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

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Abstract

This paper studies how gender-biased technological change in agriculture affected women's work in 20th-century Norway. In the 1950s, dairy farms began widely adopting milking machines to replace the hand milking of cows, a task typically performed by young women. We show that milking machines pushed young rural women out of farming in dairy-intensive municipalities. The displaced women moved to cities where they acquired more education and found better-paying skilled employment. Our results suggest that the adoption of milking machines broke up allocative inefficiencies associated with moving costs across sectors, which improved the economic status of women relative to men.

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1 Introduction

Between 1950 and 2000, agricultural employment fell by 75% in Europe and the United States, mostly due to the adoption of labor-saving technologies that automated traditional farming tasks.[1] Because traditional farming was subject to a strong gender division of labor (e.g., Alesina et al., 2013; Voigtländer and Voth, 2013), the various labor-saving technologies introduced during the second half of the 20th century likely displaced male and female farm workers at different rates, depending on which farming tasks were automated. However, despite the extensive literature on the drivers of structural change (e.g., Herrendorf et al., 2014; Gollin and Kaboski, 2023), the consequences of this *gender-biased* technological change are still not well understood. To what extent did this process contribute to the transformation of women's work in the 20th century? Has the automation of farming tasks brought economic hardship or gains to affected workers by pushing them out of agriculture?

This paper attempts to make progress on these questions by analyzing the relationship between gender-biased technological change, the reallocation of labor across sectors, and the long-term earning opportunities of displaced farm workers. We focus on one of the largest gender-biased automation shocks in modern agriculture: the adoption of milking machines. Since the 1950s, European dairy farmers have widely adopted milking machines to replace hand milking of cows—the most common job for hundreds of thousands of young rural women.[2] Ex-ante, the long-term effects of milking machines on young rural women are unclear. Although women had a comparative advantage working in white-collar occupations in the cities (e.g., Goldin, 1990; Ngai and Petrongolo, 2017; Rendall, 2024), migration from rural areas was associated with high social costs, leading to the misallocation of labor across sectors (e.g., Munshi and Rosenzweig, 2016; Nakamura et al., 2021).[3] We find that the adoption of milking machines broke up these allocative inefficiencies and, despite its short-run costs, narrowed the gender gap by increasing the return to education and long-term earning opportunities for young women who grew up in dairy-intensive municipalities.

Our study focuses on Norway. The detailed Norwegian individual-level registry data and official agricultural statistics on the uptake of milking machines at the municipality level provide a rare opportunity to study the short- and long-run effects of gender-biased technological change at the individual level. Compared to macroeconomic studies that evaluate the

[1] Economic historians have vividly described how the mechanization of agriculture has transformed farms and displaced workers throughout the 20th century (e.g., Olmstead and Rhode, 2001).

[2] For centuries, dairying and milking the cows were common jobs for young, unmarried women in the dairy regions of Europe (Snell, 1981; Schultz, 1985; Osterud, 2014; Lampe and Sharp, 2019).

[3] Typical examples of moving costs for rural women arise from traditional gender norms on farms, the role of women in society, and the loss of access to family and informal insurance networks.

effect of technological change on places (e.g., local labor markets), our rich microdata allow us to assess its causal impact on individuals. Longitudinal data are necessary to identify the effect of technological change on individuals, which may be very different from the impact on places, as affected workers may move in response to the technology shock. With our panel of individual-level registry data, we can evaluate whether affected women left agriculture, whether they migrated out of rural areas, and how they performed in the short- and long-term. This is possible even when women's last name changes after marriage, since the Norwegian registry data provides unique personal identifiers that allow to systematically link women over time. Moreover, with our data, we can examine whether the adoption of milking machines differentially displaced men and women out of agriculture and narrowed the gender gap in income, labor force participation, and human capital investments.

In addition to the rich longitudinal data, Norway's natural features provide an ideal setting in which to evaluate the economic consequences of the introduction of milking machines. Dairying was 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 (Statistisk Sentralbyrå, 1969).[4] However, more than in other countries, the location of dairy farms in Norway is primarily determined by its unique geography, making it easier to identify the causal effects of the uptake of milking machines at the local level.

Our empirical strategy exploits plausibly exogenous variation in the local uptake of milking machines. We create an exposure measure to milking machines that combines changes in the nationwide adoption of milking machines with local differences in the intensity of the dairying sector during the pre-milking machine era. Similar to a shift-share design, we use this exposure measure to instrument for the actual uptake of milking machines at the municipality level. Importantly, we provide evidence supporting the validity of our exposure measure as an instrumental variable following the suggestions of the recent shift-share literature (Goldsmith-Pinkham et al., 2020). First, we use a Lasso procedure to assess whether the local uptake of milking machines is correlated with any other initial characteristics that might generate differential trends across locations. Reassuringly, our results are robust to adding controls selected by Lasso and flexible accounting for county-specific cohort trends. Second, we conduct a permutation test that supports the exogeneity of our exposure measure. Third, we present event studies and a placebo test showing that the outcomes of women

[4] Other dairy regions, such as Denmark, France, Switzerland, West Germany, and the Netherlands, experienced similar processes (Bieleman, 2005; Mitchell, 1998).

and men in more or less exposed rural municipalities evolved similarly in the pre-milking machine era. Finally, our estimates are also robust to: (i) alternative definitions of milking machine exposure, (ii) including potential confounders, such as education reforms and the effects of WW2, (iii) accounting for spatial correlation, and (iv) using the "Honest Approach to Parallel Trends" of Rambachan and Roth (2023).

The main empirical analysis is based on about 725,000 women and men who lived in rural municipalities at the ages of 16 to 25 between 1930 and 1970. We find that the adoption of milking machines in Norway had significant and long-lasting gender-specific effects. Young rural women from dairy-intensive municipalities were pushed out of agriculture and into urban areas. Although the displaced young women suffered significant short-term income losses, their long-term economic situation improved.[5] For a one-standard-deviation increase in milking machines per farm ($\approx$ one milking machine per 10 farms), women moved up their birth-year-specific income distribution by nearly two percentiles. Affected women benefited in the long run not only because they were more likely to work, but also because they held better-paying, skilled jobs, particularly in the public sector.

Young rural men were also affected by the mechanization of agriculture—they left the primary sector and rural areas—but to a much lesser extent than women. Hence, the displacement from agriculture caused by milking machines was gender-biased. We show that this significantly reduced gender differences in income and labor force participation in the long term. The income differences between affected men and women were reduced by about 2 percentile ranks, and differences in labor force participation rates dropped by almost 4 percentage points. The decline in the gender gap can be attributed to the occupational upgrading of displaced rural women, while affected men remained in low-skill occupations that offered high returns on the skills they had already acquired in the primary sector.

We present two complementary mechanisms that can explain these results. First, we find that affected women invested more in higher education, which is a requirement for many white-collar jobs in the service and public sector. In fact, migration decisions were partly determined by access to higher education institutions, suggesting that the long-term effects of labor-saving technological change on displaced workers are institution-dependent. Second, we find that households had their first child later and fewer children overall when the woman of the household was exposed to milking machines at age 16-25. These results suggest that automation of hand milking increased the opportunity costs of having children for young displaced rural women since they had to leave their hometowns to acquire more education

[5] This finding is consistent with workers' fears that labor-saving technological progress curtails employment and lowers wages; see Caprettini and Voth (2020) for a historical setting and Acemoglu and Autor (2011) and Acemoglu and Restrepo (2020) for a modern setting.

to take up higher-skilled jobs in the cities.

Our paper contributes to a growing body of literature on automation.[6] Compared to the macroeconomic literature evaluating the effects of automation on local labor markets and industries (e.g., Graetz and Michaels, 2018; Acemoglu and Restrepo, 2020; Dauth et al., 2021), we use the rich individual longitudinal data from Norway to provide new insights into the long-term impact of automation on displaced workers. Our findings complement studies that found short-term negative effects of automation on displaced workers (e.g., Acemoglu and Autor, 2011; Caprettini and Voth, 2020; Feigenbaum and Gross, 2022). In particular, we show that migration and task reinstatement can lead to long-term welfare gains for affected workers. Our finding that affected rural women acquire more education to secure high-skilled jobs in Norway's expanding service sector provides empirical support for a theoretical literature suggesting that automation can have positive long-term effects through occupational reinstatement (Acemoglu and Restrepo, 2019).

We also add to the literature on the evolution of female labor force participation over the 20th century in industrialized countries (e.g., Goldin, 1994, 2006; Costa, 2000; Olivetti and Petrongolo, 2016). The adoption of milking machines pushed women out of rural areas and transformed women's work by increasing their educational attainment and occupational status. Our results suggest that this gender-biased technology shock reduced the gender gap by breaking up deeply rooted gender norms within labor markets (e.g., Alesina et al., 2013; Fernández, 2013; Giuliano, 2015, 2018). It also relates to studies showing that automation, particularly the adoption of computers, reduced the gender gap. One reason is that the displacement of routine-intensive occupations induced women more than men to increase college enrollment to take up high-skill occupations (e.g., Beaudry and Lewis, 2014; Chuan and Zhang, 2023; Cortés et al., 2024).

Our work relates to studies of the drivers and effects of structural change (e.g., Herrendorf et al., 2014; Gollin and Kaboski, 2023; Helm et al., 2023).[7] A small branch of the literature studies the gender effects of structural change in the context of middle and high-income countries from a macroeconomic perspective (e.g., Olivetti, 2014; Moro et al., 2017; Ngai and Petrongolo, 2017; Rendall, 2018). We complement this literature by using the rich Norwegian individual-level registry data that allow us to identify how a specific technology

[6] Recent examples are Acemoglu and Restrepo (2019), Atack et al. (2019), and Feigenbaum and Gross (2022). We refer readers to Restrepo (2023) for a recent survey of the automation literature.

[7] The focus of recent empirical studies has been on evaluating the consequences of increases in agricultural productivity on structural change (e.g., Bustos et al., 2016; Carillo, 2021; Gollin et al., 2021; Moorthy, 2025). A historical example of how increased agricultural productivity leads to structural change is the increasing urbanization in Europe in the 18th and 19th centuries as a result of the introduction of the potato (Nunn and Qian, 2011; Berger, 2019a). It is worth noting that negative productivity shocks in agriculture unrelated to technological change can also trigger structural change (e.g., Ager et al., 2020).

shock in agriculture changed women's work and thus contributed to the process of structural transformation.

Finally, there is a large body of work that considers barriers to migration and the selection of workers into specific locations as the main reasons behind rural-urban wage gaps (e.g., Gollin et al., 2014; Munshi and Rosenzweig, 2016; Bryan and Morten, 2019). A few studies rely on forced migration or natural disasters to study the misallocation of labor across sectors and places (Becker et al., 2020; Nakamura et al., 2021; Sarvimäki et al., 2022). Instead, we consider the large-scale adoption of milking machines as a quasi-natural experiment that substantially reduced the barriers to moving by eliminating the job opportunities for women on farms, thereby facilitating structural transformation.[8]

2 Historical background

2.1 The structural transformation in Norway

Norway's modernization process began in the 1820s, more than a century before our period of study (1930-1970).[9] Between the 1820s and 1920s, the share of the population living in urban areas increased from around 10 to 45 percent, which led to a concentration of economic activity in the cities (Statistisk Sentralbyrå, 1978). 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). Second, the expansion of the manufacturing sector attracted people to urban areas.

Nevertheless, Norway was still a rural society at the turn of the 20th century compared to other Western European countries (Bairoch and Goertz, 1986). Most women were not in the active labor force at that time, and those who reported an occupation were mostly farmhands, servants, or worked in textile occupations. One reason for these patterns was that Norway industrialized late. Before the 1890s, less than 10 percent of the labor force engaged in actual factory production, and industrial activities were concentrated in the largest urban areas. Rapid and extensive industrialization occurred only after the adoption of hydroelectric power in the 1890s as a main source of energy.[10] By 1920, hydroelectric power plants were

[8] 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, and it also suggests that a big push was needed since moving to cities comes with high economic and social costs (e.g., Lagakos, 2020; Nakamura et al., 2021; Lagakos and Shu, 2023).

[9] Compared to other Scandinavian countries, Norway's economic performance was between Sweden and Denmark from 1800 to 1939 (Grytten, 2020, 2022).

[10] Several historians consider the introduction of hydroelectric power as a milestone for the industrial revolution in Norway, which was mainly driven by the rapid expansion of electro-metallurgical and chemical

distributed all over Norway (Leknes and Modalsli, 2020, Figures 1 and 2). At that time, Norwegian per capita production was among the ten highest in Europe, and almost one in four employees worked in the manufacturing sector (Cameron, 1985; Venneslan, 2009; Grytten, 2020).

The expansion of the manufacturing sector attracted more people to cities, but new industry sites also emerged in the countryside in the first half of the 20th century. This was particularly the case in western Norway, where waterfalls are widespread and provide an accessible source of energy for industry development in the countryside. Industrial production also developed to a certain extent in northern Norway (Venneslan, 2009; Grytten, 2020). This process of rural industrialization was not specific to Norway but was also common in other Scandinavian countries (Nilsen, 2014; Berger, 2019b; Lampe and Sharp, 2019). The jobs in rural industry were mostly tailored to men, as shown by the historical occupational statistics from the 1900 and 1910 Norwegian Censuses. Almost 15 percent of men in rural areas worked in manufacturing, compared to 5 percent of women, a ratio of 3 to 1.

The interwar period was characterized by macroeconomic instability and high unemployment outside of agriculture. Industrialization and urbanization stagnated in the 1920s and 1930s, and the primary sector remained the most important employer in Norway (Broadberry, 1984; Grytten, 1995, 2022). Specifically, in 1930 over 35 percent of the total workforce was employed in the primary sector, including a large share of part-time small farmers and farm workers. Among the rural male population, it was very common to do other types of seasonal work in addition to farming.[11] According to the occupation statistics of the 1930 Census, the share of rural men working in manufacturing was almost 17 percent compared to less than 3 percent of rural women. For rural women, the most common types of employment were agricultural work and personal services, such as maids or housekeeping (Almås, 2020; Hodne and Grytten, 2000).

Det Statistiske Centralbyrå (1935, pp.119-131) provides more details on the employment structure of women in rural Norway in 1930, before milking machines were adopted on Norwegian farms. One striking feature is the very skewed female labor force participation by age. While close to 40 percent of rural women aged 15-25 did work, about 80 percent of rural women over age 25 were not in the labor force—most of them were listed as housewives. Of the employed rural women aged 15-25, about 10 percent worked in white-collar jobs and the remaining 90 percent worked as (low-skilled) laborers. Less than 15 percent of these young, low-skilled laborers were hired in crafts and industry. The overwhelming majority,

industries (Venneslan, 2009; Leknes and Modalsli, 2020; Grytten, 2020).

[11] These tasks, e.g., in fishing, the timber industry, or construction, were usually carried out by male crofters, who comprised a large share of the rural population in Norway. They typically rented small landholdings that were not large enough to feed their families.

85 percent, worked as maids on farms and rural households, or were hired as agricultural laborers. In contrast, of the employed rural women aged 26-60, about 15 percent worked in white-collar jobs, 65 percent were employed as laborers, and 20 percent were self-employed. Moreover, 5 percent of young rural women aged 15-25 were at school and 13 percent were married. In contrast, almost 70 percent of the rural women aged 26-60 were married, and of these, only 5 percent worked.

