
	Årsverk i alt[1] *Total man-years*[1]							
1928—29	257 513	311 742	124 390	172 265	86 945	92 872	46 178	46 605
1938—39	276 266	313 037	131 151	174 301	91 134	92 745	53 981	45 991
1948—49	236 959	277 001	132 950	177 600	67 729	75 791	36 280	23 610
1951—52	213 200	258 800	131 600	179 100	55 000	62 900	26 600	16 800
1953—54	195 400	241 800	125 600	175 200	48 400	53 300	21 400	13 300
1955—56	191 100	232 300	123 400	170 800	47 900	49 400	19 800	12 100
1958—59	178 621	205 850	117 295	159 437	38 694	36 612	22 632	9 801
1961—62	164 031	196 925	108 126	158 541	37 456	31 142	18 449	7 242
1965—66	141 787	169 764	99 383	142 516	28 718	22 304	13 686	4 944
	Av dette i jordbruket[2] *Of which in agriculture*[2]							
1958—59	159 522	69 808	106 420	45 254	36 291	18 765	16 811	5 789
1961—62	147 714	66 224	98 599	45 804	35 285	16 118	13 830	4 302

Noter [1] Medregnet arbeid i egen skog og husarbeid. [2] Ikke medregnet skogs- og husarbeid.
Notes [1] Including forestry and household work. [2] Excluding forestry and household work.

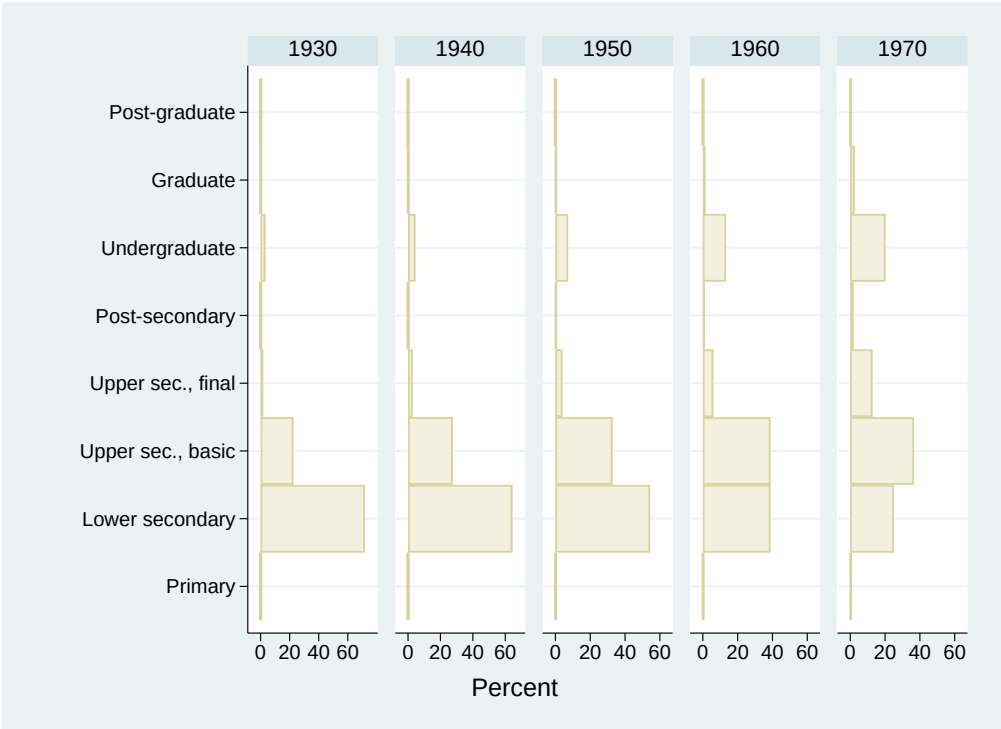
NOTE.— This figure shows the labor input on farms by gender and by type of worker (holders and spouses, other family members, and hired workers) for the years 1928-29 to 1965-66. Source: Central Bureau of Statistics of Norway (1968, Table 78).

Figure 4: Comparison of income ranks based on income at ages 45, 52, and 62



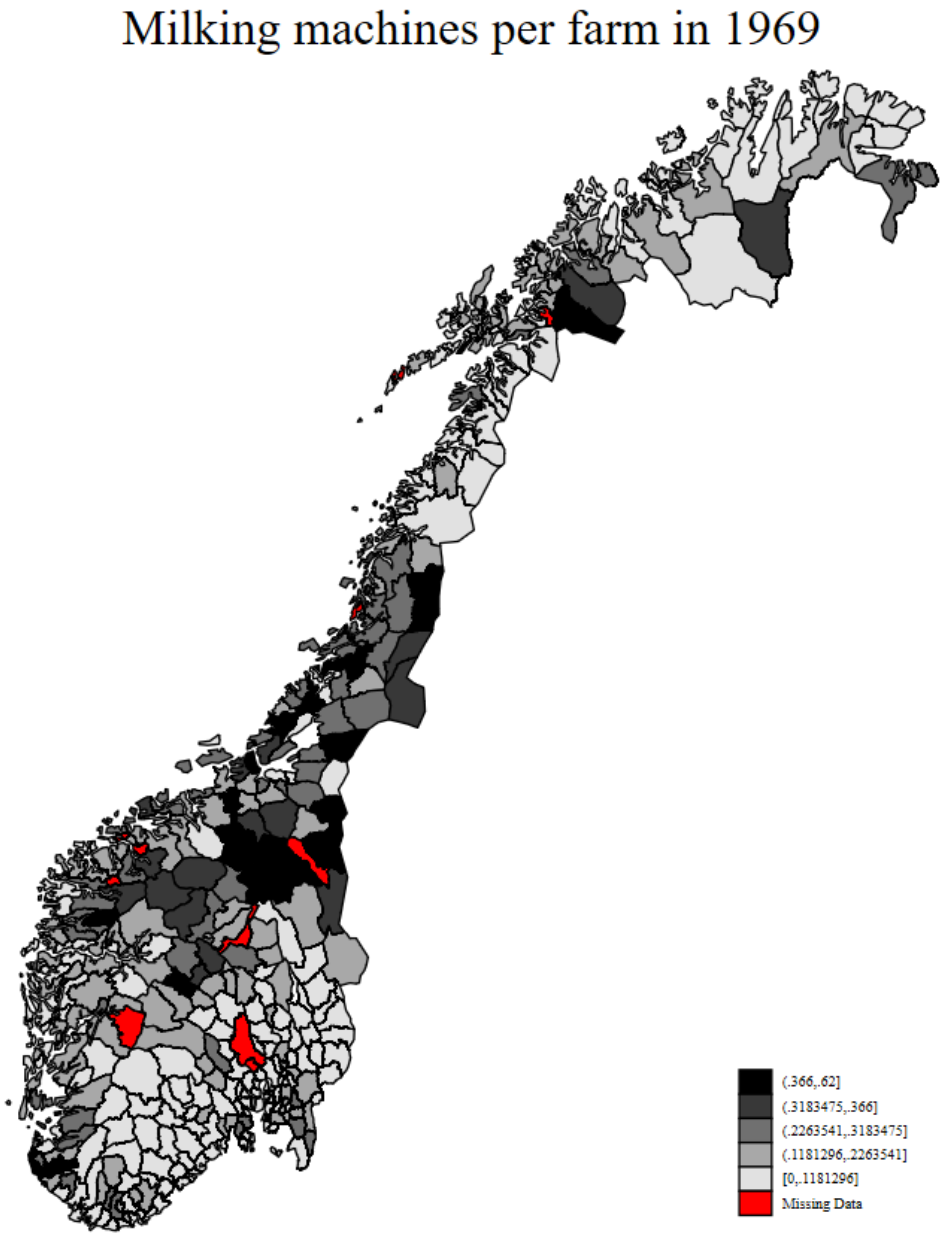
Note: Income ranks calculated over birth-year cohorts for all women in our baseline sample with income data at ages 45, 52, and 62.