Agricultural employment decreased substantially between 1950 and 1970.[12] This period saw an acceleration in the mechanization of agriculture similar to that in other parts of Scandinavia and Western Europe. Agricultural production became more capital-intensive (see Appendix Figure A.2), in part due to rising labor costs and the removal of trade barriers. At the same time, employment in the primary sector fell. While 900,000 residents reported the primary sector as their main source of income in 1950, only 365,000 did so in 1970, which corresponds to a decline of 60 percent (Statistisk Sentralbyrå, 1980, Table 17).

The mechanization of agriculture reduced both women's and men's opportunities to take on farm jobs, but the historical narrative suggests women were more affected. The reason is that men could stay in rural areas and perform the aforementioned seasonal jobs, e.g., in the rural industry, timber, and construction. These alternative rural jobs offered high returns to the skills men had already acquired as seasonal and agricultural workers. For rural women, employment opportunities outside the farm were limited. Instead, the expanding service and public sector played an important part in absorbing displaced female agricultural workers. Between 1950 and 1970, many young rural women left the farms, invested in their education, and moved to more densely populated areas to find work, e.g., in social services, teaching, childcare, or as office workers. The availability of white collar jobs, especially in public services, increased the labor force participation rate of women from around 25 percent in 1950 to over 50 percent by 1980 (Almås et al., 1983; Brandth, 2002; Olivetti, 2014; Almås, 2020).

The different employment opportunities for displaced male and female farm workers contributed to the fact that, although both women and men left rural areas between 1950 and 1970, women did so at a higher rate. This is also reflected in the skewed gender ratio in rural communities in 1970: for every 1,000 men, there were only 962 women. In contrast, there were more women than men living in cities (Statistisk Sentralbyrå, 1978). Overall, urbanization increased rapidly during this period due to (gender-biased) rural-to-urban migration, while rural areas faced substantial population losses (immigration to Norway remained neg-

[12] After WWII, Norway joined the Bretton Woods agreement, 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 role of the public sector (Acemoglu et al., 2021).

ligible throughout this period). The rural population fell by 15 percent between 1950 and 1970, while the urban population increased by 50 percent and the number of urban settlements rose from 450 to 520 during this period. Smaller urban communities (up to 10,000 inhabitants), where many public service jobs were created, accounted for about one-third of the urban population increase in the 1950s and 1960s. In 1970, approximately two-thirds of Norway's population lived in urban areas—an urbanization rate that was still lower than that of other Scandinavian countries and the United States (Myklebost, 1984; Hansen, 1989). Since 1970, and thus after our focus, Norway experienced a massive oil and gas boom, which led to convergence to the urbanization path of the United States, and Norway outperformed its major trading partners (including Denmark and Sweden) in terms of GDP per capita (Bennett et al., 2022; Grytten, 2022).

2.2 The role of milking machines

How did the adoption of milking machines contribute to the structural transformation in Norway? Historically, dairy farming has been the largest activity in the Norwegian agricultural sector.[13] On dairy farms, the main task of women—aside from housework—was milking cows. Women also worked outdoors alongside men in haymaking and other seasonal harvest activities. In contrast, men mainly worked outdoors and typically complemented their farming employment with other seasonal work in the rural sector (Almås, 2020). This division of labor was deeply rooted in farming communities, where "[d]airying 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). Data from the 1910 Norwegian Census reveal that only 679 of 51,383 dairy farm workers in rural areas were men (1.32%). This traditional gender division of farm tasks is well documented in Norway and the other Nordic countries (e.g., Almås and Haugen, 1991; Sommestad, 1994; Kaarlenkaski, 2018).

Milking cows remained women's main chore on dairy farms until the adoption of milking machines. While the first milking machines were patented in the United States in the late 19th century, widespread adoption across Europe and the United States only took place after WWII (e.g., Bateman, 1969; Bieleman, 2005; Settele, 2018).[14] Norway was no exception to this pattern, as Panel (a) of Figure 1 illustrates. Although there was a slow uptake in

[13] Farming in Norway was traditionally based on family farms and milk production. Family farms were the most common type of farm in Norway and other parts of Europe. Typically, parents, their children, and extended family members worked on the farm, together with seasonal and permanently hired workers. The most important farm products in Norway were milk, products derived from milk, and meat associated with milk production (Espeli et al., 2006).

[14] The reasons for this delayed adoption are manifold. Bateman (1969, p.211), for example, describes how farmers hesitated to adopt milking machines because they were fire hazards that often injured cows.

the 1930s, the adoption of milking machines only accelerated after the 1950s. The most important factor behind this take-off is that, in 1951, Norway lifted all import restrictions on agricultural equipment (Espeli, 1990).

Milking machines had a profound impact on dairy farming (Bieleman, 2005). Compared to hand milking, these machines could milk a substantially larger number of cows. For example, in 1964, a milking machine in a parlor with eight workstations could milk 30 cows per hour. In comparison, one person could hand-milk only seven or eight cows per hour, with decreasing productivity as fatigue accumulated (Settele, 2018). Importantly, milking machines were affordable and profitable even for small farms. The reason is that milking machines were typically used in cowsheds, so they did not require building new indoor facilities. In addition, the machines themselves were relatively cheap. For a farmer in 1950, the price of a milking machine was about half the annual wage of a male servant.[15]

This new technology increased total productivity in the dairy industry: On average, the milk extracted from a cow over a year rose from around 2,000 kilograms in 1950 to more than 4,000 kilograms in 1969 (see Appendix Figure A.3).[16] Other Nordic countries and the Netherlands experienced similar changes in productivity (Bieleman, 2005). Under a stable demand, such an increase in productivity could decrease milk prices and reduce the incomes of dairy farmers. Yet, there is no evidence that this was the case in Norway between 1950 and 1970. The nominal retail price for a liter of milk doubled from 0.5 NOK in the early 1950s to slightly above 1 NOK by the end of the 1960s, under a stable inflation rate (Statistisk Sentralbyrå, 1978, Table 290).

Similarly, the incomes of dairy farmers did not fall.[17] One reason why milk prices and dairy farmer incomes did not fall is that there was a surge in the demand for milk. This came in part from a growing population. In fact, while productivity and total milk production increased, milk production per capita remained constant at about half a liter per person (Statistisk Sentralbyrå, 1974). In addition, there was an increase in the demand for other processed dairy products such as butter and cheese (Cohen, 1980). Another reason was that the Norwegian government subsidized dairy farms. In the 1960s around 1/3 of the retail

[15] According to Almås (personal interview) the price of a milking machine was ca. NOK 2,000 in 1950. This 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.

[16] 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 (Espeli et al., 2006).

[17] Statistics from dairy companies—who received 60-90 percent of Norway's total milk production in 1950-1960—reveal that their payments to producers (dairy farmers) increased from 0.448 NOK per kilogram of milk in 1950 to 0.887 NOK in 1970 and that producers received around 95 percent of the dairy companies' net income (Statistisk Sentralbyrå, 1969, Table 146).

price consisted of subsidies (Bateman, 1963). Finally, dairy farmers' incomes did not fall because milking machines allowed them to reduce costs by having fewer (heavier) cows that could produce more milk. In detail, milk production per capita remained constant despite a decline in the number of cows.

The most important economic impact of milking machines was on employment. Milking machines automated tasks related to hand milking. These tasks were typically performed by women due to the traditional division of labor on dairy farms. Specifically, young women aged around 16-25 commonly worked as milkmaids on farms before getting married (see, e.g., Almås (2002)). Milking cows, therefore, provided a large source of jobs to women entering the labor market in rural areas.[18] When dairy farms adopted milking machines, the demand for hand milking disappeared, displacing young female workers in general, and milkmaids and servants in particular (Thorsen, 1986; Brandth, 2002). Almås et al. (1983) describe this process as "the masculinization of Norwegian agriculture", since a large part of the work in family farms was taken over by the men in the family—affecting also farmers' wives and daughters (see Appendix Figure A.4). As a result, there was an exodus of young women from farms in the late 1940s, 1950s, and 1960s. Facilitated by the expansion of the service and public sector, most of these women found new jobs outside of agriculture in growing urban settlements (Almås et al., 1983; Myklebost, 1984; Hansen, 1989).

Although young men's typical jobs on dairy farms were not *directly* replaced by milking machines, their employment opportunities also declined, mainly because of the general mechanization of agricultural tasks in the second half of the 20th century. The adoption of milking machines and the associated exodus of young rural women potentially reinforced the displacement of male labor on dairy farms because of the complementarity of tasks between female and male farm workers and the economic disruption caused by women leaving rural areas.[19] On aggregate, the share of rural men employed in agriculture was reduced from around 22 percent in 1950 to 8 percent in 1970. However, men left agriculture to a lesser extent than women (Almås et al., 1983; Almås, 2020). Displaced men also moved from rural to urban areas, but again at a lower rate than women. The reason is that men were still in demand for seasonal jobs in rural areas, such as construction or the timber industry. In contrast, displaced rural women had a comparative advantage in the new jobs in urban areas, especially in the expanding public sector (Almås et al., 1983). Another reason why men stayed put more than women is that, during our study period, first-born sons inherited farm property in Norway ahead of women until the Act on Allodial Rights of 1974.

[18] Appendix Figure A.5 illustrates that the distribution of Norwegian dairy farm workers in 1910 is concentrated among young women.

[19] An obvious example of the complementarity between male and female labor in the primary sector was haymaking, where men cut the hay and women gathered it up (Osterud, 2014, p.667).

In summary, milking machines were part of the general mechanization of agriculture in Norway that pushed labor off the farms. The historical narrative suggests that women and men were both displaced but, because of the gender division of labor in traditional agriculture, women were generally more affected: While displaced women had a comparative advantage in urban employment and in the expanding public sector, displaced men continued to have employment opportunities in the rural areas. Hence, in our empirical analysis, we expect that the adoption of milking machines reduced agricultural employment and increased the incentives to move out of rural areas for women relatively more than for men—therefore affecting gender gaps. In the remainder of the paper, we bring this prediction to the data and evaluate how women and men exposed to the adoption of milking machines when young fared later in life. We further evaluate the consequences of this gender-biased labor-saving technology for gender gaps in income, labor force participation, and human capital investments.

3 Data

In this section, we describe our primary data sources: (i) linked individual-level administrative datasets from the Norwegian Registry Data, and (ii) municipality-level data on the adoption of milking machines from the Census of Agriculture. Other secondary datasets are introduced in the relevant sections of the empirical analysis below.

In our analysis, we focus on adult outcomes of women and men who were born in rural municipalities. We classify municipalities as rural if they report no urban population and at least one farm in the 1929 Census of Agriculture.[20] Our main sample includes around 725,000 women and men aged 16-25 in 1930, 1940, 1950, 1960, or 1970 (the census years). Specifically, we consider 16 to 25 year-olds because dairy farms traditionally hired milkmaids at this age to perform hand milking and related tasks (see Appendix Figure A.5), and because this was the cohort considered to be at most risk concerning internal geographic mobility (see Appendix Figure A.15). We refer readers to Appendix Table A.2 for detailed summary statistics for our main sample.

3.1 Registry data

Our individual-level data are from the administrative registries provided by Statistics Norway. We use the linked central population register covering the full Norwegian population from 1960 to 2019, the full count population censuses of 1960, 1970, and 1980, the education

[20]The classification into urban versus rural population is provided by Statistics Norway.

register, and the tax and earnings register. These registers provide information on place of birth and residence, occupation, earnings, educational attainment, and fertility.

From the central population register, we use the municipality of birth to build our sample of rural women and men and to measure their exposure to the adoption of milking machines when young. We measure exposure at age 16-25, when women would have traditionally been hired as milkmaids, and use the municipality of birth as a proxy for the municipality of residence at age 16-25. This assignment avoids capturing the effect of endogenous migration decisions. In addition, the central population register allows us to reconstruct a woman's completed fertility and her age at first birth. Importantly, the central population registry includes unique personal identifiers, which we use to follow *both* women and men over time and to match them to the registers on tax and earnings, education, and full count censuses. Note that these unique identifiers allow us to link all women, notwithstanding changes in their last names 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 personal identifiers.

We supplement these data with full-count population censuses from 1960, 1970, and 1980.[21] These censuses provide each individual's occupation, which we use to evaluate the displacement effect of milking machines out of agriculture. In detail, we classify occupations into farming and non-farming activities and evaluate how the diffusion of milking machines when an individual was aged 16-25 affected occupational choice after age 25, as reported in the subsequent census.[22] The occupations registered in the censuses are self-reported and cover almost the entire population. On average, 9 percent of women in our sample worked in agriculture after the age of 25.[23] Among men, the corresponding figure is just under 18 percent. We also use the decennial occupation data to examine the effects on the occupations' skill content. Specifically, we use the classification of occupations matched with skill content from O*Net to group non-farming occupations into high-, medium-, and low-skilled jobs (Autor, 2019). Around 12.5 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

[21]Full count censuses in 1930, 1940, and 1950 do not contain personal identifiers and, hence, cannot be linked across registries.

[22]For individuals aged 16-25 in 1930, 1940, and 1950, we look at their occupation in the 1960 Census; for individuals aged 16-25 in 1960, we look at their occupation in the 1970 Census; and for individuals aged 16-25 in 1970, we look at their occupation in the 1980 Census. When an individual's occupation is missing in a given census, we look at their reported occupation in a later census. Because occupations are measured at different ages for the earlier cohorts (1930-40), we show that results on displacement from agriculture occupations are robust to excluding earlier cohorts (see Table 2, column (3)).

[23]Before the introduction of milking machines, 40 percent of rural women aged 15-25 worked, mostly as low-skilled maids on farms and in rural households. In contrast, 80 percent of rural women were not in the labor force after age 25 and were instead listed as housewives in the 1930 Census. See Section 2.1 for details.

25. Among men, the corresponding figure is 27 percent for high-skill jobs and 56 percent for medium-skill jobs. Moreover, we identify public-sector occupations based on up to four-digit occupation classifications. These comprise mostly white-collar jobs such as teachers or nurses (see Appendix Table A.19).

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 long-distance migration patterns by gender and to evaluate how the diffusion of milking machines affected the decision to migrate.[24] About 40 percent of women in our sample moved outside their county of birth, compared to 35 percent of men.

In addition, we measure earnings by linking individuals to 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 by gender. For short-term effects, we follow the year-by-year income trajectory of rural women and men turning 16 in 1970. The short-term analysis is restricted to this cohort because this is the only cohort in our sample for which *yearly* income data are available from the start of their working life. For long-term effects, we consider our full main sample and measure their income as middle-aged adults. For both short- and long-term income measures, we follow the recommendation by Chen and Roth (2024) 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 yearly gross earnings (for the short-term analysis) and on gross earnings at the age of 45 (for the long-term analysis). Because the tax registry only started in 1967, we use gross earnings at older ages for those who were above 45 in 1967. In detail, we use income at age 52 for individuals aged 16-25 in 1940 and pre-tax earnings at age 62 for individuals aged 16-25 in 1930.

Appendix Figure A.6 shows that there is a high correlation between income percentile ranks at ages 45, 52, and 62. Appendix Table A.6 shows that our results are robust to excluding these earlier cohorts. Similarly, several studies show that percentile ranks are less sensitive to the age at which income is measured than the income in levels (e.g., Chetty and Hendren, 2018). In levels, the average adult earnings were approximately 65,000 Norwegian kroner (NOK) for women and NOK 128,000 for men in our sample.[25] To measure labor force participation (LFP), we consider adults to be working if they report positive earnings at age

[24] We define long-distance migration as moving outside one's county (*fylke*) of birth. We also construct measures of long-distance rural-to-urban migration (i.e., to towns above 10,000 inhabitants in 1969), rural-to-rural migration within one's county of birth, and migration to a town with higher education institutions. Unless otherwise stated, these variables are based on ever moving as reported in the Censuses of 1960–1990.