Figure 5: Education distribution over time (1930–1970)



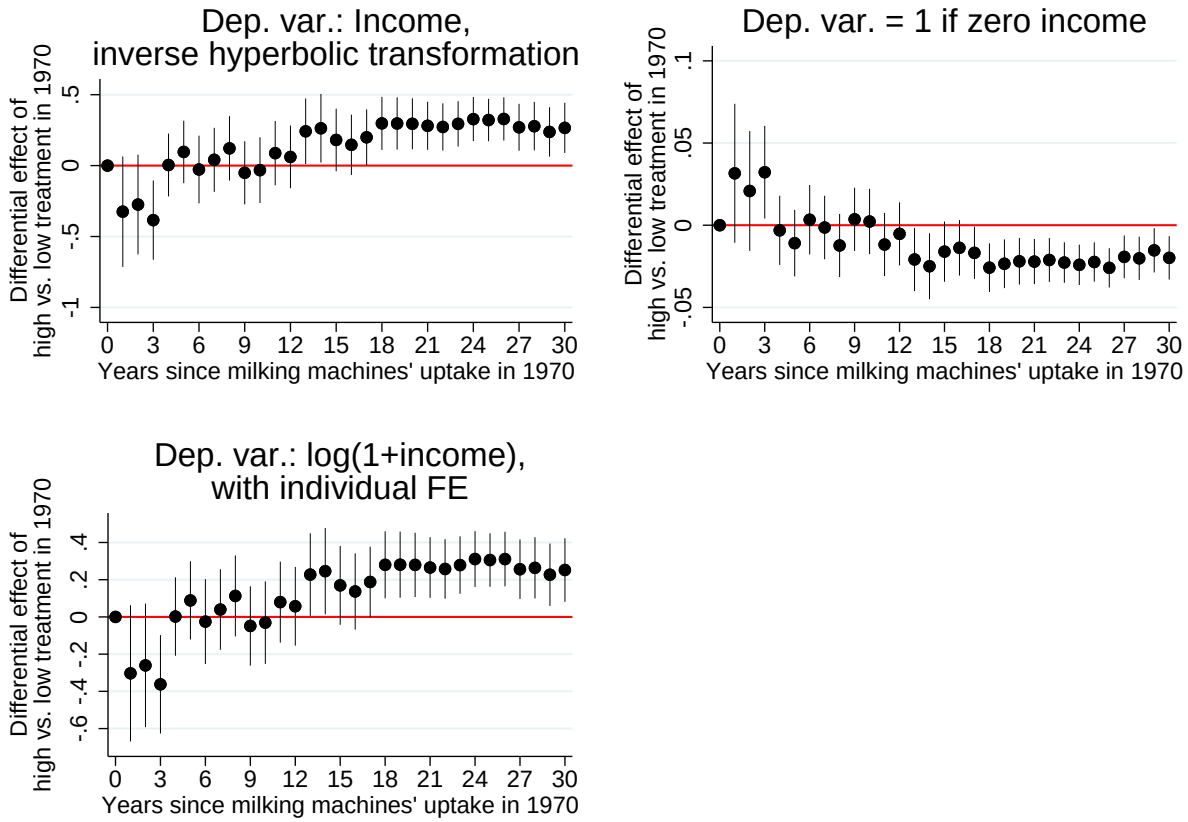
Sample: This figure plots the education distribution of rural women aged 16–25 in 1930, 1940, 1950, 1960, and 1970.

Figure 6



NOTE.— This figure shows the distribution of milking machines per farm in 1969 across Norwegian municipalities. A darker color refers to higher values of milking machines per farm. Red polygons denote missing observations. Source: Census of Agriculture (own calculations).

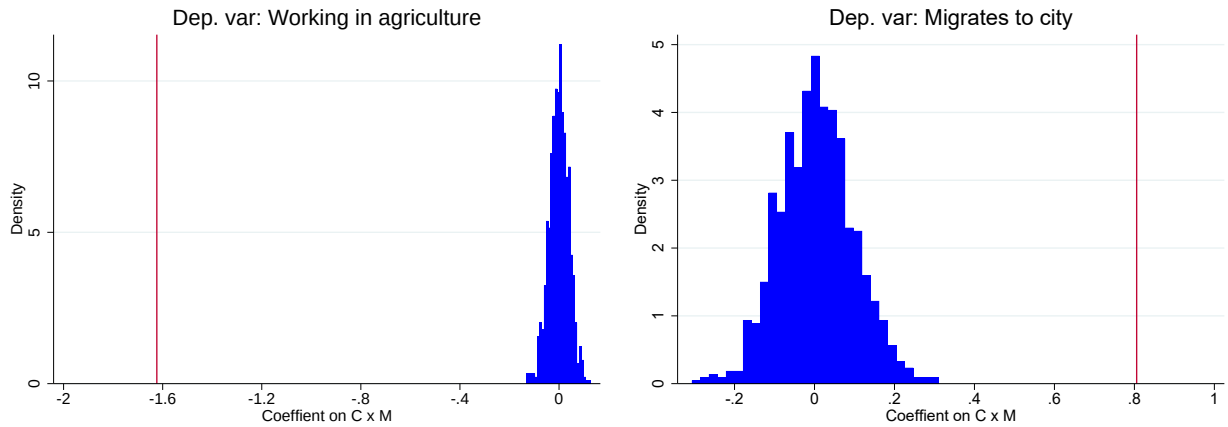
Figure 7: Robustness checks for contemporaneous effects—Year-by-year evolution of young women's incomes, by treatment intensity in 1970



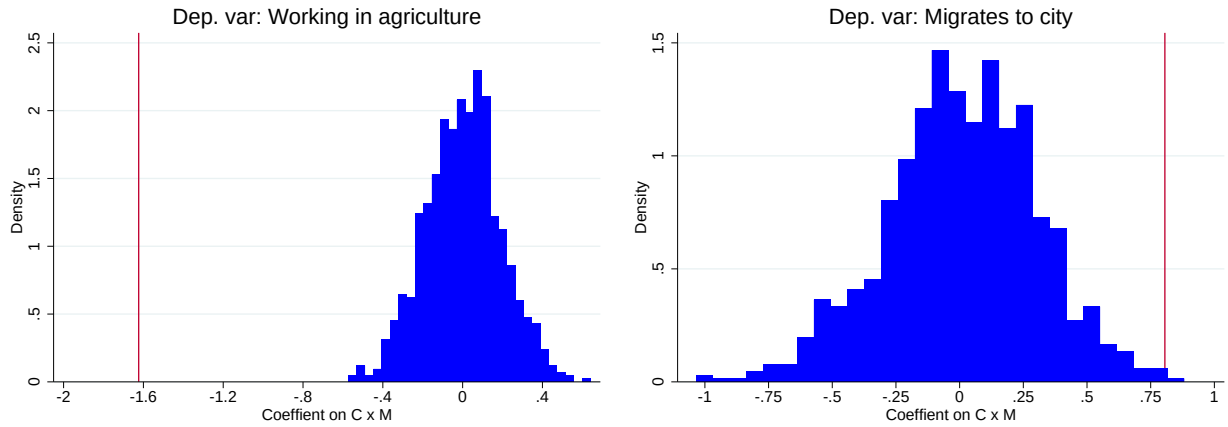
NOTE.— This figure plots estimates and 95% confidence intervals of γ_t from alternative specifications of Equation (9). The top-left panel uses the inverse hyperbolic transformation of income as the dependent variable. The top-right panel uses an indicator for zero income as the dependent variable. The bottom panel uses our baseline dependent variable (i.e., $log(1 + income)$) but adds individual fixed effects to Equation (9) (instead of the municipality fixed effects). As before, the sample is a panel of 8,935 women in rural municipalities who turned 16 in 1970 and their incomes over 30 years, from 1970 to 2000. Standard errors are clustered by municipality.

Figure 8: Permutation test—Results Table 1 (Column 4) and Table 2 (Column 2)