[25] This gender wage gap is comparable to that in the US, where in 1970 women's mean weekly wages were around 55 percent of men's (Bailey et al., 2024, Figure I).

45. Since this excludes the earliest cohorts (individuals aged 16-25 in 1930 and 1940), we also consider alternative LFP definitions using occupation data from the censuses (Appendix Table A.5).

Finally, we measure educational attainment using the educational database provided by Statistics Norway. This data is based on reports submitted directly by educational institutions to Statistics Norway every year since 1970. This minimizes any measurement error from misreporting. On average, 10 percent of the women and men in our sample attained undergraduate education or higher (see Appendix Figure A.7).

3.2 Agriculture censuses

We combine our individual-level data with aggregated municipality-level census statistics on Norwegian farms. These agricultural censuses cover our entire study period. They were collected in 1929, 1939, 1949, 1959, and 1969.

Agricultural censuses report detailed statistics on the number of farms, agricultural machinery, equipment, crops, and livestock in each municipality. However, there is no information on agricultural output. For our analysis, we use the number of milking machines per farm in each municipality in each census year as a measure of local technology adoption. Over our study period, an average rural municipality had seven milking machines per 100 farms, although as discussed above, there is considerable heterogeneity across time and space (see Figure 1 and Appendix Figure A.10). In addition, we use the number of dairy cows per farm in each municipality in 1930 to capture the intensity of (formal and informal) female labor engaged in milking cows prior to the introduction of milking machines. The agricultural censuses also report information that is useful to construct control variables. Specifically, we use a Lasso to select initial municipality-specific characteristics that could also have affected the diffusion of milking machines over time, such as the agricultural intensity and the farm size distribution.

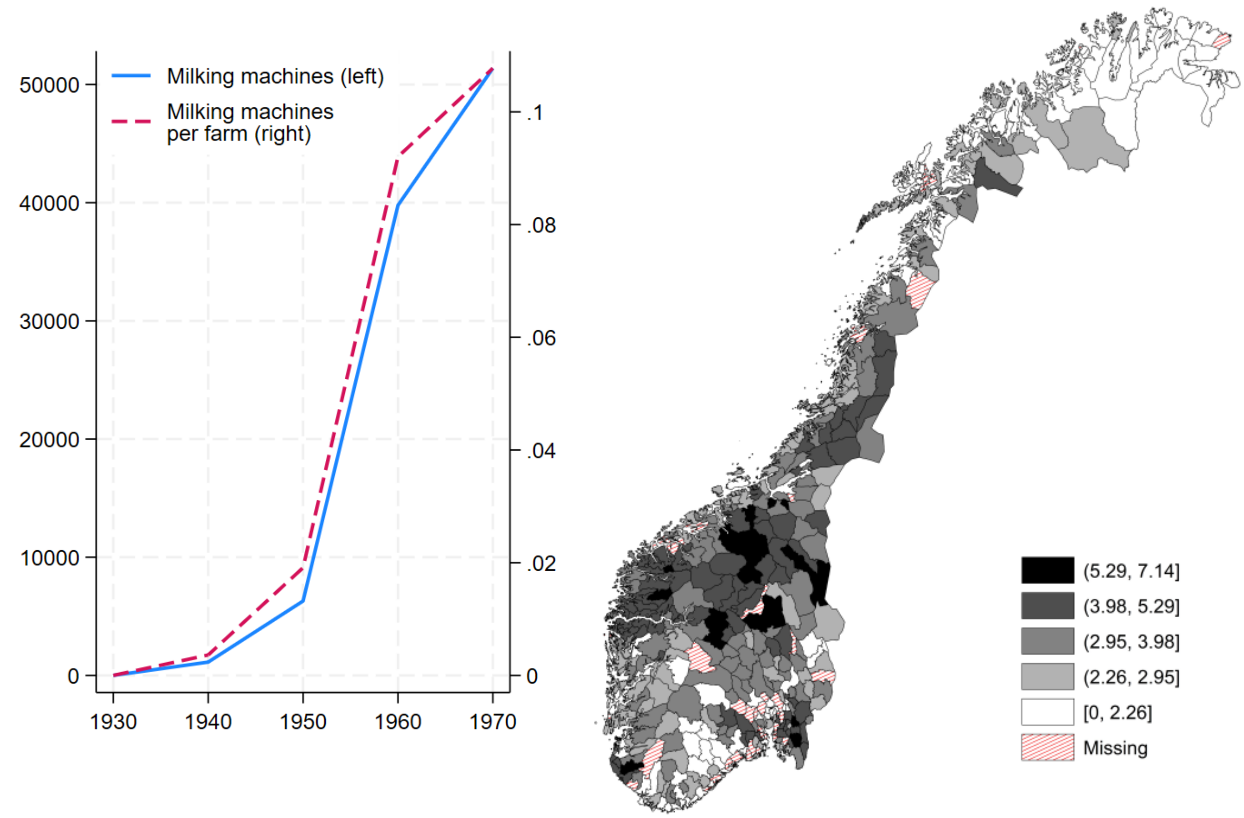
4 Research design

Our goal is to estimate the causal effect of the adoption of milking machines on our main outcomes of interest: displacement from farming, migration, income, and labor force participation. We use an instrumental variables approach that exploits plausibly exogenous variation in the local uptake of milking machines. We do so by constructing an exposure measure to milking machines, which combines changes in the nationwide adoption of milking machines (Panel (a) of Figure 1) with local differences in the importance of dairy farming

Figure 1: Exposure to milking machines.

(a) Diffusion of milking machines (1930–70)

(b) Milk cows per farm in 1930



Note.— Panel (a) 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). Panel (b) shows the distribution of the number of milk cows per farm across Norwegian municipalities in 1930; Source: Population Census of 1930 (own calculations).

across municipalities in the pre-milking machines era (Panel (b) of Figure 1).

Conceptually, our estimation strategy is similar to a shift-share instrumental variables approach (Bartik, 1991).[26] Our exposure measure uses municipality-level variation in milk cows per farm in 1930 as the initial "shares" and the nationwide roll-out of milking machines per farm between 1930 and 1970 as the "shift." We then use this exposure measure to instrument the uptake of milking machines per farm at the municipality level. However, our design departs from the classic shift-share approach in important aspects: One is that we have an additional dimension, gender, that we use to compare two groups differently affected by milking machines; another is that we have a single "share" and a clear zero date

[26]Our idea of using an exposure measure to capture the local impact of a technology shock is similar to studies evaluating the impact of trade liberalization or immigration restrictions on local economies (e.g., Kovak, 2013; Dix-Carneiro and Kovak, 2017; Abramitzky et al., 2023). See Adao et al. (2019) and Borusyak et al. (2022) for further discussions of shift-share designs.

that we can use to validate our research design. Specifically, we follow the suggestions of Goldsmith-Pinkham et al. (2020) to validate shift-share designs that, like ours, are based on the exogeneity of the shares, and use a Lasso method to select relevant controls. These validity checks are presented in Section 4.3.

4.1 Measuring local milking machine exposure

Formally, we define our local milking machine exposure measure, $E_{j,d(b)}$, as:

$$E_{j,d(b)} = \frac{\bar{M}_{d(b)}}{\bar{F}_{d(b)}} \times \frac{C_{j,1930}}{F_{j,1930}} \ , \tag{1}$$

which consists of two components: The first component is the total number of milking machines in Norway, $\bar{M}_{d(b)}$, normalized by the total number of farms in Norway, $\bar{F}_{d(b)}$, at the census year $d(b)$ when birth cohort b was aged 16-25; the ages at which women were traditionally hired as milkmaids. This component can be interpreted as the national "shift" in the adoption of milking machines. It captures the cohort variation generated by the diffusion of milking machines in Norway, which took off after 1951 when Norway lifted all import restrictions on agricultural equipment (Espeli, 1990).

The second component captures the intensity of (*formal and informal*) female labor engaged in milking cows in municipality j in 1930 before the first milking machines were adopted in Norway. Specifically, $C_{j,1930}$ denotes the number of milk cows in municipality j in 1930, and $F_{j,1930}$ the number of farms in municipality j in 1930. Because milking machines automated cow milking, a task previously performed by milkmaids, the number of milk cows per farm in 1930 captures the treatment intensity at the municipality level. Although we use the nationwide roll-out of milking machines, the municipality-level differences in milk cows per farm in 1930 generate local variation in exposure to this technology shock. Importantly, this component is a proxy for the local "share" of women employed as milkmaids, including women who were hired without a formal contract (e.g., family members). For robustness, we show that results are very similar when using the share of female labor *formally* hired as milkmaids in 1930 instead of the number of milk cows per farm in 1930.[27]

[27]Our preferred specification considers the number of milk cows per farm and not the share of milkmaids because, in addition to capturing informal labor, this measure is picked by our Lasso procedure as a determinant of milking machine adoption (see Appendix Table A.3).

4.2 Two-stage least squares

Our main specification is an instrumental variables approach estimated via two-stage least squares (2SLS). We use local milking machine exposure as defined in Equation (1) to capture exogenous variation in the number of milking machines per farm adopted at each municipality over time. The first-stage equation is outlined as follows:

$$M_{j,d(b)} = \alpha_j + \beta_b + \tau E_{j,d(b)} + \sum_t \mathbf{1}[b=t] \times \mathbf{X}_j' \theta_t + e_{j,b} \ , \tag{2}$$

where $M_{j,d(b)}$ is the number of milking machines per farm in municipality j at the census year $d(b)$; and α_j and β_b are fixed effects for municipalities and birth cohorts. The set of controls, X_j', includes two measures of agricultural intensity in 1930 (the share of improved farmland and the number of farms per capita) and a measure of the farm size distribution in 1930 (the ratio of large to small farms), both interacted by birth cohort fixed effects. We select these flexible trends based on a Lasso procedure (see Appendix Table A.3).

The corresponding second-stage equation is:

$$Y_{i,j,b} = \alpha_j + \beta_b + \gamma \hat{M}_{j,d(b)} + \sum_t \mathbf{1}[b=t] \times \mathbf{X}_j' \theta_t + \epsilon_{i,j,b}, \tag{3}$$

where Y_{ijb} denotes the outcome of interest for individual i born in year b in municipality j; α_j and β_b are fixed effects for municipalities and birth cohorts; and $\hat{M}_{j,d(b)}$ is the instrumented number of milking machines per farm in municipality j at the time when birth cohort b was aged 16-25. We also flexibly account for county-specific trends by adding to Equations (2) and (3) county-by-birth cohort fixed effects. We also include two additional municipality-level controls interacted by birth cohort fixed effects: the capital intensity in agriculture in 1930 (proxied by an indicator for the early adoption of tractors) and the average female income in 1930.

To capture gender effects, we pool together women and men and extend Equation (3) by adding gender dummies and interacting them with each included variable in the model:

$$Y_{i,j,b} = \sum_{s \in (wom,men)} \mathbf{1}[g_i = s] \times \left\{ \alpha_j^s + \beta_b^s + \gamma^s \ \hat{M}_{j,d(b)} + \sum_t \mathbf{1}[c=t] \times \mathbf{X}_j' \theta_t^s \right\} + \epsilon_{i,j,b} \ , \tag{4}$$

where $g_i \in (wom, men)$ denotes the gender of individual i. Equation (4) is essentially a fully-interacted version of Equation (3) with separate effects for women and men: the coefficient γ^{wom} captures the effect of the adoption of milking machines on women, γ^{men} the effect on men, and $\gamma^{wom} - \gamma^{men}$ the differential gender effect.[28]

Standard errors are clustered at the municipality level to account for correlations within a municipality in a given year and over time. We also show that our results are robust when accounting for different degrees of spatial correlation using Conley standard errors with different distance cutoffs (Conley, 1999). Throughout our analysis, we keep municipality borders constant based on the "kommuner" classification of 1980.

4.3 Threats to identification

Our exposure design is conceptually similar to a shift-share instrumental variable approach. In the framework developed by Goldsmith-Pinkham et al. (2020), such an approach relies on assuming that shares are exogenous.[29] In our case, this assumption implies that the initial "shares" (i.e., the number of milk cows per farm in 1930) do not predict the evolution of young women and men's labor market outcomes, income, or migration decisions, except through the local rate of adoption of milking machines. This section presents several validity checks proposed by Goldsmith-Pinkham et al. (2020) to assess the credibility of this assumption.

Before doing so, it is important to note three crucial differences between our exposure design and classic shift-share approaches. First, compared to the classic shift-share design, where it is not always possible to establish a zero date to test for pre-trends, we have a clear zero date when the first milking machines were adopted in Norwegian farms, which we use below to validate our research design. Second, we use a single "share" (the initial female employment in farming) rather than multiple shares as in canonical shift-share designs (e.g., multiple industry shares). Therefore, it is not necessary to examine the sensitivity of our results to misspecification of multiple instruments as captured by their Rotemberg weights. Finally, our design also differs from the canonical case because we have a third dimension, gender, which accounts for time-variant, municipality-specific unobserved factors that potentially affect both young women and men. Any confounding factor that would bias $\hat{\gamma}^s$ would therefore need to be correlated not only with the shares but also to have a differential impact on women and men.

As a first validity check, we explore correlations between the diffusion of milking machines and a wide range of initial (year 1930) municipality characteristics. These validity checks

[28]Note that Equation (4) is a cell means model which does not include a common constant. This allows estimating the two main effects γ^{wom} and γ^{men} separately.

[29]Borusyak et al. (2022) present an alternative framework in which the validity of the shift-share instruments relies on the exogeneity of the "shifters." They note that this framework is well-suited for settings where units are exposed to a large number of idiosyncratic shifters, while Goldsmith-Pinkham et al. (2020)'s framework applies to situations where units are differentially exposed to a limited number of common shocks, as in our case where the nationwide adoption of milking machines is the single shifter.

are informative of potential confounders that might generate differential trends in outcomes across municipalities, and could therefore violate our identifying assumption (Goldsmith-Pinkham et al., 2020, p.2605). Specifically, we use a Lasso procedure to select the relevant control variables that might be correlated with both the endogenous regressor, $M_{j,d(b)}$, and the outcome variables. Reassuringly, the uptake of milking machines across municipalities is not strongly associated with most potential correlates besides the number of milk cows per farm. The Lasso procedure only selects 3 out of 23 potential correlates: farms per capita, the share of improved farmland, and the ratio of large to small farms (see Appendix Table A.3).[30] We added the selected controls interacted with birth cohort fixed effects to our estimating equations (see Equations 2 and 3). These flexible trends' specifications capture the possibility that rural municipalities were on a different trajectory of structural transformation already before the arrival of milking machines. In addition, we include county-by-birth cohort fixed effects to flexibly account for county-specific time-varying unobservables that may violate the exogeneity of our exposure measure. We further show that the number of milk cows per farm is not positively correlated with municipality wealth and wages in 1930 and that the farm size distribution has not substantially changed over time (see Appendix Figures A.13 and A.14).

The second validity check is a permutation test that reshuffles the number of milk cows per farm in 1930 among municipalities. This test can be used to support our identifying assumption: If the initial number of milk cows per farm is endogenous and women's and men's outcomes only reflect the existence of pre-trends, then the coefficients from the permutations will remain different from zero and close to our baseline estimates. Instead, if the initial number of milk cows per farm is exogenous, the coefficients from the permutations will be centered around zero. To perform this permutation test, we consider the reduced-form version of Equation (4), where the main outcomes of interest are regressed on our exposure measure, $E_{j,d(b)}$. For each permutation, $E_{j,d(b)}$ is the interaction between the "reshuffled" share (milk cows per farm reshuffled among rural municipalities and within age cohorts) and the "true" shift (the national roll-out of milking machines). We estimate 1,000 coefficients from these permutations for the effect on women (γ^{wom}), the effect on men (γ^{men}), and the differential gender effect ($\gamma^{wom} - \gamma^{men}$). Estimated coefficients in these placebo regressions have a distribution centered around zero. The true coefficient for women and for women-

[30] All other potential correlates in Appendix Table A.3—the share of milkmaids, the share of female employment in agriculture, the female labor force participation rate, the female net-migration rate, population density, an indicator for early adoption of tractors, the share of the female population between, respectively, 15 and 19, 20 and 39, 40 and 59, 60 and over, the share of manufacturing workers, the capital-labor ratio, the municipality area, average male and female income, average male and female wealth, the crude birth rate, the crude death rate, and the share of married people—are not selected by the Lasso procedure.

men differences is larger in magnitude than all but 0-0.1 percent of the estimates from the permutations (see Appendix Figure A.8). This strongly supports the exogeneity of the shares in our exposure design.

Third, as suggested by Goldsmith-Pinkham et al. (2020), we evaluate the validity of our exposure instrument by regressing current shocks on past outcomes measured before the sample period. Figure 2 presents the results of this exercise. In detail, it shows reduced-form estimates of Equation (4), where we regress outcomes in the Censuses of 1900 and 1910 (past outcomes) on our measure of exposure to milking machine adoption in 1930-40, 1940-50, 1950-60, and 1930-70 (current shocks).[31] The figure shows these placebo estimates for women, men, and women-men differences in three adult outcomes: whether an individual works in agriculture (panel a); whether an individual has migrated from their county of birth (panel b); and whether an individual participates in the labor force (panel c). All these regressions include the full set of controls as outlined in Section 4.2.

In the presence of pre-trends, outcomes measured in 1900 and 1910 would appear different in municipalities with high and low exposure to milking machines, even if the actual diffusion only took place decades later. Reassuringly, there are no signs of pre-trends. The point estimates are very small, close to zero, and statistically insignificant, suggesting that these outcomes were not already on different trajectories in dairy-intensive municipalities at the beginning of the 20th century. These results are in stark contrast to the baseline estimates in red, obtained from regressing our local exposure measure in 1930-70 (current shocks) on outcomes from the Censuses of 1950-70 (current outcomes). We discuss these results in detail in Section 5.2.

Fourth, we can also use information from our sample period (1930-1970) to test whether women's and men's outcomes evolved similarly before the mass adoption of milking machines (e.g., before the 1940s) across municipalities with different exposure to milking machines. As proposed in Goldsmith-Pinkham et al. (2020), we estimate the following (reduced-form) event-study specification:

$$Y_{i,j,b} = \sum_{s} \mathbf{1}[g_i = s] \times \left\{ \alpha_j^s + \beta_b^s + \sum_{t \neq 1940} \gamma_t^s \; \mathbf{1}[d(b) = t] \times \frac{C_{j,1930}}{F_{j,1930}} + \sum_{t} \mathbf{1}[b = t] \times \mathbf{X}_j' \theta_t^s \right\} + u_{i,j,b} \,, \tag{5}$$

where we regress our main outcomes of interest, Y_{ijc}, on the number of milk cows per farm in 1930, $\frac{C_{j,1930}}{F_{j,1930}}$ (i.e., the treatment intensity), interacted by a set of indicator variables,

[31] We consider a sample of 304,229 rural women and men aged 16-25 in 1880 and 1890 and measure their labor market outcomes after age 25 in the historical complete count census records of Norway in 1900 and 1910. These are provided by the Norwegian Historical Data Centre (University of Tromsø) and the Minnesota Population Center (2020). The data contain detailed information about individuals' occupations, their municipality of birth and residence, and labor force participation.

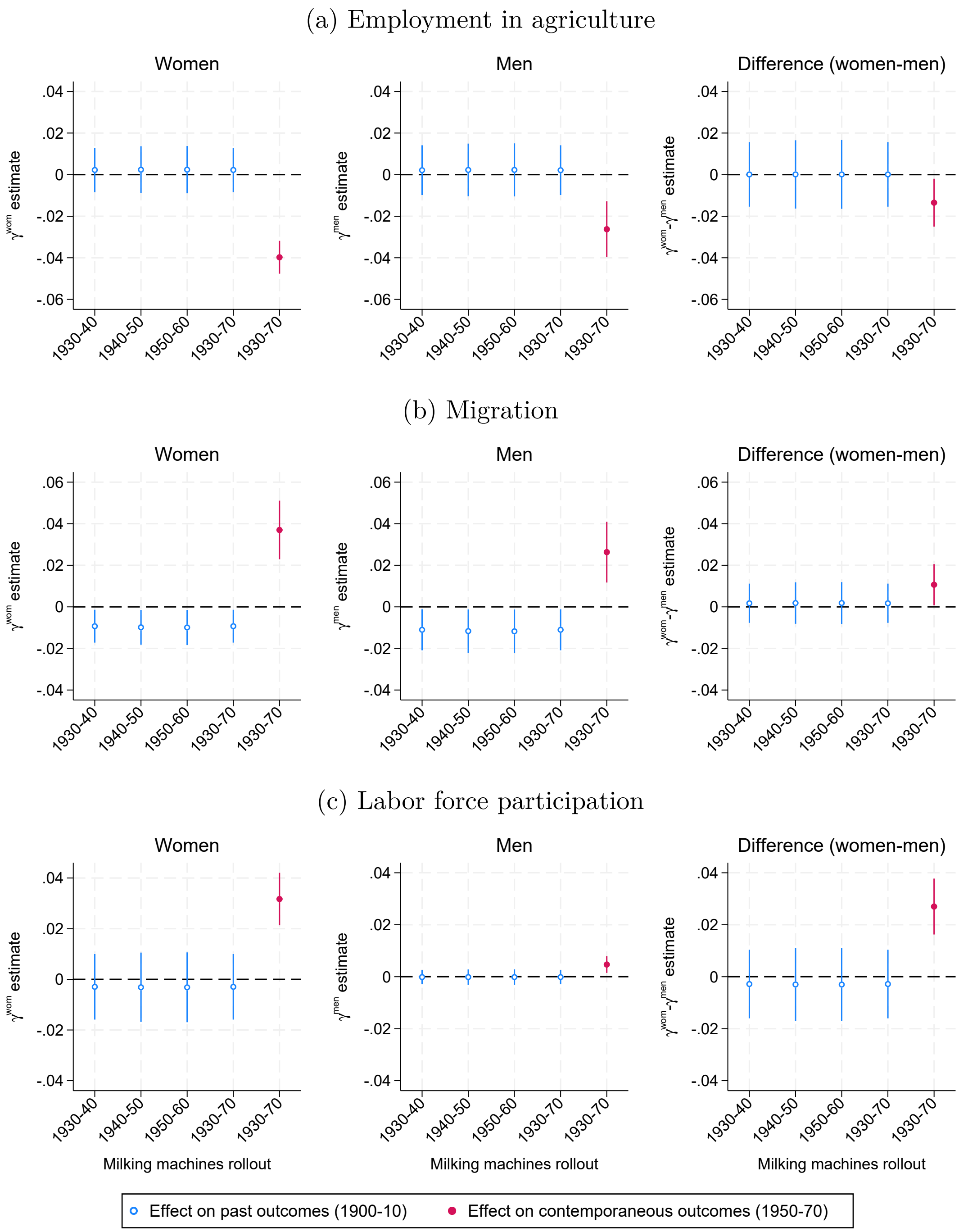


Figure 2: Placebo test based on the Censuses of 1900 and 1910 (N=304,229)

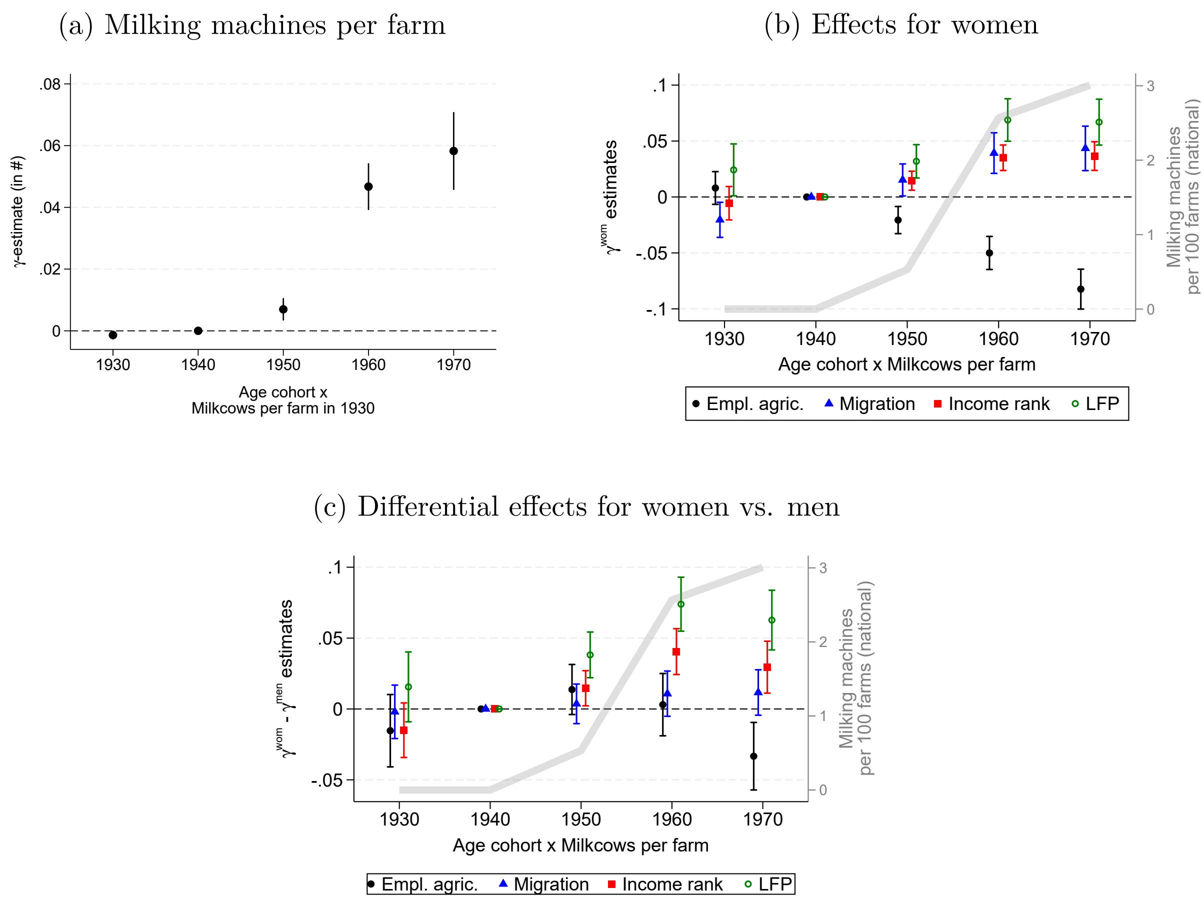
Note.— This figure reports pre-trends based on four placebo tests (blue hollow circles), where we regress "past" outcomes (individual-level outcomes of adult rural women and men in 1900 and 1910) on "current" shocks (our milking machine exposure measure for 1930-40, 1940-50, 1950-60, and 1930-70). For comparison, we also report baseline estimates (red circles), where we regress contemporaneous outcomes from the 1950-70 censuses on our exposure measure. Estimates are based on the reduced-form version of equation (3) and reported with their corresponding 95-percent level confidence intervals. The sample is 304,229 rural women and men in the 1900 and 1910 census records. Standard errors are clustered at the municipality level.

$\mathbf{1}[d(b) = t]$, for birth cohorts, b, who entered the labor market at different decades, $d(b)$. Note that this specification only exploits the dynamic response to cross-sectional variation in the "shares"; the full variation in exposure will be exploited in the main analysis. As before, we include municipality (α_j) and cohort (β_b) fixed effects, and the full set of controls interacted by birth-cohort fixed effects as outlined in Section 4.2. We refer to the 1930s as the pre-treatment cohorts and the 1950s, 1960s, and 1970s as the post-treatment cohorts. The 1940s are the omitted reference cohorts. The set of γ_t coefficients captures how the relationship between an individual's long-term outcome and the treatment intensity differs across cohorts. We capture gender effects by pooling together women and men and interacting all right-hand-side variables with gender dummies $g_i \in (wom, men)$.

Figure 3 presents the event-study estimates based on Equation (5), along with the national roll-out of milking machines in Norway over time (gray line). Panel (a) displays the results using milking machines per farm as the dependent variable. The estimated γ_t-coefficients show that rural municipalities with more milk cows in the pre-milking machines era had a higher uptake of milking machines per farm in the 1950s, 1960s, and 1970s. This finding supports the relevance of our instrument and is in line with the historical narrative. Panel (b) reports estimates for the effect on women's long-term outcomes of interest (γ_t^{wom}), and Panel (c) for the effect on women-men differences ($\gamma_t^{wom} - \gamma_t^{men}$). These event-study estimates allow us to evaluate whether the outcomes of pre-treatment cohorts with different treatment intensities follow parallel trends before the uptake of milking machines. Panel (b) shows that the number of milk cows in the pre-milking machines era predicts a similar proportion of women working in agriculture as adults and having the same income rank. There are detectable pre-trends in female labor force participation rates and long-distance migration, but when considering the women-men differences in Panel (c), these are closer to zero and no longer statistically significant.

As explained above, under our exposure design with gender effects, our estimates would be biased by a pre-trend only if it is correlated with our shares *and* has a differential impact on women and men. Because we can reject the latter in Panel (c) of Figure 3, our main estimates should not be affected by the aforementioned pre-trends in women's migration and labor force participation. Instead, these pre-trends are likely the result of the temporary effects of the interwar period and WWII rather than long-term structural changes in the economy. This is reinforced by the fact that the validation exercise based on the 1900 and 1910 censuses, which are not affected by the interwar period, shows no detectable pre-trends. To further address these concerns, we implement the "Honest Approach to Parallel Trends" of Rambachan and Roth (2023) and show that post-treatment violations of parallel trends would need to be 1.5-2 times as large as the maximal pre-treatment violations to explain

Figure 3: Cohort-specific relationship between long-term outcomes and pre-milking machines dairy intensity.



NOTE.— This figure plots the γ-estimates and 95% confidence intervals from equation (5). Panel (a) shows the effect on the number of milking machines adopted; Panel (b) the effect on women, γ_t^{wom} (left y-axis); Panel (c) the women-men differences, $\gamma_t^{wom} - \gamma_t^{men}$ (left y-axis). The gray line indicates the number of milking machines per 100 farms in Norway (right y-axis). The x-axis is the decade at which cohorts were aged 16–25. The sample is women and men born in rural municipalities with at least one farm in 1929, who were aged 16–25 in 1930–1970. Income and labor force participation is measured at age 45 for cohorts aged 16–25 in 1950, 1960, and 1970, and at age 52 and 62 for cohorts aged 16-25 in 1940 and 1930, respectively. The number of observations (women and men) is N=726,537 for employment in agriculture and migration; N=687,621 for income rank; and N=549,058 for LFP.

our results away—an unlikely scenario given that these pre-trends likely reflect temporary shocks (see Section 5.2 and Appendix Figure A.9 for details).