PANEL A: Without keeping roll-out structure



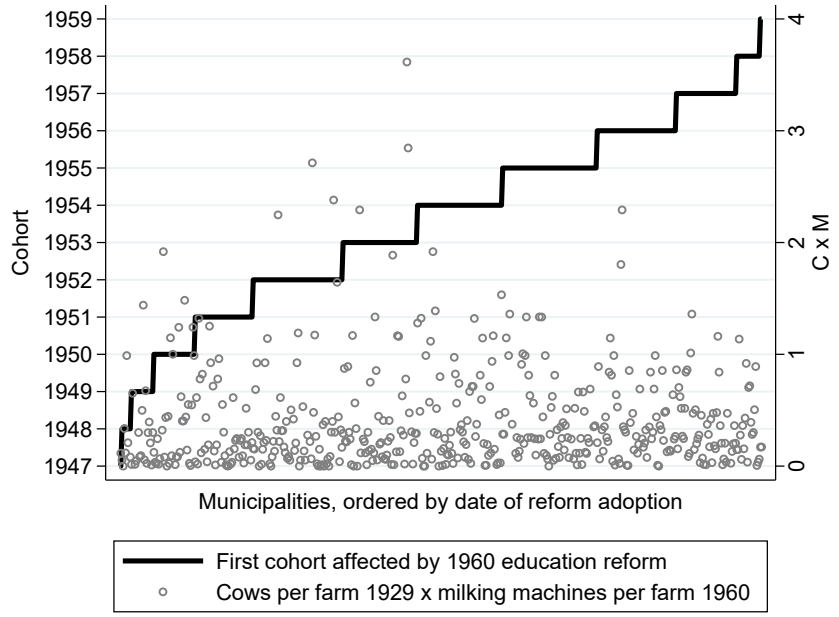
PANEL B: Keeping roll-out structure



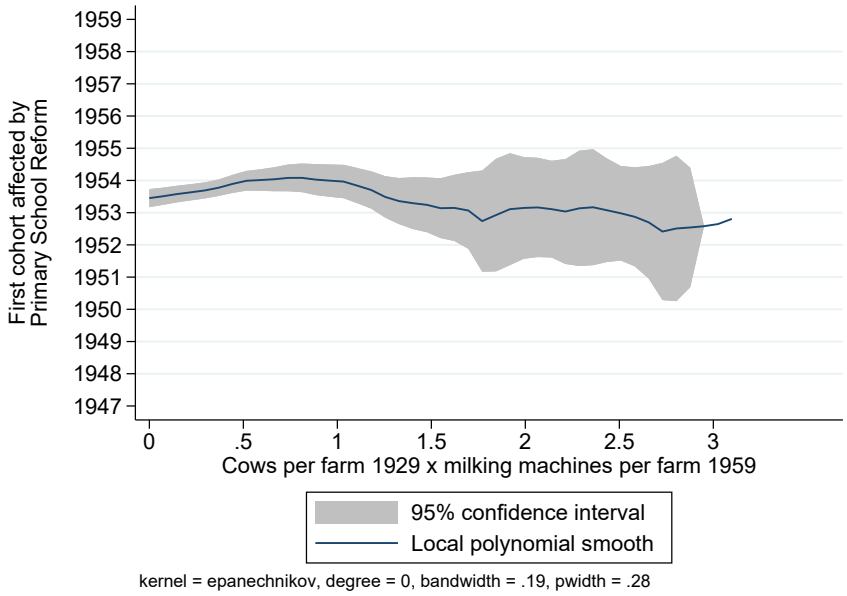
NOTE.— The figure displayed in Panel A shows the distribution of coefficients for the treatment effect ($C_{j'}^{1929} \times M_{j',c}$) in 1,000 placebo regressions, where $C_{j*}^{1929} \times M_{j*,c}$ is permuted among all rural municipalities j within age cohorts. The figure displayed in Panel B shows the distribution of coefficients for the treatment effect ($C_{j'}^{1929} \times M_{j',c}$) in 1,000 placebo regressions, where $C_{j*}^{1929} \times M_{j*,c}$ is permuted among all municipalities j. All regressions include the full set of fixed effects and controls as in Table 1 (Column 4) and Table 2 (Column 2). The permutation test is based on our baseline sample of N=381,002 women. The red line indicates our main estimate. All coefficients are standardized.

Figure 9: The roll-out of the Primary School Reform and the diffusion of milking machines across municipalities

PANEL A. Scatter plot



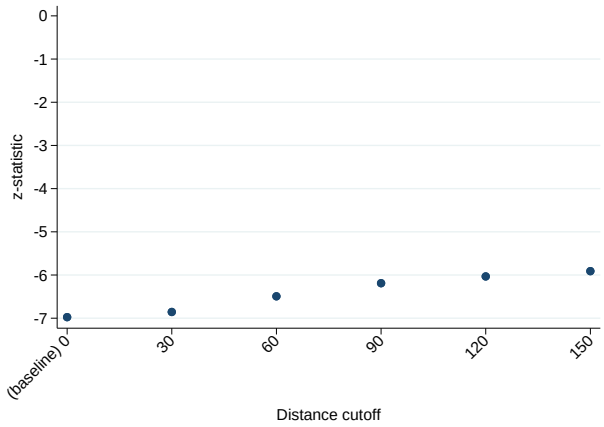
PANEL B. Local polynomial smooth



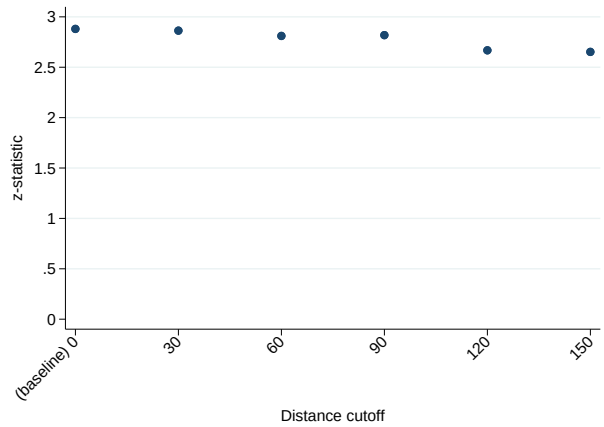
NOTE.— The sample consists of 497 municipalities based on their 1960 borders, with at least one farm in 1929. Data on the first cohort affected by the Primary School Reform in each municipality is from Black et al. (2005).

Figure 10: Conley Standard Errors with different distance cutoffs

PANEL A: Conley SE for point estimate of Table 1 (Column 4)

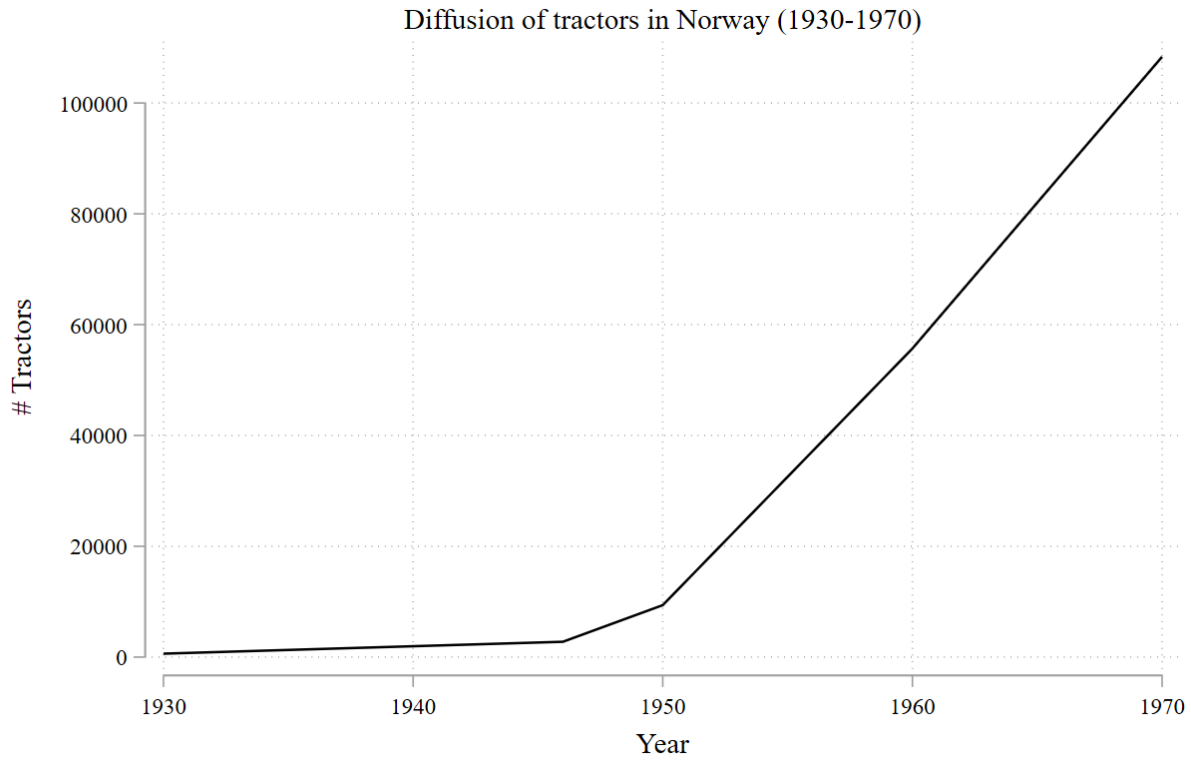


PANEL B: Conley SE for point estimate of Table 2 (Column 2)