The small event-study estimates for the pre-treatment cohorts contrast those for the post-treatment cohorts. Panel (b) shows that in dairy-intensive municipalities, women were more likely to work outside the agriculture sector, migrate out of their county of birth, had higher incomes, and higher rates of labor force participation. These patterns are similar for the post-treatment cohorts when looking at women-men differences in Panel (c), albeit the estimated coefficients are smaller. This reflects the fact that the spread of milking machines eventually also affected men - albeit to a much lesser extent than women (see Section 2.2). Altogether, this provides some preliminary, reduced-form evidence that the adoption of milking machines triggered a process of structural change that, in the long-term, benefited women.

5 Results

5.1 Contemporaneous income effects

We begin the presentation of our results by showing the short-term income effects of the adoption of milking machines. It has been documented elsewhere that, in the short run, labor automation brings economic hardship to displaced workers (e.g., Acemoglu and Restrepo, 2020). The historical narrative suggests that in Norway milking machines had similar short-term negative effects, as young rural women lost their jobs as milkmaids and incurred large displacement costs: For example, during the 1950s, women's foregone income from not working as a milkmaid was around NOK 3,100 per year (with board). This would cover around one-quarter of the expenditure of a working-class household with two children in a Norwegian city at that time.[32]

Ideally, to evaluate short-term effects we would use yearly income data for all women and men in our sample and trace how their incomes evolved year-by-year after milking machines were adopted. However, Norway's tax registry provides yearly income data only from 1967. Therefore, the short-run analysis is restricted by construction to women and men who turned 16 in 1970—the only cohort in our main sample for whom we can track yearly income responses from the beginning of their working lives. Importantly, the Census of Agriculture reports a large-scale uptake of milking machines from 40,000 in 1960 to 50,000 in 1970 (Panel (a) of Figure 1). Hence, the evolution of the incomes of these young women and men in the years following 1970 can illustrate the short-term effects of introducing milking machines well.

Specifically, our short-term analysis is based on a panel of 18,014 women and men whom we have observed over 25 years since they entered the labor market in 1970 (N=450,350). We estimate the short-term income effects of milking machines by gender as follows:

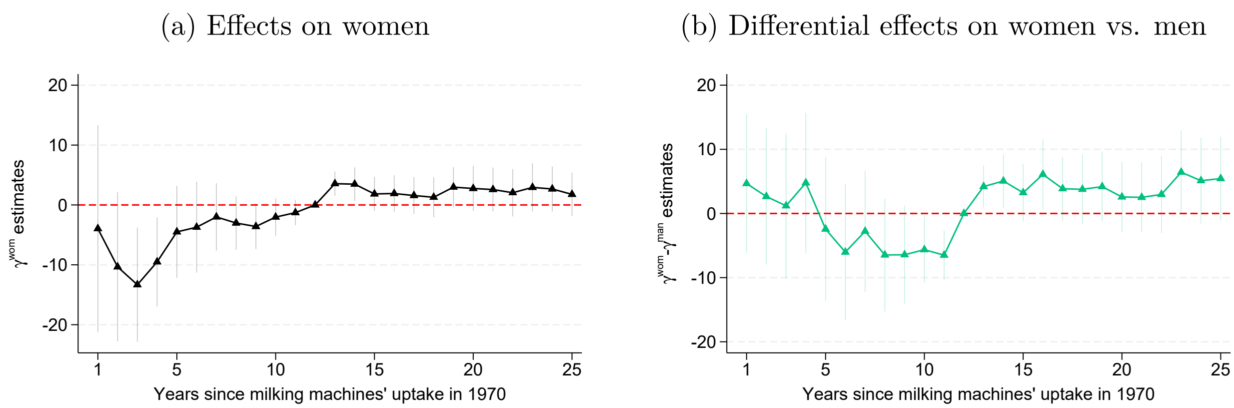
$$r(y_{i,j,t}) = \sum_{s \in (wom,men)} \mathbf{1}[g_i = s] \times \{\alpha_0^s + \alpha_j^s + \alpha_t^s + \sum_{k \neq 12} \gamma_k^s \, \mathbf{1}[t - 1970 = k] \times M_{j,1970}\} + u_{i,j,t} \ , \quad (6)$$

where y_{ijt} is the income in year $t \in \{1970, ..., 1995\}$ of individual i who was born in rural

[32] For more details, see Statistical Yearbook of Norway 1955, Tables 237 and 250.

municipality j and who turned 16 in 1970. We follow the recommendation by Chen and Roth (2024, p. 916) and transform income data into percentile ranks. In detail, $r(y_{i,j,t})$ is the percentile rank of income y in year t, relative to all the incomes in year t of men and women in this sample. α_j and α_t are fixed effects for municipalities and years. The main variable of interest is the interaction between the number of milking machines per farm in municipality j in 1970, $M_{j,1970}$, and $\mathbf{1}[t-1970=k]$, a set of dummy variables for the number of years since 1970 (when the relevant uptake of milking machines took place for this sample). The omitted year is 1982.[33] As before, we capture gender effects by pooling together women and men and interacting all variables with gender dummies $g_i \in (wom, men)$. Equation (6) is essentially a fully interacted model that reports separate effects of milking machines on income by gender. Hence, the γ_k^s coefficients capture the differential evolution of incomes by gender s in municipalities where milking machines were adopted at different rates in 1970, compared to differences 12 years after 1970.

Figure 4: Income dynamics since the uptake of milking machines in 1970



NOTE.— This figure plots estimates with their corresponding 95% confidence intervals from equation (6). Panel (a) shows $\hat{\gamma}^{wom}$, Panel (b) shows $\hat{\gamma}^{wom} - \hat{\gamma}^{men}$. The sample is a panel of 18,014 women and men born in rural municipalities who turned 16 in 1970 and their incomes over 25 years from 1970 to 1995 (N=450,325). Standard errors are clustered by municipality.

Figure 4 displays estimates from Equation (6). Panel (a) shows the effect on women, $\hat{\gamma}^{wom}$; Panel (b) the differential gender effect, $\hat{\gamma}^{wom} - \hat{\gamma}^{men}$. For each additional milking machine per farm, women's incomes declined by 4-13 percentile ranks in the first five years and by 1-4 percentile ranks in the following five years. These short-run effects were larger for women than for men. The first 10-12 years saw women's incomes declining up to 6

[33]We choose 1982 as the omitted category because it is the middle year in our panel, and hence, allows us to capture short-term effects relative to income differences in the medium term. In addition, estimating a cell means model without omitted category and no constant yields estimates close to zero for γ_{1982}^{wom} and for $\gamma_{1982}^{wom} - \gamma_{1982}^{men}$. Hence the documented effects are relative to a "zero effect".

percentile ranks more than men's incomes for every additional milking machine per farm, although the differences are only statistically significant after the first five years. Altogether, this is consistent with the negative income effects of losing access to milkmaid jobs.

The estimates in Figure 4 also suggest that the negative effects on young women's incomes are short-lived and reverse around 15 years after the uptake of milking machines. By then, women originally from municipalities with a higher uptake are consistently higher in the income distribution than women from municipalities with a lower uptake. Similarly, for every additional milking machine per farm, women improve their position relative to men by 5 percentile ranks. These findings indicate that the diffusion of milking machines improved the long-term earning opportunities for affected young women, despite the initial displacement costs.[34] In the next section, we study these long-term effects in detail and show that they are associated with a structural transformation of women's work.

Table 1: The diffusion of milking machines in 1970 and short-term income effects

	(1) Women	(2) Men	(3) Difference
Milking machines per farm in 1970			
× 1-10 years after 1970s rollout	-0.199***	-0.047	-0.160**
	(0.073)	(0.075)	(0.079)
× 11-20 years after 1970s rollout	-0.018	0.025	-0.041
	(0.039)	(0.023)	(0.045)
× 21-25 years after 1970s rollout	ref.	ref.	ref.
Municipality FE	Y	Y	Y
Year FE	Y	Y	Y

NOTE.— This figure plots QMLE Poisson estimates using aggregate time periods based on Equation (6). Column (1) shows the proportional treatment effect for women, $\exp(\hat{\gamma}^{wom}) - 1$, Column (2) for men, $\exp(\hat{\gamma}^{men}) - 1$, and Column (3) for the differential women vs. men effect, $\exp(\hat{\gamma}^{wom} - \hat{\gamma}^{men}) - 1$. The sample is a panel of 18,014 women and men born in rural municipalities who turned 16 in 1970 and their incomes over 25 years from 1970 to 1995 (N=450,325). Standard errors are clustered by municipality; *p<0.1; **p<0.05; ***p<0.01.

Table 1 reports estimates based on a more parsimonious version of Equation (6) which

[34] Although summing these estimates over time seems to suggest that short-term effects outweigh long-term benefits, note that the income variation in the first years (e.g., ages 16-20) is much smaller than the income variation in the latter years (e.g., ages 35-40). That is, a reduction in 5 ranks at age 16 implies an income loss that is much smaller in magnitude than an increase in 5 ranks at age 40. Hence, in the aggregate, the long-term effects still outweigh short-term costs, as illustrated by the analysis of short-term income responses in log-levels (e.g., see Panel (b) of Appendix Figure A.1).

uses more aggregated time periods. To obtain an approximate percentage interpretation of the short-term effect of milking machines on incomes, we estimate Poisson quasi-maximum likelihood (QMLE) regressions following the suggestions by Chen and Roth (2024). Columns (1) and (2) show the results for the proportional treatment effects on women, $\exp(\hat{\gamma}^{wom})-1$, and men, $\exp(\hat{\gamma}^{men})-1$. For every additional milking machine per farm in their municipality in 1970, women experienced a 20% drop in their income rank in the first decade after the introduction, compared to the corresponding effect 21-25 years later. In contrast, men's incomes were not significantly affected by the uptake of miking machines in the short run. The differential gender effects, $\exp(\hat{\gamma}^{wom}-\hat{\gamma}^{men})-1$, are presented in column (3). The income differences peaked during the first decade after the adoption of milking machines, which saw women's incomes declining by around 16% more than men's incomes in municipalities with a stronger uptake. After that, women's and men's incomes gradually converged, and 11-20 years after the shock the differences are small and no longer statistically significant.

These negative short-term effects can also be observed for earlier cohorts for which a yearly panel with individual incomes does not exist (available only since 1967). Using household-level data from the 1960 Census, we document a negative association between the uptake of milking machines in 1960 and the share of household members who were employed in 1960.[35] We also find a positive association with contemporaneous student activity in the household. This suggests that young women stayed longer at school as a result of reduced earning opportunities when milking machines replaced the jobs of milkmaids (see Appendix Table A.1 for details).

Finally, our short-run results are robust to alternative specifications that deal with zero-valued outcomes (Chen and Roth, 2024)—namely estimating average proportional treatment effects from a Poisson QMLE regression on income; log effects with calibrated extensive-margin values; log effects for the intensive margin alone; and separate expensive margin estimates. This suggests that our short-run estimates are not driven by extreme incomes in the tail of the distribution (see Appendix A.1 and Appendix Figure A.1 for details).

5.2 Main results: long-term effects

We begin our long-term analysis by assessing whether young women exposed to the diffusion of milking machines were pushed out of agriculture as middle-aged adults and whether this long-term displacement was gender biased.

Table 2 presents 2SLS estimates of Equation (4) based on our main sample of all women

[35] We consider the share of employed household members to measure negative short-term effects at the household level. The estimate is based on a cross-section of households in rural municipalities with at least one woman aged 16-25 in 1960.

and men born in rural municipalities and aged 16 to 25 between 1930 and 1970. The number of milking machines per farm is standardized and instrumented with the local exposure to milking machines (see Equations (1) and (2)). Hence, the parameter of interest, $\hat{\gamma}^{2SLS}$, captures the effect of one standard deviation increase in milking machines per farm, which corresponds to one additional milking machine per ten farms. We report $\hat{\gamma}^{2SLS}$ by gender and test for the equality of the effects for men and women. We consider three different specifications: The first specification (column 1) is a parsimonious model including fixed effects for municipalities and birth cohorts and flexible trends for the baseline controls. The second specification (column 2) is our baseline specification, which further accounts for county-by-birth year fixed effects. The third specification (column 3) restricts the sample to the 1950-1970 cohorts, and hence is based on self-reported occupations at age 26-35 in the Censuses immediately following the diffusion of milking machines.

All three specifications show that women who were more affected by the diffusion of milking machines at the age of 16-25 were less likely to work in agriculture as middle-aged adults.[36] The 2SLS coefficient for women, $\hat{\gamma}^{wom}$, is always negative and statistically significant at the 1-percent level. The estimates are also quantitatively sizable. They imply that a one-standard-deviation increase in milking machines per farm decreases a woman's likelihood of working in agriculture after the adoption of milking machines by 3.7-5.2 percentage points, or by 40-57% of the sample mean for women (0.091).

For men, the estimated coefficient is also negative. This is consistent with the historical evidence described in Section 2, which suggests that—although men were not directly employed as milkmaids—they were eventually affected by the mechanization of agriculture and had to find employment elsewhere in rural areas. However, the estimated effect for men is always substantially smaller (in absolute terms) than for women. The null hypothesis that the estimated coefficient is the same for men and women (i.e., $H_0 : \hat{\gamma}^{wom} = \hat{\gamma}^{men}$) can be rejected with a p-value of 0.015 in our baseline specification in column (2). In column (3), which restricts the sample to the 1950-1970 cohorts, the effect on men is close to zero and no longer statistically significant. It corresponds to less than 1/3 of the effect size on women. This suggests that, although men were also affected by the mechanization of agriculture, the long-term displacement caused by milking machines was gender-biased and affected women substantially more.

Columns (4)-(7) of Table 2 report the corresponding reduced-form and first-stage estimates, and OLS estimates of Equation (4). All these specifications consider the full sample and include the full set of controls as in our baseline IV specification (column 2). The

[36] 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 A.4).