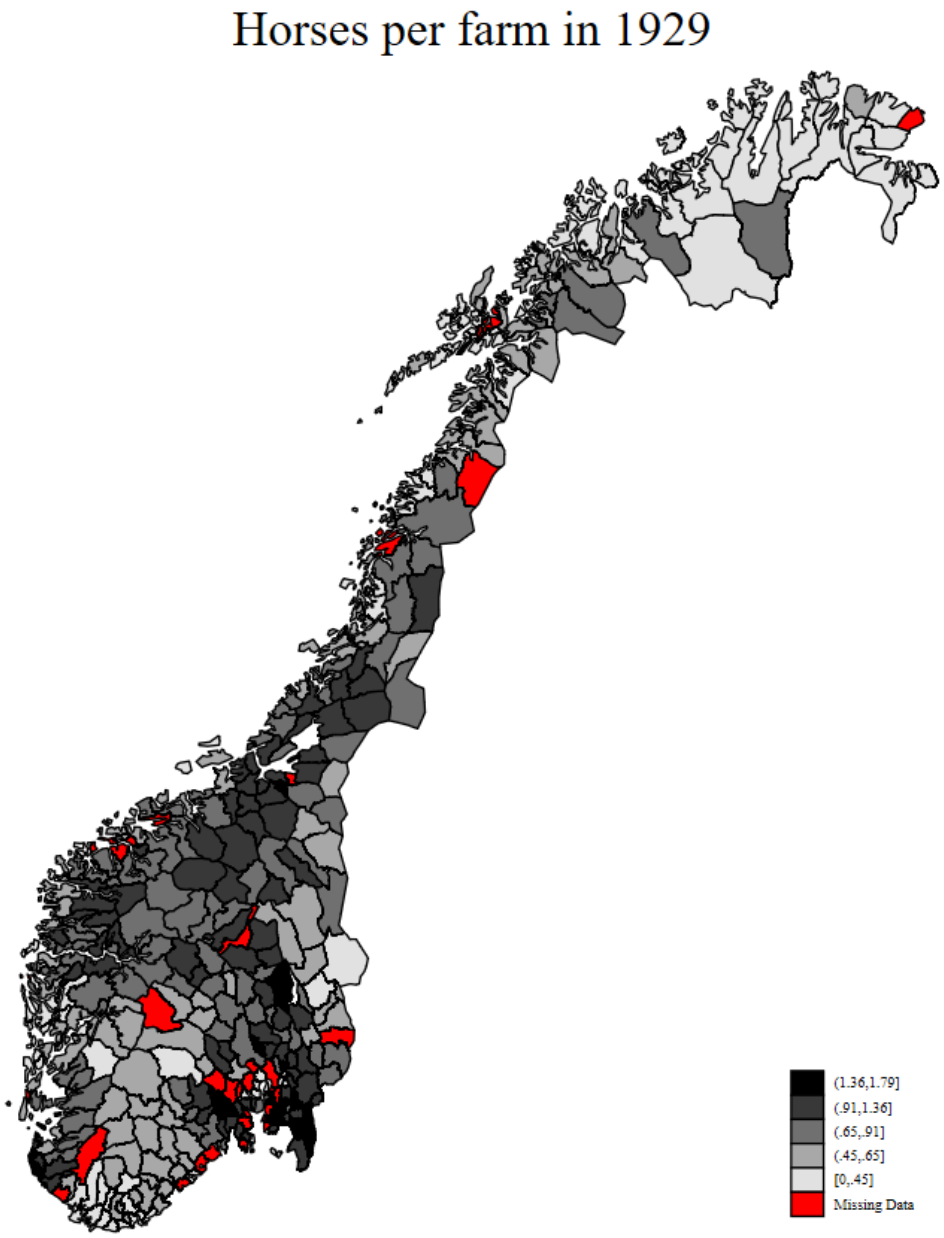
NOTE.— The figures in Panels A and B show spatially-adjusted z-statistics for the treatment effect ($C_j^{1929} \times M_{jc}$) in our baseline specifications with the full set of FE and controls and the full sample (N=381,002); see Tables 1 and 2 for further details. The baseline cutoff is the point at which the spatial error correlation is assumed to be 0; calculated using `acreg` (Colella et al. 2019).

Figure 11



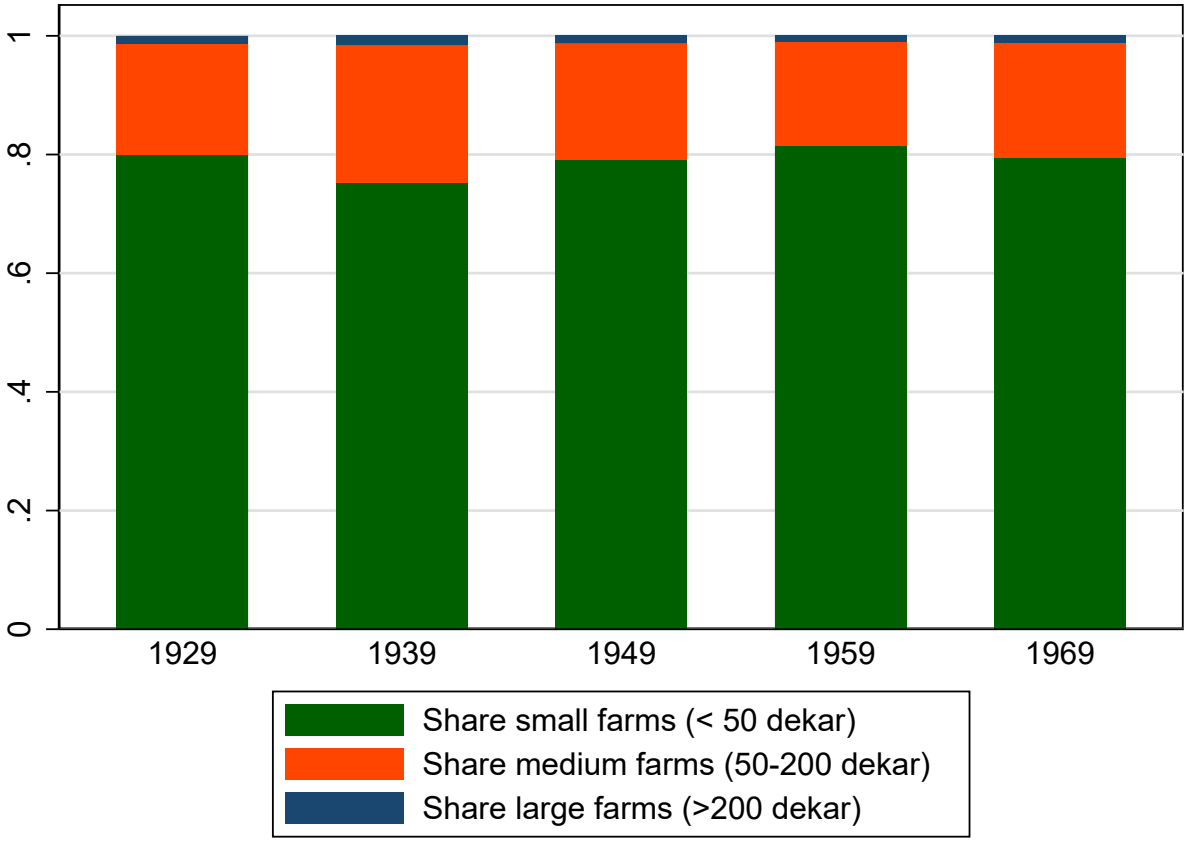
NOTE.— This figure shows the number of tractors in Norway from 1930 to 1970. Source: Census of Agriculture (own calculations).

Figure 12



Note.— This figure shows the distribution of horses per farm in 1929 across Norwegian municipalities. A darker color refers to higher values of horses per farm. Red polygons denote missing observations. Source: Census of Agriculture (own calculations).

Figure 13: Farm size distribution over time (1929–1969)



Note: This figure plots the distribution of farms by size (below 50 dekar, 50-200 dekar, and above 200 dekar). Source: Census of Agriculture (own calculations).

Table 1: Summary statistics for women in baseline sample

	Mean	Standard deviation	Observations
Technology diffusion in municipality of birth:			
Milking machines per farm	0.07	0.10	381,002
Milking machines per farm (cohort 16-25 in 1930)	0.00	0.00	45,316
Milking machines per farm (cohort 16-25 in 1940)	0.00	0.01	79,052
Milking machines per farm (cohort 16-25 in 1950)	0.02	0.03	78,337
Milking machines per farm (cohort 16-25 in 1960)	0.11	0.10	80,429
Milking machines per farm (cohort 16-25 in 1970)	0.15	0.12	97,868
Dairy cows per farm in 1929	3.08	1.24	381,002
Tractors per farm	0.12	0.16	381,002
Horses per farm in 1929	0.70	0.36	381,002
Outcomes for all women:			
Percent working in agriculture after age 25	9.13	28.80	381,002
Percent ever migrating	68.90	46.29	381,002
Percent ever migrating to urban area	37.80	48.49	381,002
Percent ever migrating to rural area	31.09	46.29	381,002
Percent ever migrating outside county	39.89	48.97	381,002
Percent ever migrating within county	29.00	45.38	381,002
Income at age 45† in NOK	64,971.81	82,444.24	344,459
Percent upper secondary education or more	16.83	37.41	378,317
Percent post-secondary education or more	11.50	31.90	378,317
Percent undergraduate education or more	10.78	31.01	378,317
Outcomes for women in non-agriculture occupation:			
Percent in high-skill occupation	12.46	33.03	346,215
Percent in mid-skill occupation	18.34	38.70	346,215
Percent in low-skill occupation	34.30	47.47	346,215
Municipality-level controls:			
Share improved farmland in 1929	0.70	0.24	381,002
Farms p.c. in 1929	0.13	0.04	381,002
Ratio large to small farms (contemporaneous)	0.07	0.25	379,654
Ratio large to small farms (in 1929)	0.12	0.24	381,002
Hydropower potential	0.43	0.78	366,416
Year of initial hydropower production	1912	5.35	98,889
Hydropower status in 1900-1910	0.07	0.26	368,277

Note.— This table shows summary statistics for our baseline sample: women born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1950, 1960, or 1970. †Income is measured at age 45 for cohorts aged 16–25 in 1950, 1960, and 1970 and at age 52 and 62 for the cohorts aged 16–25 in 1940 and 1930, respectively.