Table 2: The diffusion of milking machines and long-term employment in agriculture

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
				Reduced	First stage		
	IV	IV	IV	form	women	men	OLS
Milking machines (women)	-0.052***	-0.044***	-0.037***	.	.	.	-0.017***
	(0.007)	(0.005)	(0.005)				(0.002)
Milking machines (men)	-0.039***	-0.029***	-0.012	.	.	.	-0.011***
	(0.009)	(0.008)	(0.009)				(0.004)
Cows 1930 × National rollout (wom)	.	.	.	-0.040***	0.896***	.	.
				(0.004)	(0.087)		
Cows 1930 × National rollout (men)	.	.	.	-0.026***	.	0.904***	.
				(0.007)		(0.091)	
p-value (women = men)	0.073	0.015	0.001	0.022	.	.	0.103
Municipality and cohort FE	Y	Y	Y	Y	Y	Y	Y
Flexible trends (Lasso)	Y	Y	Y	Y	Y	Y	Y
County-by-byear FE	.	Y	Y	Y	Y	Y	Y
Sample restricted to 1950-70	.	.	Y	.	.	.	.
F-stat	.	.	.	.	105.4	99.4	.
Mean dep. variable	0.13	0.13	0.10	0.13	.	.	0.13
Observations	726,537	726,537	512,059	726,537	379,366	347,171	726,537

Note.— This table shows IV, reduced-form, and OLS estimates are based on equation (4). The sample includes women and men born in rural municipalities with at least one farm in 1930, who were aged 16–25 in the census years 1930-70 (except in col. 3). Independent variables are normalized to have a mean of zero and an SD of one. Flexible trends selected with a LASSO procedure (see Appendix Table A.3) include two municipality-level measures of agricultural intensity in 1930 × birth cohort FE; the municipality-level farm-size distribution in 1930 × birth cohort FE; a municipality-level measure of capital intensity in 1930 × birth cohort FE; and the municipality-level female income in 1930 × birth cohort FE. The specifications also include county-by-birth year fixed effects (except in col.1). See Section 3 for data sources and Section 4.2 for more details on the specification. Standard errors in parentheses clustered at the municipality level; *p<.05; **p<.01; ***p<.001.

reduced-form effect of milking machines on displacement from agriculture is more than 40% larger for women than for men (column 4), and the equality of both coefficients can be rejected with a p-value of 0.022. The first-stage estimates (columns 5-6) are consistent with the evidence presented in Panel (a) of Figure 3 that our measure of exposure to milking machines predicts well its actual rate of adoption. There is also no sign of a weak instrument: the Kleibergen-Paap F-Statistic of instrument strength is far above the rule of thumb cutoff of 10. The OLS estimate (column 7) is statistically significant but substantially smaller than the 2SLS estimates (columns 1-3). The reason why 2SLS estimates are larger is that they capture *local average treatment effects* (LATE) for young women on dairy farms, who according to the historical narrative had higher economic returns to moving than the average person in the rural population—the average treatment effect (ATE); see Imbens and Angrist (1994).[37]

Altogether, these results suggest that the adoption of milking machines displaced young

[37]The larger 2SLS estimates are also consistent with our conceptual framework in Appendix A.3, which predicts heterogeneity in returns from leaving the rural sector and a positive selection for young affected women (see Panel (b) of Appendix Figure A.19).

women from traditional milkmaid jobs, and that these women found employment outside the primary sector in the long run. Although rural men were also affected by the mechanization of agriculture, the long-term displacement from agriculture caused by milking machines was gender-biased and affected women much more.

Next, we turn our attention to other long-term outcomes. We examine whether the large-scale adoption of milking machines also pushed women to migrate out of rural areas, as suggested by the historical narrative in Section 2.1. We also document the long-term effects on incomes and labor force participation to gauge the extent to which milking machines transformed women's work and helped reduce gender gaps in the labor market.

Panel A of Table 3 presents 2SLS estimates based on Equation (4) for the three aforementioned outcomes: long-distance migration, income rank, and labor force participation. As before, we pool women and men together and report the estimated effect of milking machines for each gender along with a test for the equality of the effects for men and women. All specifications include the full set of controls in our baseline specification (column (2) of Table 2). We also report the corresponding reduced-form (Panel B) and OLS estimates (Panel C) for comparison.

Column (1) shows that municipalities with a higher uptake of milking machines experienced a substantial out-migration of young female workers. The 2SLS estimate is positive and statistically significant at the 1-percent level. Quantitatively, a one-standard-deviation increase in milking machines per farm increased the likelihood of young rural women leaving their county of birth by 4 percentage points, or about 10 percent of the sample mean for women (0.398). As before, we find some evidence on long-distance migration for men, albeit the estimated coefficient is smaller and only 0.7 of the effect size for women. A test for the equality of both coefficients can be rejected with a p-value of 0.03. These results suggest that the diffusion of milking machines not only reduced female employment in agriculture but also pushed them out of their county of birth in larger quantities than men, triggering a gender-biased process of structural change.[38]

Did this process reduce the gender gaps in income? Column (2) of Table 3 shows that in line with the evidence presented in Section 5.1, affected women ended up at a higher echelon of the income distribution in the long term. The 2SLS estimate for women implies that, for a one-standard-deviation increase in milking machines per farm, women climbed up the income distribution by almost two percentiles. In contrast, affected men did not gain from the diffusion of milking machines in the long run: the estimated coefficient on men is close

[38]This is consistent with descriptive reports from Statistics Norway, which state that between 1960 and 1980 "women 20–24 years old have the highest mobility. Women also have a higher total mobility than men, and their period of high mobility starts earlier than for men" (Lian, 1981, p.32 and Appendix Figure A.15).

Table 3: The diffusion of milking machines and long-term outcomes

	(1) Migration	(2) Income pctile rank	(3) Labor force participation
Panel A. IV			
Milking machines (women)	0.041***	1.892***	0.038***
	(0.008)	(0.305)	(0.007)
Milking machines (men)	0.029***	0.031	0.006**
	(0.009)	(0.371)	(0.002)
p-value (women = men)	0.030	0.000	0.000
Panel B. Reduced form			
Milkcows 1930 × National rollout (women)	0.037***	1.692***	0.032***
	(0.007)	(0.263)	(0.005)
Milkcows 1930 × National rollout (men)	0.026***	0.028	0.005***
	(0.007)	(0.331)	(0.002)
p-value (women = men)	0.035	0.000	0.000
Panel C. OLS			
Milking machines (women)	0.011***	0.637***	0.011***
	(0.004)	(0.137)	(0.003)
Milking machines (men)	0.007*	-0.114	0.001
	(0.004)	(0.154)	(0.001)
p-value (women = men)	0.178	0.000	0.000
Municipality and cohort FE	Y	Y	Y
Flexible trends (Lasso)	Y	Y	Y
County-by-byear FE	Y	Y	Y
Mean dep. variable	0.38	49.87	0.87
F-stat first stage (women)	105.4	101.3	81.8
F-stat first stage (men)	99.4	99.2	79.8
Observations	726,537	687,621	549,058

NOTE.— This table shows IV, reduced-form, and OLS estimates based on equations (2) and (4). Migration (col. 1) is a dummy equal to one if an individual migrated out of their county of birth. Income rank (col. 2) is measured at age 45 for cohorts aged 16–25 in 1950, 1960, and 1970 and at age 52 and 62 for cohorts aged 16-25 in 1940 and 1930, respectively. Labor force participation (col. 3) is a dummy variable equal to one if the individual reports a positive income at age 45. The sample includes women and men born in rural municipalities with at least one farm in 1930, who were aged 16–25 in the census years 1930–1970. In cols. 7-8, the sample is restricted to cohorts for which we know their income at age 45. Independent variables are normalized to have a mean of zero and an SD of one. All specifications are fully-interacted models, where gender dummies are interacted with fixed effects for municipality and birth cohort; flexible trends selected with a LASSO procedure (see Appendix Table A.3) and defined as in Table 2; and county-by-birth cohort fixed effects. Standard errors in parentheses clustered at the municipality level; *p<.05; **p<.01; ***p<.001.

to zero and statistically insignificant. Hence, the income differences between these women and men were reduced by about 2 percentile ranks as a result of the adoption of milking machines. As before, a test for the equality of coefficients rejects that women and men were equally affected with a p-value of 0.000.[39]

In addition to lowering the gender income gap, we find that the adoption of milking machines also reduced gender differences in labor force participation. The estimates in column (3) show that the gender-specific differences in labor force participation rates decreased by more than 3 percentage points as a result of the adoption of milking machines. In detail, for every one standard deviation increase in the number of milking machines per farm young women (men) increased their labor force participation as middle-aged adults by 3.8 (0.6) percentage points, or by 4.4 (0.7) percent relative to the sample mean. These gender-specific differences are statistically significant and robust to the use of alternative definitions of labor force participation (Appendix Table A.5).

Importantly, women more 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 participate in the labor force (extensive margin), but also because earned higher incomes (in log-levels) (see Appendix Table A.6). We also document that these results are most likely driven by women who left their birthplace and moved to cities (Appendix Table A.7).

We perform several robustness checks and extensions of the long-term analysis. Our results are robust to modifying our exposure measure in Equation (1) by replacing the number of milk cows per farm with the share of women employed as milkmaids in 1930 to proxy dairy-farming suitability before the diffusion of milking machines (Appendix Table A.8).[40] Estimates are also very similar across stratified samples with municipalities that had no milking machines by 1950 versus municipalities that had adopted them by 1950 (Appendix Table A.9). They are also not confounded by local access to hydroelectric power—the main mode of electricity production in Norway during our study period (Appendix Table A.11). Importantly, we show that our results are not simply a byproduct of education reforms (e.g., Porzio et al., 2022)—the Folk School Law (1936) and the Primary School Reform (1959), which were the two major social-democratic reforms of Norway's schooling system during our sample period (Appendix Table A.12).[41] Standard errors are similar when we account

[39] As explained in Section 3.1, 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. Because the tax registry only started in 1967, we use income at age 52 and 62 for earlier cohorts who were over 45 in 1967. Results remain unchanged if we exclude these earlier cohorts and if we construct income percentile ranks based on incomes at age 40 (Appendix Table A.6).

[40] Note that these shares capture only paid labor. The effects are qualitatively similar but smaller in magnitude than the effects using cows per farm (which capture paid and unpaid labor). This suggests that the effects of unpaid labor played an important role.

[41] 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, and, hence, before the widespread adoption of milking machines. The Primary School Reform, on the other hand, increased compulsory education from

for spatial dependence in the error term using Conley (1999) standard errors with different distance cutoffs (Appendix Figure A.12). We also extend our analysis to learn more about the receiving urban areas. First, we show that our results are robust to excluding women and men who migrated to Oslo (Appendix Table A.10). Second, we narrow the focus on the 10 largest cities. Oslo, Bergen, and Trondheim absorbed between 22-25% of rural female migrants. That said, 1 out 3 women who migrated out of their birthplace did so to smaller urban areas of 10,000 to 50,000 inhabitants (Appendix Table A.18). Third, we map the share of rural female migrants by destination. Migration was relatively widespread and not only directed at the growing towns around Oslo (Appendix Figures A.16 to A.18). Finally, as explained above, WWII may have affected some women's outcomes, even if only temporarily. Nevertheless, we show in Appendix Table A.13 that our estimates are robust to controlling for trends by the intensity of WWII, captured by German investments in industry, airports, and coastal infrastructure in each municipality (Abramitzky et al., 2024).

Moreover, we explore the robustness of our estimates to violations of the parallel-trends assumption. We implement the "Honest Approach to Parallel Trends" of Rambachan and Roth (2023). Specifically, we estimate robust confidence sets for the effect of milking machines on post-treatment cohorts (i.e., aged 16-25 after 1950), assuming that the post-treatment violation of parallel trends (i.e., in 1950–70) is $\hat{M}$ times the maximum pre-treatment violation of parallel trends (i.e., in 1930–1940).[42] Our results disappear only under an $\hat{M}$ of 1.5 to 2. That is, post-treatment violations of parallel trends need to be 1.5 to 2 times as large as the maximal pre-treatment violations to explain away the estimates for women (see Appendix Figure A.9). Considering that the pre-trends violations discussed in Section 4.3 do not concern all outcomes, they disappear for women-men comparisons, and likely reflect temporary effects of WWII, it is plausible to assume that $\hat{M} < 1$ in our setting. Namely, that the differential factors in the post-treatment period were smaller than in the pre-treatment period. Given this fact, and the additional validation exercise based on the 1900-10 censuses (Figure 2), potential pre-trends are unlikely to drive our main results.

Overall, our results show that the introduction of milking machines had different consequences for young women and men in rural Norway. Substantially more young women than men left farming and migrated out of rural areas. This not only led to higher labor force

7 to 9 years and was implemented by different municipalities at different points in time from 1960 to 1972 (Black et al., 2005). However, Appendix Figure A.11 shows that the roll-out of this reform and the large-scale adoption of milking machines were two orthogonal processes.

[42] In detail, the "Honest DiD" are based on estimates of $Y_{i,j,b} = \alpha_j + \beta_b + \sum_{t \neq 1940} \gamma_t \, \mathbf{1}[d(b) = t] \times \frac{C_{j,1930}}{F_{j,1930}} + \sum_t \mathbf{1}[b = t] \times \mathbf{X}'_j \theta_t + u_{i,j,b}$, where we consider two pre-treatment cohorts (1930 and 1940) to evaluate the maximum violation of parallel trends, and one post-treatment cohort (1950-1970) to evaluate the treatment effect of milking machines on women's adult outcomes $Y_{i,j,b}$. Because we only cannot reject pre-trends for women's migration and LFP, we restrict this robustness check to women's outcomes.

participation and incomes in the long term but also to a decline in the gender gap.

6 Mechanisms

Why did the automation of hand milking result in long-term income gains for displaced women? In this section, we examine two complementary mechanisms: First, as suggested by Acemoglu and Restrepo (2019), automation can benefit displaced workers if employment opportunities in new occupations emerge and labor is reinstated. This process typically requires investments in education, upskilling, and occupation upgrading of displaced workers. In our setting, this corresponds to the possibility that young women on dairy farms responded to the disappearance of hand milking by learning new skills that enabled them to reorient themselves to better-paid, higher-skilled jobs, particularly the new occupations in the expanding public sector. In Section 6.1, we provide evidence for this mechanism.

Second, automation can lead to long-term gains if it lowers barriers to migration out of rural areas and removes allocative inefficiencies across sectors (Munshi and Rosenzweig, 2016). Nakamura et al. (2021) and Sarvimäki et al. (2022) provide examples of how large shocks—natural disasters and forced migration—can lead to long-term gains by breaking allocative inefficiencies. For female labor in our setting, barriers to moving across sectors partly stemmed from traditional norms on the gender division of labor on farms, family ties, larger opportunity costs of having children, and, more generally, social norms about the role of women. For example, during our study period there existed a strong norm, especially in rural areas, that women should not work outside the house or the farm after marrying and having children (Goldin, 2024). In Section 6.2, we examine whether milking machines triggered changes in fertility and marriage which, in turn, might have lowered these barriers and facilitated female labor force participation and their reallocation from the rural to the urban sector.[43]

6.1 Educational investments and occupational upgrading

We begin by examining the possibility that automation reinstated displaced female labor in high-skilled occupations. We do so by matching the classification of occupations with the skill content from O*Net. In addition, we explore the extent to which women reallocated to

[43] In Online Appendix A.3, we develop a simple conceptual framework that encompasses these two mechanisms. Our model combines a task-based production function that accounts for the gender division of labor and automation (Zeira, 1998; Autor et al., 2003; Acemoglu and Autor, 2011) with the key ideas of comparative advantage to explain the reallocation of labor from the rural to the urban sector (Roy, 1951). The model formalizes how automation can break up allocative inefficiencies, reinstate labor into jobs in the urban sector, and generate long-term income gains.

public sector jobs. According to the historical narrative, the expansion of the public sector in Norway provided employment opportunities in urban areas for displaced rural women after the 1950s (see Section 2.1). Public sector occupations performed by women were typically white-collar jobs, including teachers, public service administrators, social workers, and nurses. Hence, displaced young rural women would have had to invest in their education in order to take up these jobs.