Table 2: Baseline municipality characteristics by average treatment intensity (1929–69)

Variables	(1) Pre-treatment Mean	(2) Levels	(3) Differences
Share females in agriculture	0.067	0.052***	-0.006
		(0.011)	(0.007)
Share females in non-agriculture	0.167	-0.007	0.005
		(0.008)	(0.006)
Share females in industry	0.027	-0.001	-0.004
		(0.003)	(0.003)
Share females in service	0.012	-0.001	0.001
		(0.001)	(0.001)
Female laborforce participation Rate	0.234	0.045***	-0.001
		(0.011)	(0.007)
Netmigration rate females	1.055	-0.039	0.041
		(0.025)	(0.039)
Farms per capita	0.137	0.021***	0.002
		(0.006)	(0.012)
Share improved farmland	0.684	0.304***	0.053
		(0.050)	(0.037)
Tractor per agricultural worker	0.002	0.001	
		(0.001)	
Average farmsize	39.12	45.184***	-6.150
		(5.736)	(4.073)
Share male age 15-19	0.101	-0.002	-0.004
		(0.003)	(0.003)
Share male age 20-39	0.289	-0.011**	-0.002
		(0.005)	(0.005)
Share females age 15-19	0.093	-0.003	0.001
		(0.003)	(0.003)
Share females age 20-39	0.273	0.000	0.003
		(0.005)	(0.004)
Population density	0.017	-0.018***	-0.003**
		(0.006)	(0.001)
Observations		366	366

NOTE.— Column 1 reports average baseline municipality characteristics in 1929/1930. All variables are reported in levels. Column 2 (3) reports the estimated coefficient of regressing the indicated municipality characteristic in 1929/1930 (the differences in the indicated municipality characteristics between 1919 and 1929) on treatment intensity (average 1929–1969). Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 3: Short-run effects of the diffusion of milking machines, using 1960 Census data

	(1) % of individuals in household who are employed	(2) % of individuals in household who are employed	(3) Student activity (100 = yes)	(4) Student activity (100 = yes)
$C_j^{1929} \times M_j^{1960}$	-0.23*	-0.27**	0.66*	0.71**
	(0.13)	(0.13)	(0.34)	(0.32)
Observations	73,375	73,375	77,163	77,163
R-squared	0.04	0.04	0.16	0.16
Municipality FE	no	no	no	no
Birth year FE	yes	yes	yes	yes
County-by-byear FE	yes	yes	yes	yes
Imp. farmland^{1929} × byear FE	no	yes	no	yes
Farms p.c.^{1929} × byear FE	no	yes	no	yes
Mean dep. variable	46.64	46.64	15.56	15.56
Effect size %	-0.50	-0.60	4.20	4.50

NOTE.— This table shows the short-run effect of the diffusion of milking machines in 1960 on the percentage of individuals employed in each household (in Columns 1-2) and on an indicator of student activity (100 = yes; 0 otherwise) (in Columns 3-4), both measured in the 1960 Census. The sample is a cross-section of women aged 16–25 in 1960 born in rural municipalities with at least one farm in 1929. Estimates are based on $Y_{ijc} = \beta_c + \gamma(C_j^{1929} \times M_j^{1960}) + \mathbf{X}'_{jc}\eta + \epsilon_{ijc}$, where i indexes women, j their municipality of birth, c their birth year. The variable $C_j^{1929} \times M_j^{1960}$ is the interaction between the number of cows per farm in 1929 and the number of milking machines per farm in 1960 in a woman's municipality of birth (j). The vector of control variables $\mathbf{X}$ is defined as in Table 1. Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 4: The diffusion of milking machines and women's employment in agriculture—Conditional on working

	(1) works in agriculture	(2) works in agriculture	(3) works in agriculture	(4) works in agriculture
$C_j^{1929} \times M_{jc}$	-2.10***	-2.10***	-2.19***	-1.79***
	(0.35)	(0.28)	(0.29)	(0.28)
Observations	260,190	260,190	260,190	260,190
R-squared	0.09	0.10	0.10	0.10
Municipality FE	yes	yes	yes	yes
Birth year FE	yes	yes	yes	yes
County-by-byear FE	no	yes	yes	yes
Improved farmland^{1929} $\times$ byear FE	no	no	yes	yes
Farms p.c.^{1929} $\times$ byear FE	no	no	no	yes
Mean dep. variable	13.37	13.37	13.37	13.37
Effect size %	-15.70	-15.70	-16.40	-13.40

Note.— This table shows the effect of the diffusion of milking machines on whether women worked in agriculture after the treatment conditional on working. The sample includes all working women born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1930, 1940, 1950, 1960, or 1970. The dependent variable is a dummy variable equal to 100 if a woman is employed in the agricultural sector after the age of 25. The variable C_j^{1929} is the number of cows per farm in 1929 in a woman's municipality of birth (j). The variable M_{jc} is the number of milking machines per farm in a woman's municipality of birth j when she was aged 16–25 (c). The interaction between these two variables, $C_j^{1929} \times M_{jc}$, is our treatment-intensity measure. All regressions include fixed effects for a woman's municipality of birth and birth year. We further include county-by-birth year fixed effects (Columns 2-4), the share of improved farmland in 1929 (columns 3-4), and the number of farms per capita in 1929 (Column 4) in each municipality interacted with the women's birth year indicators. Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 5: The diffusion of milking machines and women's income at ages 40–45

	(1) income>0 Age 40	(2) log(income+1) Age 40	(3) income>0 Age 45	(4) log(income+1) Age 45
$C_j^{1929} \times M_{jc}$	1.19***	0.12***	0.91***	0.11***
	(0.28)	(0.03)	(0.22)	(0.02)
Observations	234,732	234,732	234,732	234,732
R-squared	0.19	0.27	0.07	0.014
Municipality FE	yes	yes	yes	yes
Birth year FE	yes	yes	yes	yes
County-by-byear FE	yes	yes	yes	yes
Improved farmland^{1929} × byear FE	yes	yes	yes	yes
Farms p.c.^{1929} × byear FE	yes	yes	yes	yes

Note.— This table shows the effect of the diffusion of milking machines on women's income at the age of 40–45. The sample includes women born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1950, 1960, or 1970, and whose income at ages 40 and 45 is listed in the tax registry (1967–2010). The dependent variable is a dummy variable equal to 100 if a woman reported any income at age 40 (Column 1) or 45 (Column 3), and log(income +1) at age 40 (Column 2) and at age 45 (Column 4). The variable C_j^{1929} is the number of cows per farm in 1929 in a woman's municipality of birth (j). The variable M_{jc} is the number of milking machines per farm in a woman's municipality of birth j when she was aged 16–25 (c). The interaction between these two variables, $C_j^{1929} \times M_{jc}$, is our treatment-intensity measure. This variable is normalized to have a mean of zero and an SD of one. All regressions include fixed effects for a woman's municipality of birth and birth year, county-by-birth year fixed effects, and the share of improved farmland in 1929 and the number of farms per capita in 1929 in each municipality interacted with women's birth year indicators. Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 6: Decomposition of the income effect by mover status

	(1) income>0 Age 40	(2) ln(income+1) Age 40	(3) income>0 Age 45	(4) ln(income+1) Age 45
Stayers (omitted)	-	-	-	-
Migrates to rural	1.76***	0.23***	1.34***	0.23***
	(0.34)	(0.04)	(0.25)	(0.03)
Migrates to urban	6.04***	0.79***	3.73***	0.63***
	(0.39)	(0.04)	(0.29)	(0.04)
Observations	234,732	234,732	234,732	234,732
R-squared	0.20	0.27	0.07	0.15
Municipality FE	yes	yes	yes	yes
Birth year FE	yes	yes	yes	yes
County-by-byear FE	yes	yes	yes	yes
Imp. farmland^{1929} $\times$ byear FE	yes	yes	yes	yes
Farms p.c.^{1929} $\times$ byear FE	yes	yes	yes	yes