Table 4 presents 2SLS, reduced-form, and OLS estimates of Equation (4), where we use as dependent variable an indicator equal to one for occupations with, respectively, a low-, medium-, and high-skill content, as well as for public-sector occupations. We use the same empirical strategy comparing men and women, and the same baseline controls as in Section 5.2. Our goal is to evaluate whether displaced farm workers engaged in occupational upskilling elsewhere. Therefore, we restrict the analysis of occupational upgrading to individuals who did not work in agriculture as middle-aged adults.[44]

The estimates suggest that women displaced from agriculture when young ended up in high-skill occupations as middle-aged adults, especially in the public sector. The 2SLS estimates in Panel A suggest that a one-standard-deviation increase in milking machines per farm increased a woman's likelihood of taking up a high-skill occupation by 1.1 percentage points (column 1), or by 9 percent of the sample mean for women (0.125). Conversely, it did not push affected women into medium-skill occupations (column 2), and reduced their probability to work in a low-skill occupation by 1.4 percentage points (column 3), or by 4 percent of the sample mean for women (0.343). The public sector expansion played a crucial role in this occupational upgrading. A one-standard-deviation increase in milking machines per farm increased a woman's likelihood to work in the new, high-skilled, public sector jobs by 1.4 percentage points (column 4), or by 16 percent of the sample mean for women (0.088). These effects are consistent across 2SLS, OLS, and reduced-form specifications.

In contrast to women, we find no evidence that men moved up the occupational ladder after the introduction of milking machines. The estimated 2SLS coefficients in columns (1), (3), and (4) for men are close to zero, and none is statistically significant. Young men from affected rural municipalities were neither more likely to reallocate from low- to high-skill occupations, as it was the case for women, nor to get jobs in the public sector as middle-aged adults. A test for equality of the estimates for men and women on low-skilled and public-sector occupations (which typically require high skills) can be rejected with a p-value of 0.011 and 0.01, respectively. For high-skill occupations, the point estimates for men is half the size of that of women, although it is also not precisely estimated and the test for the

[44] In addition, we restrict this sample to non-farming occupations because our data does not allow us to separate the skill content of specific jobs within the agricultural sector.

equality of the estimates cannot be rejected. Altogether, this evidence suggests that, in the long-run, the automation of hand milking created opportunities for displaced rural women (not men) to improve their socioeconomic status through occupational upgrading.

Consistent with this occupational upgrading hypothesis, we also find that affected women invested more in their formal education.[45] Specifically, column (5) presents 2SLS, reduced-form, and OLS estimates for the effect of milking machines on the likelihood of attaining undergraduate education. For these specifications, we use our full baseline sample, as individuals who remained in agriculture could, in principle, also invest more in their education. Across specifications, estimates show that rural women exposed to milking machines at the age of 16-25 were more likely to obtain at least an undergraduate degree during their lifetime. This effect is quantitatively sizable. For instance, the 2SLS estimate suggests that a one-standard deviation increase in milking machines per farm increases the likelihood of women obtaining at least undergraduate education by 1.5 percentage points, or 15 percent of the sample mean for women (0.099). In contrast, the corresponding estimate for men is half the size, and a test for the equality of the coefficients for men and women can be rejected with a p-value of 0.08. As a robustness check, we show that these effects on education—as well as the gender-specific effects documented in Tables 2 and 3—were not just a byproduct of Norway's major education reform in 1959 (see Appendix Table A.12).

Overall, our results are consistent with a strong reinstatement effect as described in Acemoglu and Restrepo (2019).This implies that human capital investments played a major role in the occupational upgrading experienced by Norwegian women after the automation of hand milking.

Next, we explore this mechanism further by examining the relationship between higher-education local infrastructure and rural out-migration. Because women displaced by milking machines required (above primary) formal education to be reinstated into high-skill jobs, we expect them to move to towns with higher-education institutions. To test this hypothesis, we present 2SLS, OLS, and reduced-form estimates of Equation (4) on our full baseline sample, where the dependent variable is migration to a town with a higher-education institution. We construct this variable using data from Machin et al. (2012) on Norway's local schooling infrastructure in the early 1960s.[46]

[45]Note that an interesting exercise would be to compare women who completed their primary or even secondary education to those who were still at school at the time when milking machines were introduced. Unfortunately, the data on milking machines is decennial, so we cannot precisely assign how many of the milking machines arrived at a municipality when a woman was aged, say, one year above or below completing secondary education.

[46]The data is for 435 municipalities in 1960, which correspond to 421 municipalities using 1980 borders, and lists whether a municipality had at least one high school (gymnasium) or higher-education institution (*Høyskole* or university) in 1963.

Table 4: Mechanisms: educational investments, occupational upgrading, and migration decisions

	(1) High-skill occupation	(2) Mid-skill occupation	(3) Low-skill occupation	(4) Public sector occupation	(5) Undergrad. education	(6) Migrates to town with higher-edu.	(7) Long-dist. rural-urban migration	(8) Short-dist. rural-rural migration
Panel A. IV estimates								
Milking machines (women)	0.011***	0.001	-0.014***	0.014***	0.015***	0.040***	0.037***	-0.004
	(0.003)	(0.004)	(0.005)	(0.003)	(0.004)	(0.008)	(0.007)	(0.004)
Milking machines (men)	0.006	0.008	0.001	0.002	0.008**	0.029***	0.026***	-0.002
	(0.006)	(0.008)	(0.003)	(0.003)	(0.004)	(0.007)	(0.008)	(0.004)
p-value (women = men)	0.341	0.412	0.011	0.001	0.081	0.049	0.049	0.583
Panel B. Reduced-form estimates								
Milkcows 1930 × National rollout (wom)	0.010***	0.000	-0.012***	0.013***	0.014***	0.036***	0.033***	-0.003
	(0.003)	(0.004)	(0.004)	(0.003)	(0.004)	(0.007)	(0.007)	(0.003)
Milkcows 1930 × National rollout (men)	0.005	0.007	0.001	0.001	0.007**	0.026***	0.023***	-0.002
	(0.005)	(0.007)	(0.002)	(0.003)	(0.003)	(0.006)	(0.006)	(0.003)
p-value (women = men)	0.360	0.419	0.011	0.002	0.091	0.057	0.060	0.587
Panel C. OLS estimates								
Milking machines (women)	0.003*	0.001	-0.008***	0.003**	0.006***	0.007**	0.010***	0.002
	(0.002)	(0.002)	(0.003)	(0.001)	(0.002)	(0.003)	(0.004)	(0.002)
Milking machines (men)	-0.005**	0.007**	0.001	-0.003**	0.002	0.005	0.006**	0.001
	(0.002)	(0.003)	(0.001)	(0.001)	(0.002)	(0.003)	(0.003)	(0.002)
p-value (women = men)	0.002	0.129	0.001	0.005	0.056	0.387	0.167	0.702
Municipality and cohort FE	Y	Y	Y	Y	Y	Y	Y	Y
Flexible trends (Lasso)	Y	Y	Y	Y	Y	Y	Y	Y
County-by-byear FE	Y	Y	Y	Y	Y	Y	Y	Y
Observations	630,744	630,744	630,744	630,744	725,253	693,288	726,537	726,537
F-stat first stage (wom / men)	104.3 / 96.6	104.3 / 96.6	104.3 / 96.6	104.3 / 96.6	105.4 / 99.5	102.9 / 97.0	105.4 / 99.4	105.4 / 99.4
Mean dep. variable	0.19	0.35	0.22	0.09	0.12	0.30	0.30	0.11

NOTE.— This table shows IV estimates based on equations (2) and (4). The sample includes women and men born in rural municipalities with at least one farm in 1930, who were aged 16–25 in the census years 1930–1970. In cols. 1-3, the sample is restricted to women and men employed outside of agriculture after age 25 and the skill content of occupations is based on O*Net (Autor 2019); In col. 6 the dependent variable is equal to 1 if an individual migrated to one of the 28 towns with a higher-education institution where academic (university) or vocational programmes (høyskole) were offered in 1963. In cols- 7-8, urban (rural) areas are towns with a population above (below) 10,000 in 1969. Independent variables are normalized to have a mean of zero and an SD of one. All specifications are fully-interacted models, where gender dummies are interacted with fixed effects for municipality and birth cohort; flexible trends selected with a LASSO procedure (see Appendix Table A.3) and defined as in Table 2; and county-by-birth cohort fixed effects. Standard errors in parentheses clustered at the municipality level; *p<.05; **p<.01; ***p<.001.

We present these results in column (6) of Table 4. The 2SLS estimate reveals that a one-standard-deviation increase in the number of milking machines per farm increases the likelihood that a potentially displaced woman moves to a town with a higher-education institution by 4 percentage points, or about 12 percent of the sample mean for women (0.327). This effect is not only driven by the five towns that had a university (Oslo, Bergen, Trondheim, Tromsø, and Ås); in 1963 there were 28 different municipalities with a college (*Høyskole*). While men followed similar migration patterns towards towns with higher-education institutions, the estimated effects are substantially smaller than for women, and we can reject the equality of estimates at the 5-percent level.

More generally, in columns (7) and (8), we contrast the effect of milking machines on long-distance rural-to-urban migration versus short-distance rural-to-rural migration. The diffusion of milking machines pushed rural women out of their county of birth into cities, where new, white-collar, public-sector jobs were being created (column 7). In contrast, there are no signs of increased migration over short distances between rural municipalities, as such rural-to-rural migration did not provide educational opportunities nor access to jobs with a higher skilled content (column 8). As before, the estimated effects are substantially smaller for men and we can reject the equality of estimates for women and men at the 5-percent level.[47] This pattern is consistent with reports from Statistics Norway that in the 60s and 70s "the typical young mover (20 years) moves single to larger centers" (Lian, 1981, p.32).

In addition, we document that these migration patterns were driven by women and men in rural municipalities without access to high schools (Appendix Tables A.15 to A.17). This further reveals that women's decision to move was partly driven by the desire to acquire more education to access high-skill employment. They also suggest that the long-term effects of mechanization are not institution-independent, as the lack of local schooling infrastructure seems to exacerbate the out-migration of displaced workers.

6.2 Fertility and Marriage

Next, we examine family choices as a second complementary mechanism. By displacing women from their traditional jobs in agriculture, milking machines may have triggered changes in fertility and marriage which, in turn, can break allocative inefficiencies by facilitating women's migration and labor force participation. This mechanism is consistent with the literature on the demographic transition showing that fertility responds to structural change (e.g., Galor, 2005; Ager et al., 2020).

[47] In detail, the average female (male) rural migrant moved 80 km (60 km), 117 km (99 km), and 127 km (111 km) away from their birthplace in 1960, 1970, and 1980, respectively (see Appendix Table A.2).

To examine this mechanism, we use data from the central population registry and reconstruct each household's family size based on women's completed fertility, i.e., the number of children ever born to women at the end of her reproductive life. We also exploit a woman's age at first birth as a crude proxy for her age at first marriage (e.g., Eriksen, 2001). For this analysis, the unit of observation is a household because fertility is a joint outcome (a man's fertility is affected by his partner's exposure to milking machines, and *vice versa*). Unfortunately, the structure of the registry data does not allow us to measure the exposure to milking machines of wife and husband separately, as we do not observe the identity of the spouses/cohabitation partners at all points in time during our study period. Hence, for this analysis, exposure to milking machines is based on the exposure of the woman in the household when she was young.

Table 5 presents 2SLS, reduced-form, and OLS estimates for the effect of milking machines on fertility outcomes, based on a version of Equation 3 estimated at the household level.[48] We find that family size was smaller in households where adult women were affected by the diffusion of milking machines at age 16-25 (column 1). In quantitative terms, however, the effect is modest. An increase in milking machines per farm by one standard deviation led to 60 fewer births per 1,000 population, which corresponds to a fertility reduction per woman of about 3 percent of the sample mean (2.07 children). We find a similar effect along the intensive margin of fertility (column 2) and a significant increase in childless households (column 3). Quantitatively, the diffusion of milking machines increased the likelihood that the household remained childless by around 1 percentage point or 6.5 percent of the sample mean. In modern societies, such increases in childlessness are often associated with a higher opportunity cost of having children and with gains in women's bargaining power in the household (Baudin et al., 2015). Finally, we find that households had their first child later if women were more affected by milking machines at a young age (column 4). This suggests that one of the responses to the automation of hand milking for young rural women was to delay marriage. Although this effect is statistically significant, it is quantitatively negligible as it barely corresponds to a one-percent increase in the age at first birth.

Altogether, these results are in line with previously documented changes in fertility behavior in Norway between 1930 and 1970 (Brunborg and Mamelund, 1994). They suggest that the automation of hand milking increased the opportunity cost of having children for young rural women. This is consistent with the idea that displaced young women had to leave their rural hometowns to acquire more education and reallocate to higher-skilled jobs in urban areas.

[48]Formally, instead of estimating the fully-interacted Equation 3, we now drop the interactions by gender and use the household as the unit of analysis.

Table 5: Mechanisms: fertility and marriage prospects, household-level analysis.

	(1)	(2)	(3)	(4)
	Family size	Family size $\mid > 0$	Childlessness (0/1)	Age at first birth (mother)
Panel A. IV				
Milking machines per farm	-0.062***	-0.069***	0.012***	0.180**
	(0.020)	(0.019)	(0.004)	(0.077)
Panel B. Reduced form				
Cows per farm 1930 × National rollout	-0.056***	-0.061***	0.011**	0.160**
	(0.018)	(0.017)	(0.004)	(0.066)
Panel C. OLS				
Milking machines per farm	-0.021**	-0.022**	0.004**	0.004
	(0.010)	(0.010)	(0.002)	(0.029)
Municipality and cohort FE	Y	Y	Y	Y
Flexible trends (Lasso)	Y	Y	Y	Y
County-by-byear FE	Y	Y	Y	Y
Mean dep. variable	2.07	2.51	0.18	25.51
F-stat first stage	105.40	101.66	105.40	101.66
Observations	379,366	312,405	379,366	312,405

NOTE.— This table shows IV, reduced-form, and OLS estimates based on equations (2) and (3), estimated at the household-level. The sample includes households with an adult woman born in a rural municipalitie with at least one farm in 1930, who was aged 16–25 in the census years 1930–1970. In col. 2 the sample is restricted to households with children by construction. Flexible trends selected with a LASSO procedure (see Appendix Table A.3) and are defined as in Table 2. Standard errors in parentheses clustered at the municipality level; *p<.05; **p<.01; ***p<.001.

6.3 Young versus older cohorts

How did older cohorts in rural areas respond to the uptake of milking machines? Here we compare the effects on women aged 36–45 when this new technology was adopted (henceforth, older women) versus women aged 16–25, when they would typically be employed as milkmaids and, hence, displaced by milking machines (henceforth, young women).