Note.— This table decomposes the income effect by mover status. The sample includes women born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1950, 1960, or 1970, and whose income at ages 40 and 45 is listed in the tax registry (1967–2010). The dependent variable is a dummy variable equal to 100 if a woman reported any income at age 40 (Column 1) or 45 (Column 3), and log(income +1) at age 40 (Column 2) and at age 45 (Column 4). The variable "Stayers" is the omitted category, "Migrate to rural" is a dummy variable equal to one if the woman moved from her birthplace to another rural municipality, and "Migrate to urban" is a dummy variable equal to one if the woman moved from her birthplace to an urban town. All regressions include fixed effects for a woman's municipality of birth and birth year, county-by-birth year fixed effects, and the share of improved farmland in 1929 and the number of farms per capita in 1929 in each municipality interacted with the women's birth year indicators. Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 7: Robustness to the roll-out of the Primary School Reform (1960-72)

	(1) works in agriculture	(2) migrates to city	(3) income rank	(4) high skill	(5) med skill	(6) low skill	(7) edu $\geq$ upper secondary
$C_j^{1929} \times M_{jc}$ (national)	-1.51***	0.67**	0.73***	0.44***	-0.24	-0.56**	0.52**
	(0.25)	(0.31)	(0.13)	(0.15)	(0.20)	(0.22)	(0.24)
$Primary\ School\ Reform_{jc}$	-0.08	2.17***	0.40	0.38	0.81	-1.18*	2.16***
	(0.38)	(0.81)	(0.32)	(0.51)	(0.52)	(0.61)	(0.68)
Observations	316,669	316,669	285,923	289,519	289,519	289,519	314,438
R-squared	0.06	0.04	0.10	0.03	0.02	0.03	0.12
Municipality FE	yes	yes	yes	yes	yes	yes	yes
Birth year FE	yes	yes	yes	yes	yes	yes	yes
County-by-byear FE	yes	yes	yes	yes	yes	yes	yes
Imp. farmland^{1929}×byear FE	yes	yes	yes	yes	yes	yes	yes
Farms p.c.^{1929}×byear FE	yes	yes	yes	yes	yes	yes	yes
Mean dep. variable	8.57	38.28	.	12.24	18.45	34.24	16.59
Effect size %	-17.60	1.80	.	3.60	-1.30	-1.60	3.10

Note.— This table replicates the main results of Tables 1–5 controlling for the Primary School Reform roll-out between 1960 and 1972. The variable $Primary\ School\ Reform_{jc}$ is an indicator equal to one if women born in cohort c studied after their municipality of birth j fully implemented the Primary School Reform, and equal to zero if they studied under the pre-reform system. The sample is smaller than in Tables 1–5 because we exclude municipalities where we have no information on when the reform was implemented. Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 8: Modification of treatment (Tables 1–5)—Share of females in agriculture in 1930

	(1) works in agriculture	(2) migrates to city	(3) income rank	(4) high skill	(5) med skill	(6) low skill	(7) edu $\geq$ upper secondary
$\%Farming_j^{1930} \times M_{jc}$	-1.64***	0.77***	0.61***	0.32***	0.05	-0.64***	0.54***
	(0.25)	(0.28)	(0.13)	(0.12)	(0.20)	(0.18)	(0.18)
Observations	381,002	381,002	344,459	346,215	346,215	346,215	378,317
R-squared	0.07	0.04	0.11	0.03	0.02	0.03	0.12
Municipality FE	yes	yes	yes	yes	yes	yes	yes
Birth year FE	yes	yes	yes	yes	yes	yes	yes
County-by-byear FE	yes	yes	yes	yes	yes	yes	yes
Imp. farmland^{1929}×byear FE	yes	yes	yes	yes	yes	yes	yes
Farms p.c.^{1929}×byear FE	yes	yes	yes	yes	yes	yes	yes
Mean dep. variable	9.13	37.80	.	12.46	18.34	34.30	16.83
Effect size %	-17.90	2.00	.	2.60	0.30	-1.90	3.20

Note.— This table replicates the main results of Tables 1–5 using the 1930 municipality share of females in agriculture in a woman's municipality of birth (j) interacted with the number of milking machines per farm in a woman's municipality of birth j when she was aged 16–25 (c) as a measure of treatment intensity. Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 9: Modification of treatment (Tables 1–5)—Share of female servants in 1930

	(1) works in agriculture	(2) migrates to city	(3) income rank	(4) high skill	(5) med skill	(6) low skill	(7) edu $\geq$ upper secondary
$\%Servants_j^{1930} \times M_{jc}$	-1.36***	0.71**	0.58***	0.26**	0.12	-0.42**	0.43**
	(0.28)	(0.29)	(0.12)	(0.11)	(0.18)	(0.18)	(0.20)
Observations	381,002	381,002	344,459	346,215	346,215	346,215	378,317
R-squared	0.06	0.04	0.11	0.03	0.02	0.03	0.12
Municipality FE	yes	yes	yes	yes	yes	yes	yes
Birth year FE	yes	yes	yes	yes	yes	yes	yes
County-by-byear FE	yes	yes	yes	yes	yes	yes	yes
Imp. farmland^{1929}×byear FE	yes	yes	yes	yes	yes	yes	yes
Farm p.c.^{1929}×byear FE	yes	yes	yes	yes	yes	yes	yes
Mean dep. variable	9.13	37.80	.	12.46	18.34	34.30	16.83
Effect size %	-14.90	1.90	.	2.10	0.70	-1.20	2.50

Note.— This table replicates the main results of Tables 1–5 using the 1930 municipality share of female agricultural servants in a woman's municipality of birth (j) interacted with the number of milking machines per farm in a woman's municipality of birth j when she was aged 16–25 (c) as a measure of treatment intensity. Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 10: Modification of treatment (Table 7)—Share of females in agriculture in 1930

	(1) works in agriculture	(2) migrates to city	(3) income rank	(4) high skill	(5) low skill	(6) med skill	(7) edu ≥ upper secondary
$\%Farming_j^{1930} \times M_{jc}$	-1.18***	0.96***	0.40***	0.17	-0.65***	0.04	0.55***
	(0.27)	(0.34)	(0.15)	(0.14)	(0.23)	(0.25)	(0.20)
$\%Farming_j^{1930} \times M_{jc} \times man$	1.39***	-0.66**	-0.47***	-0.55**	0.62**	0.52	-0.36
	(0.28)	(0.32)	(0.17)	(0.26)	(0.25)	(0.38)	(0.27)
$H_j^{1929} \times T_{jc}$	-1.18***	-0.34	0.50***	0.34**	-0.11	-0.02	-0.08
	(0.24)	(0.44)	(0.15)	(0.17)	(0.32)	(0.26)	(0.24)
$H_j^{1929} \times T_{jc} \times man$	-1.15***	0.18	-0.62*	-0.33	0.43	0.25	0.11
	(0.38)	(0.29)	(0.32)	(0.34)	(0.36)	(0.48)	(0.39)
Observations	729,723	729,723	690,989	633,686	633,686	633,686	724,200
R-squared	0.11	0.05	0.34	0.07	0.12	0.18	0.14
Effect $\%Farming_j^{1930} \times M_{jc}$ for men	.212	.303	-.077	-.376	-.031	.561	.192
pvalue	0.515	0.403	0.647	0.16	0.76	0.13	0.435
Man	yes	yes	yes	yes	yes	yes	yes
Municipality × man FE	yes	yes	yes	yes	yes	yes	yes
Birth year FE	yes	yes	yes	yes	yes	yes	yes
County-by-byear × man FE	yes	yes	yes	yes	yes	yes	yes
Imp. farmland^{1929} × byear FE	yes	yes	yes	yes	yes	yes	yes
Farms p.c.^{1929} × byear FE	yes	yes	yes	yes	yes	yes	yes
Mean dep. variable	13.16	35.11		19.15	22.27	35.51	23.37

Note.— This table shows the effect of the diffusion of milking machines on various outcomes for men and women, accounting for the diffusion of tractors as in Table 6, but using the 1930 municipality share of females in agriculture in a woman's municipality of birth (j) interacted with the number of milking machines per farm in a woman's municipality of birth j when she was aged 16–25 (c) as a measure of treatment intensity. The variable $H_j^{1929} \times T_{jc}$ is the corresponding interaction between the number of horses per farm in 1929 and the number of tractors per farm when he/she was aged 16–25. The variable *man* indicates whether the individual under analysis is a man. Control variables are defined as in Table 1. The sample includes men and women born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1930, 1940, 1950, 1960, or 1970. Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 11: Modification of treatment (Table 7)—Share of female servants in 1930

	(1) works in agriculture	(2) migrates to city	(3) income rank	(4) high skill	(5) low skill	(6) med skill	(7) edu. (+USF)
$\%Servants_j^{1930} \times M_{jc}$	-0.95***	0.78**	0.41***	0.11	-0.37*	0.17	0.40*
	(0.32)	(0.33)	(0.14)	(0.12)	(0.21)	(0.21)	(0.22)
$\%Servants_j^{1930} \times M_{jc} \times man$	1.07***	-0.36	-0.46***	-0.37	0.33	0.25	-0.13
	(0.32)	(0.32)	(0.16)	(0.22)	(0.24)	(0.41)	(0.24)
$H_j^{1929} \times T_{jc}$	-1.39***	-0.17	0.52***	0.39**	-0.32	-0.09	0.04
	(0.24)	(0.43)	(0.14)	(0.16)	(0.32)	(0.25)	(0.24)
$H_j^{1929} \times T_{jc} \times man$	-0.86**	-0.05	-0.67**	-0.49	0.65*	0.45	-0.05
	(0.36)	(0.28)	(0.31)	(0.31)	(0.36)	(0.47)	(0.36)
Observations	729,723	729,723	690,989	633,686	633,686	633,686	724,200
R-squared	0.11	0.05	0.34	0.07	0.12	0.18	0.14
Effect $\%Servants_j^{1930} \times M_{jc}$ for men	.117	.424	-.049	-.258	-.035	.422	.268
pvalue	0.754	0.144	0.75	0.24	0.73	0.18	0.206
Man	yes	yes	yes	yes	yes	yes	yes
Municipality × man FE	yes	yes	yes	yes	yes	yes	yes
Birth year FE	yes	yes	yes	yes	yes	yes	yes
County-by-byear × man FE	yes	yes	yes	yes	yes	yes	yes
Imp. farmland^{1929} × byear FE	yes	yes	yes	yes	yes	yes	yes
Farms p.c.^{1929} × byear FE	yes	yes	yes	yes	yes	yes	yes
Mean dep. variable	13.16	35.11		19.15	22.27	35.51	23.37

Note.— This table shows the effect of the diffusion of milking machines on various outcomes for men and women, accounting for the diffusion of tractors as in Table 6, but using the 1930 municipality share of female agricultural servants in a woman's municipality of birth (j) interacted with the number of milking machines per farm in a woman's municipality of birth j when she was aged 16–25 (c) as a measure of treatment intensity. The variable $H_j^{1929} \times T_{jc}$ is the corresponding interaction between the number of horses per farm in 1929 and the number of tractors per farm when he/she was aged 16–25. The variable *man* indicates whether the individual under analysis is a man. Control variables are defined as in Table 1. The sample includes men and women born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1930, 1940, 1950, 1960, or 1970. Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 12: Modification of treatment (Tables 1–5)—National roll-out of milking machines

	(1) works in agriculture	(2) migrates to city	(3) income rank	(4) high skill	(5) med skill	(6) low skill	(7) edu $\geq$ upper secondary
$C_j^{1929} \times M_c$ (national)	-3.33***	2.55***	1.60***	1.20***	0.26	-1.29***	1.08***
	(0.37)	(0.62)	(0.22)	(0.25)	(0.33)	(0.41)	(0.38)
Observations	381,002	381,002	344,459	346,215	346,215	346,215	378,317
Municipality FE	yes	yes	yes	yes	yes	yes	yes
Birth year FE	yes	yes	yes	yes	yes	yes	yes
County-by-byear FE	yes	yes	yes	yes	yes	yes	yes
Imp. farmland^{1929}×byear FE	yes	yes	yes	yes	yes	yes	yes
Farms p.c.^{1929}×byear FE	yes	yes	yes	yes	yes	yes	yes
Mean dep. variable	9.13	29.0	.	12.46	18.34	34.3	16.8
Effect size (%)	-36.5	-1.5	.	9.7	1.4	-3.8	6.4

Note.— This table replicates the main results of Tables 1–5 using the number of cows per farm in 1929 in a woman's municipality of birth (j) interacted with the national number of milking machines per farm when a woman was aged 16–25(c) as a measure of treatment intensity. Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 13: The diffusion of milking machines and women's employment in agriculture—Comparing stratified samples

	(1) $M = 0$ in 1940	(2) $M > 0$ in 1940	(3) $M = 0$ in 1950	(4) $M > 0$ in 1950	(5) $M = 0$ in 1960	(6) $M > 0$ in 1960
Panel A. Dep. variable: works in agriculture						
$C_j^{1929} \times M_{jc}$	-1.68***	-1.62***	-1.74***	-1.64***	-1.74*	-1.66***
	(0.21)	(0.38)	(0.41)	(0.28)	(0.91)	(0.24)
Observations	215,941	165,061	107,024	273,977	10,287	370,709
R-squared	0.07	0.06	0.07	0.06	0.09	0.07
Mean dep. variable	9.87	8.16	9.33	9.05	6.76	9.20
Effect size %	-17.00	-19.90	-18.60	-18.10	-25.70	-18.00
Panel B. Dep. variable: migrates to city						
$C_j^{1929} \times M_{jc}$	0.68**	0.78*	0.35	0.82**	0.92***	0.84***
	(0.29)	(0.47)	(0.45)	(0.33)	(0.17)	(0.28)
Observations	215,941	165,061	107,024	273,977	10,287	370,709
R-squared	0.06	0.03	0.07	0.04	0.08	0.04
Mean dep. variable	9.87	8.16	9.33	9.05	6.76	9.20
Effect size %	6.90	9.60	3.80	9.00	13.60	9.10
Municipality FE	yes	yes	yes	yes	yes	yes
Birth year FE	yes	yes	yes	yes	yes	yes
County-by-byear FE	yes	yes	yes	yes	yes	yes
Imp. farmland^{1929} $\times$ byear FE	yes	yes	yes	yes	yes	yes
Farm pc^{1929} $\times$ byear FE	yes	yes	yes	yes	yes	yes

NOTE.— This table shows the effect of the diffusion of milking machines on whether women worked in agriculture after the treatment (Panel A) and migrated to cities (Panel B), comparing stratified samples. All samples include women born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1930, 1940, 1950, 1960, or 1970. Columns (1)-(2) compare the effect on 1940 switchers (women in municipalities with a positive number of milking machines in 1940) vs. the effect on non-switchers (women in municipalities with zero milking machines in 1940). Columns (3)-(4) and (5)-(6) compare the effects for switchers vs. non.switchers in 1950 and 1960, respectively. The dependent variable is a dummy variable equal to 100 if a woman is employed in the agricultural sector after the age of 25 (Panel A), and a dummy variable equal to 100 if a women moved out of her birthplace into a city. The variable C_j^{1929} is the number of cows per farm in 1929 in a woman's municipality of birth (j). The variable M_{jc} is the number of milking machines per farm in a woman's municipality of birth j when she was aged 16–25 (c). The interaction between these two variables, $C_j^{1929} \times M_{jc}$, is our treatment-intensity measure. All regressions include fixed effects for a woman's municipality of birth and birth year, county-by-birth year fixed effects, the share of improved farmland in 1929 and the number of farms per capita in 1929 in each municipality interacted with the women's birth year indicators. Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 14: The diffusion of milking machines and women's employment in agriculture—Controlling for farm size distribution

	(1) works in agriculture	(2) works in agriculture	(3) works in agriculture	(4) works in agriculture	(5) works in agriculture
$C_j^{1929} \times M_{jc}$	-1.62***	-1.32***	-1.62***	-1.75***	-1.65***
	(0.23)	(0.27)	(0.21)	(0.24)	(0.23)
Observations	381,002	381,002	381,002	381,002	379,654
R-squared	0.06	0.07	0.07	0.07	0.06
Municipality FE	yes	yes	yes	yes	yes
Birth year FE	yes	yes	yes	yes	yes
County-by-byear FE	yes	yes	yes	yes	yes
Imp. farmland^{1929} × byear FE	yes	yes	yes	yes	yes
Farms p.c.^{1929} × byear FE	yes	yes	yes	yes	yes
Farm distribution^{1929} × byear FE	no	yes	no	no	no
Farm distribution contemporaneous	no	no	yes	no	no
Ratio large/small farms^{1929} × byear FE	no	no	no	yes	no
Ratio large/small farms contemporaneous	no	no	no	no	yes
Share non-liable farms^{1929} × byear FE	no	yes	no	yes	no
Mean dep. variable	9.13	9.13	9.13	9.13	9.13
Effect size %	-17.80	-14.40	-17.70	-19.20	-18.10

NOTE.— This table shows the effect of the diffusion of milking machines on whether women worked in agriculture after the treatment controlling for different measures of the farm size distribution. The sample includes women born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1930, 1940, 1950, 1960, or 1970. The dependent variable is a dummy variable equal to 100 if a woman is employed in the agricultural sector after the age of 25. The variable C_j^{1929} is the number of cows per farm in 1929 in a woman's municipality of birth (j). The variable M_{jc} is the number of milking machines per farm in a woman's municipality of birth j when she was aged 16–25 (c). The interaction between these two variables, $C_j^{1929} \times M_{jc}$, is our treatment-intensity measure. All regressions include fixed effects for a woman's municipality of birth and birth year, county-by-birth year fixed effects, the share of improved farmland in 1929 and the number of farms per capita in 1929 in each municipality interacted with the women's birth year indicators. Column (1) displays the baseline results of Table 1 (Column 4). Controls for the farm size distribution in 1929 × birth year FE are added in Column (2); controls for the farm size distribution in the contemporaneous census year are added in Column (3); the ratio of large-to-small farms in 1929 × birth year FE is added in Column (4); and the ratio of large-to-small farms in the contemporaneous census year are added in Column (5). Columns (2) and (4) also control for the share of non-separately liable farms in 1929 x birth year FE. Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 15: The diffusion of milking machines and women's decision to migrate to a city—Controlling for farm size distribution

	(1) migrates to city	(2) migrates to city	(3) migrates to city	(4) migrates to city	(5) migrates to city
$C_j^{1929} \times M_{jc}$	0.81***	0.68**	0.73***	0.91***	0.84***
	(0.28)	(0.32)	(0.26)	(0.29)	(0.28)
Observations	381,002	381,002	381,002	381,002	379,654
R-squared	0.04	0.05	0.04	0.04	0.04
Municipality FE	yes	yes	yes	yes	yes
Birth year FE	yes	yes	yes	yes	yes
County-by-byear FE	yes	yes	yes	yes	yes
Imp. farmland^{1929} × byear FE	yes	yes	yes	yes	yes
Farms p.c.^{1929} × byear FE	yes	yes	yes	yes	yes
Farm distribution^{1929} × byear FE	no	yes	no	no	no
Farm distribution contemporaneous	no	no	yes	no	no
Ratio large/small farms^{1929} × byear FE	no	no	no	yes	no
Ratio large/small farms contemporaneous	no	no	no	no	yes
Share non-liable farms^{1929} × byear FE	no	yes	no	yes	no
Mean dep. variable	37.80	37.80	37.80	37.80	37.80
Effect size %	2.10	1.80	1.90	2.40	2.20

NOTE.— This table shows the effect of the diffusion of milking machines on females' decision to migrate to a city, controlling for different measures of the farm size distribution. The sample includes women born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1930, 1940, 1950, 1960, or 1970. The dependent variable is a dummy variable equal to 100 if a woman moved out of her birthplace to a city. The variable C_j^{1929} is the number of cows per farm in 1929 in a woman's municipality of birth (j). The variable M_{jc} is the number of milking machines per farm in a woman's municipality of birth j when she was aged 16–25 (c). The interaction between these two variables, $C_j^{1929} \times M_{jc}$, is our treatment-intensity measure. All regressions include fixed effects for a woman's municipality of birth and birth year, county-by-birth year fixed effects, the share of improved farmland in 1929 and the number of farms per capita in 1929 in each municipality interacted with the women's birth year indicators. Column (1) displays the baseline results of Table 2 (Column 2). Controls for the farm size distribution in 1929 × birth year FE are added in Column (2); controls for the farm size distribution in the contemporaneous census year are added in Column (3); the ratio of large-t-small farms in 1929 × birth year FE is added in Column (4); and the ratio of large-to-small farms in the contemporaneous census year are added in Column (5). Columns (2) and (4) also control for the share of non-separately liable farms in 1929 x birth year FE. Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 16: The diffusion of milking machines, women's employment in agriculture, and their decision to migrate to a city—Controlling for access to hydroelectric power plants

	(1) works in agriculture	(2) works in agriculture	(3) works in agriculture	(4) migrates to city	(5) migrates to city	(6) migrates to city
$C_j^{1929} \times M_{jc}$	-1.89***	-2.45***	-1.89***	0.84***	0.86*	0.84***
	(0.25)	(0.36)	(0.25)	(0.28)	(0.51)	(0.28)
Observations	366,416	98,889	368,277	366,416	98,889	368,277
R-squared	0.06	0.06	0.06	0.04	0.04	0.04
Municipality FE	yes	yes	yes	yes	yes	yes
Birth year FE	yes	yes	yes	yes	yes	yes
County-by-byear FE	yes	yes	yes	yes	yes	yes
Imp. farmland^{1929} × byear FE	yes	yes	yes	yes	yes	yes
Hydropower instrument × byear FE	yes	no	no	yes	no	no
Hydropower initial × byear FE	no	yes	no	no	yes	no
Hydropower 1900-10 status	no	no	yes	no	no	yes
Mean dep. variable	9.15	8.23	9.12	37.80	36.08	37.80
Effect size %	-20.60	-29.80	-20.70	2.20	2.40	2.20

Note.— This table shows the effect of the diffusion of milking machines on whether women worked in agriculture and their decision to whether or not to migrate to a city, controlling for different measures of access to hydroelectric power plants. The sample includes women born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1930, 1940, 1950, 1960, or 1970. The dependent variable is a dummy variable equal to 100 if a woman is employed in the agricultural sector after the age of 25 (Columns 1-3) and a dummy variable equal to 100 if a woman moved out of her birthplace to a city (Columns 4-6). The variable C_j^{1929} is the number of cows per farm in 1929 in a woman's municipality of birth (j). The variable M_{jc} is the number of milking machines per farm in a woman's municipality of birth j when she was aged 16–25 (c). The interaction between these two variables, $C_j^{1929} \times M_{jc}$, is our treatment-intensity measure. All regressions include fixed effects for a woman's municipality of birth and birth year, county-by-birth year fixed effects, the share of improved farmland in 1929 and the number of farms per capita in 1929 in each municipality interacted with the women's birth year indicators. Columns (1) and (4) control for the hydropower potential × birth year FE; Columns (2) and (5) control for the initial year of hydropower production (note: some municipalities have no information on hydropower in 1900-1902); and Columns (3) and (6) control for the hydropower status between 1900 and 1910 (early adopters). Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.

Table 17: The diffusion of milking machines and tractors—Results for women only

	(1) works in agriculture	(2) migrates to city	(3) income rank	(4) high skill	(5) low skill	(6) med skill	(7) edu $\geq$ upper secondary
$C_j^{1929} \times M_{jc}$	-1.05***	1.18***	0.54***	0.16	-0.66**	-0.17	0.59**
	(0.31)	(0.37)	(0.16)	(0.17)	(0.29)	(0.25)	(0.26)
$H_j^{1929} \times T_{jc}$	-0.99***	-0.64	0.32*	0.35*	0.07	0.12	-0.16
	(0.30)	(0.49)	(0.17)	(0.19)	(0.36)	(0.28)	(0.25)
Observations	381,002	381,002	344,459	346,215	346,215	346,215	378,317
R-squared	0.07	0.04	0.11	0.03	0.03	0.02	0.12
Municipality FE	yes	yes	yes	yes	yes	yes	yes
Birth year FE	yes	yes	yes	yes	yes	yes	yes
County FE	no	no	no	no	no	no	no
County-by-byear FE	yes	yes	yes	yes	yes	yes	yes
Imp. farmland^{1929}×byear FE	yes	yes	yes	yes	yes	yes	yes
Farms p.c.^{1929}×byear FE	yes	yes	yes	yes	yes	yes	yes
Mean dep. variable	9.13	37.80		12.46	34.30	18.34	16.83

Note.— This table shows the effect of the diffusion of milking machines on various outcomes for women, accounting for the diffusion of tractors. The variable $C_j^{1929} \times M_{jc}$ is the interaction between the cows per farm in a woman's municipality of birth (j) in 1929 and milking machines per farm in the municipality when she was aged 16–25 (c). The variable $H_j^{1929} \times T_{jc}$ is the corresponding interaction between the number of horses per farm in 1929 and the number of tractors per farm when she was aged 16–25. These two variables are normalized to have a mean of zero and an SD of one. Control variables are defined as in Table 1. The sample includes women born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1930, 1940, 1950, 1960, or 1970. Standard errors (in parentheses) account for arbitrary heteroskedasticity and are clustered at the municipality level. ***, **, and * indicate significance at the 1, 5, and 10 percent level.