Specifically, our analysis is based on Equation (3), where instead of comparing women versus men we compare young versus older women living in the same municipality.[49] The sample includes women living in a rural municipality at age 16–25 (young) and 36–45 (older) in the census years 1950, 1960, and 1970. Note that we exclude earlier census years because the registry data does not cover women aged 36-45 before 1950; i.e., born before 1905. We measure exposure (Equation 1) and the number of milking machines per farm in a woman's municipality of residence when she was, respectively, young or older, based on residencies

[49] Formally, we replace the gender dummy g_i by a cohort dummy for young versus older women.

reported in the 1960 and 1970 census. Our main outcomes are defined as in Section 5.2.[50]

Table 6: The diffusion of milking machines on young versus older women, 2SLS estimates

	(1) Employed agriculture	(2) Migration	(3) Income pctile rank	(4) Labor force participation
Milking machines per farm (young)	-0.078***	0.037***	1.913***	0.039***
	(0.011)	(0.010)	(0.481)	(0.010)
Milking machines per farm (older)	0.067***	-0.004	0.637	-0.000
	(0.008)	(0.003)	(0.551)	(0.011)
p-value (younger = older)	0.000	0.000	0.116	0.029
Municipality and birth year FE	Y	Y	Y	Y
Flexible trends (Lasso)	Y	Y	Y	Y
County-by-byear FE	Y	Y	Y	Y
Mean dep. variable	0.08	0.29	32.73	0.74
F-stat first stage (younger)	73.72	73.72	73.02	73.02
F-stat first stage (older)	78.34	78.34	73.48	73.48
Observations	319,092	319,092	289,187	289,187

Note.— This table shows IV estimates based on equation (3) comparing "young" versus "older" women. The sample includes women living in a rural municipality at 16–25 (young) and 36–45 (older) in 1950, 1960, and 1970. All specifications are fully-interacted models, where cohort dummies are interacted with fixed effects for municipality and birth cohort; flexible trends selected with a LASSO procedure (see Appendix Table A.3) and defined as in Table 2; and county-by-birth cohort fixed effects. Independent variables are normalized to have a mean of zero and an SD of one. Standard errors (in parentheses) clustered at the municipality level; *p<.05; **p<.01; ***p<.001.

Table 6 presents the 2SLS estimates comparing the effect of milking machines on young versus older women. The corresponding reduced-form and OLS estimates are shown in Appendix Table A.14. The estimates reveal striking differences by cohort. For young women, milking machines reduced employment in the agricultural sector and increased the probability to migrate out of rural areas, long-term incomes, and labor force participation. The estimates are qualitatively and quantitatively similar to those in Section 5.2. For older women, instead, the adoption of milking machines did not trigger significant changes in migration, long-term incomes, or labor force participation. The estimates for older women are generally close to and not statistically different from zero. The exception is employment in agriculture, which was positively associated with the adoption of milking machines for older women. This is consistent with the historical narrative (see Section 2), which describes how

[50]For young women, all outcome variables are identical to Section 5.2. Similarly, for older women employment in agriculture and migration are based on the occupation and residency reported in the following census; income rank is defined as in Section 5.2; and FLFP is equal to one if older women in 1950, 1960, and 1970 reported a positive income at, respectively, age 45, 52, and 62. We use different ages because the income registry only starts in 1967 so we do not observe income at age 45 for everyone.

milking machines first displaced young milkmaids, while farmers' wives in particular and older women in general initially remained in employment in the farms (see, e.g., Almås et al. (1983) and Appendix Figure A.4).

7 Conclusion

In this paper, 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 young 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 short-term and long-term effects of the roll-out of milking machines at the micro-level. The introduction of milking machines had different consequences for young men and women in the rural areas of Norway. Affected young women were pushed out of agriculture and moved to urban areas, where they invested more in their education and eventually earned higher incomes as middle-aged adults. While young rural men were also affected by the mechanization of agriculture, we show that the adoption of milking machines was gender-biased and affected women much more. This contributed to reducing gender gaps in labor force participation and income, and to the transformation of women's work in the 20th century. More generally, our results suggest that technological change can resolve the misallocation of workers across sectors thereby improving their economic status in the long-run.

These findings have 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 displacement effect outweighs productivity gains and the reinstatement effect of creating new labor-intensive tasks. In our case, the creation of new jobs in the expanding service and public sectors appears to be the dominant force. As in other European countries, Norway's economy was in a transition phase after WWII with remarkable growth rates. 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 the local schooling infrastructure so that they could take up new and better job opportunities.

It should be clear from this discussion that the effects of automation are institution-dependent and that the introduction of gender-biased labor-saving technologies in agriculture might not always benefit displaced workers. The effects will likely depend on their comparative advantage, perceptions about gender norms, the geographic mobility of labor, local schooling infrastructure, and gender-specific job opportunities in rural and urban areas.

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APPENDIX – FOR ONLINE PUBLICATION

A.1 Appendix for short-term estimates

Table A.1 reports estimates for the short-term effect of the roll-out of milking machines in 1960 using household-level data from the 1960 Census. Estimates are based on:

$$Y_{i,j,b} = \beta_b + \gamma M_{j,1960} + \sum_t \mathbf{1}[b = t] \times \mathbf{X}'_{j,b}\theta_t + \epsilon_{ijb} \tag{A.1}$$

where i indexes households, j municipalities, and b the birth cohort of the woman aged 16-25 in 1960. The outcome variable Y is the share of individuals employed in each household on an indicator of student activity in the household (1 = yes; 0 otherwise). The variable $M_{j,1960}$ is the number of milking machines per farm in 1960 in municipality j. The estimation sample is a cross-section of households in rural municipalities with at least one farm in 1929 and at least one woman aged 16–25 in 1960.

Table A.1: Short-run effects of the diffusion of milking machines on households, using 1960 Census data

	(1)	(2)	(3)	(4)
	Household members in employment (share)	Household members in employment (share)	Student activity in household (0/1)	Student activity in household (0/1)
Milking machines per farm	-0.026*	-0.030*	0.078*	0.132***
	(0.015)	(0.017)	(0.040)	(0.040)
Observations	73,064	73,064	76,850	76,850
Birth year FE	Y	Y	Y	Y
Flexible trends Lasso)	.	Y	.	Y
County-by-byear FE	.	Y	.	Y
Mean dep. variable	0.466	0.466	0.155	0.155

Note.— This table shows the short-run effect of the roll-out of milking machines in 1960 on two household-level outcomes measured in the 1960 Census: the share of individuals employed in the household (Cols. 1-2), and an indicator of student activity in the household (1 = yes; 0 otherwise) (Cols. 3-4). The sample is a cross-section of households in rural municipalities with at least one farm in 1929, with at least one women aged 16–25 in 1960. Estimates are based on equation (A.1). The vector of flexible trends **X** is defined as in Table **??**. Standard errors (in parentheses) clustered at the municipality level; *p<.05; **p<.01; ***p<.001.

Figure A.1 shows estimates for the short-term effects of milking machines on income under alternative specifications of equation (11). In Panel (a), we follow the recommendations of Chen and Roth (2024) to obtain an approximate percentage interpretation when the outcome variable takes zero values. In detail, Chen and Roth (2024) show that the log- or arcsinh-transformations, $log(1+y)$ or $arcsinh(y)$, are not unit-invariant when outcome y is zero-valued, and hence, should not be interpreted as percentage effects. Instead, to obtain an approximate percentage, they recommend using Poisson quasi-maximum likelihood (QMLE) regressions, which in our setting take the form:

$$Y_{i,j,t} = exp\left(\sum_{s\in(wom,men)} \mathbf{1}[g_i = s] \times \{\alpha_0^s + \alpha_j^s + \alpha_t^s + \sum_{k\neq 12} \gamma_k^s \, \mathbf{1}[t - 1970 = k] \times M_{j,1970}\} \right) u_{i,j,t} \, , \tag{A.2}$$

where Y_{ijt} is the (untransformed) income in year $t \in \{1970, ..., 1995\}$ of individual i who was born in rural municipality j and who turned 16 in 1970. α_j and α_t are fixed effects for municipalities and years. The main variable of interest is the interaction between $M_{j,1970}$, the number of milking machines per farm in municipality j in 1970, and $\mathbf{1}[t - 1970 = k]$, a set of dummy variables for the number of years since 1970—when the relevant uptake of milking machines took place for this sample. The γ_t coefficients capture the differential evolution of incomes in municipalities where milking machines were adopted at different rates, relative to the differences 12 years after the 1970s rollout.[51] The implied estimate of the proportional treatment effects is $\exp(\hat{\gamma}_t) - 1$, which has an approximate percentage interpretation (Chen and Roth, 2024). As in Section 5.1, we capture gender effects by pooling together women and men and interacting all right-hand-side variables with gender dummies $g_i \in (wom, men)$.

In Panel (b), we show log effects with calibrated extensive-margin values. Chen and Roth (2024) suggest this exercise as an alternative to the average proportional treatment effects explained above. The main advantage is that log effects with calibrated extensive-margin values are not influenced by observations in the tail of the income distribution. To estimate them, we first normalize the dependent variable so that 1 corresponds to the value of the minimum nonzero income in the data. That is, we divide $Y_{i,j,t}$ by $Y_{min} = min\,(Y_{i,j,t} | Y_{i,j,t} > 0) = 100$ NOK.

[51] In detail, we choose 1982 as the omitted category to capture short-term effects relative to income differences in the medium term. In addition, estimating a cell means model without omitted category and no constant yields a zero-effect for γ_{1982}^{wom} and for $\gamma_{1982}^{wom} - \gamma_{1982}^{men}$.

We then estimate a modified version of Equation (A.2) by OLS:

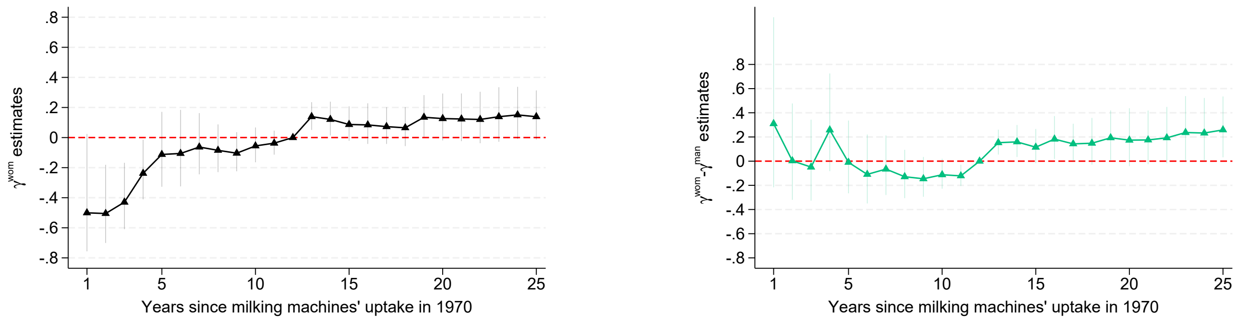
$$m(Y_{i,j,t}) = \sum_{s\in(wom,men)} \mathbf{1}[g_i = s] \times \{\alpha_0^s + \alpha_j^s + \alpha_t^s + \sum_{k\neq 1995} \gamma_k^s \, \mathbf{1}[t-1970 = k] \times M_{j,1970}\} + u_{i,j,t} \ , \tag{A.3}$$

In Panels (c) and (d), we show log effects on the intensive margin and effects on the extensive margin, respectively. Specifically, in Panel (b) we estimate Equation (A.3) using $log(Y_{i,j,t})$ as the dependent variable, and restricting the sample to observations with positive incomes, $Y_{i,j,t} > 0$. In Panel (c), we estimate Equation (A.3) using an indicator variable equal to one if $Y_{i,j,t} = 0$ and zero otherwise as the dependent variable. To capture the potential effects of displacement from milkmaid employment, we restrict the sample to women (and men) employed at age 16; i.e., with $Y_{i,j,1} > 0$.

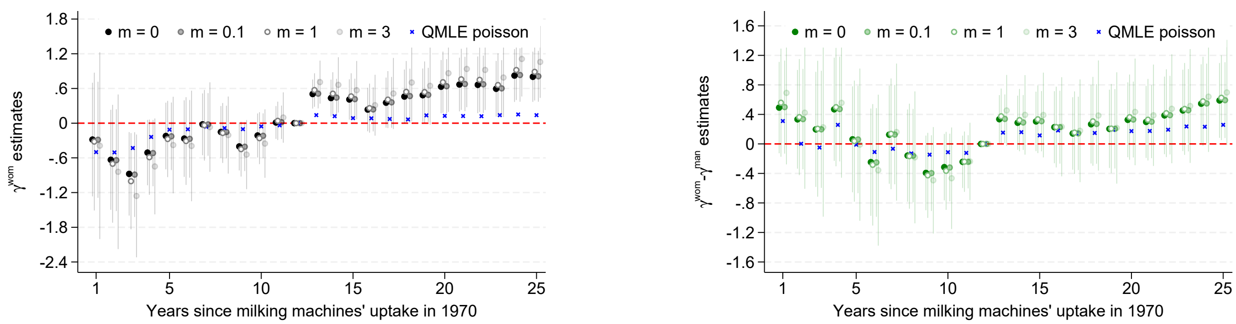
As in the main text, Appendix Figure A.1 shows estimates for the short-term effects on women (black) alongside estimates for the differential effect on women vs. men (green). These correspond to $\exp(\hat{\gamma}^{wom}) - 1$ (black) and for $\exp(\hat{\gamma}^{wom} - \hat{\gamma}^{men}) - 1$ in Panel (a) and to $\hat{\gamma}^{wom}$ and $\hat{\gamma}^{wom} - \hat{\gamma}^{men}$ in Panels (b) to (d).

Figure A.1: Robustness checks for contemporaneous effects

(a) QMLE estimates



(b) Calibrated extensive margin values



(c) Intensive margin effect

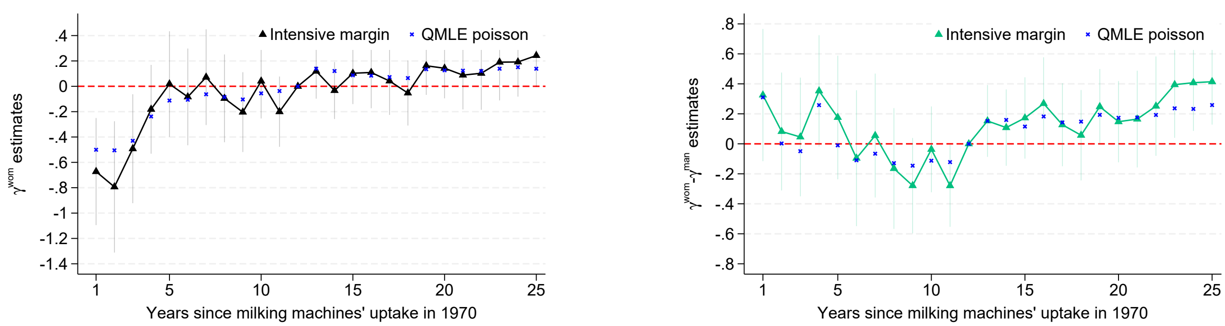


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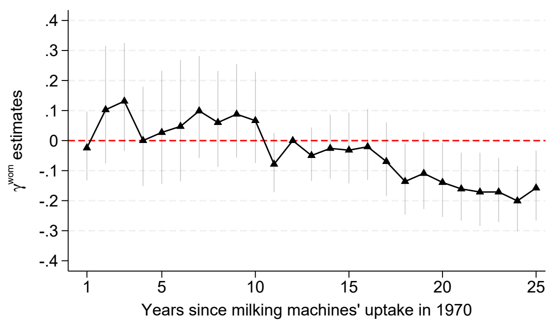
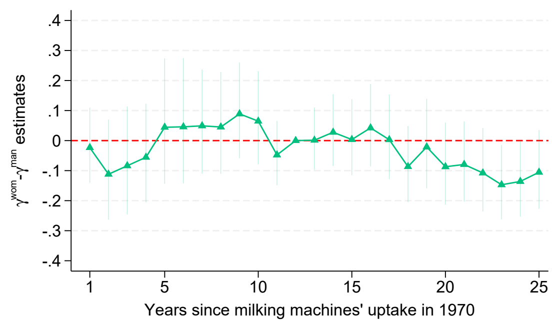
Figure A.1: Robustness checks for contemporaneous effects (continued)

(d) Extensive margin effect (zero incomes)

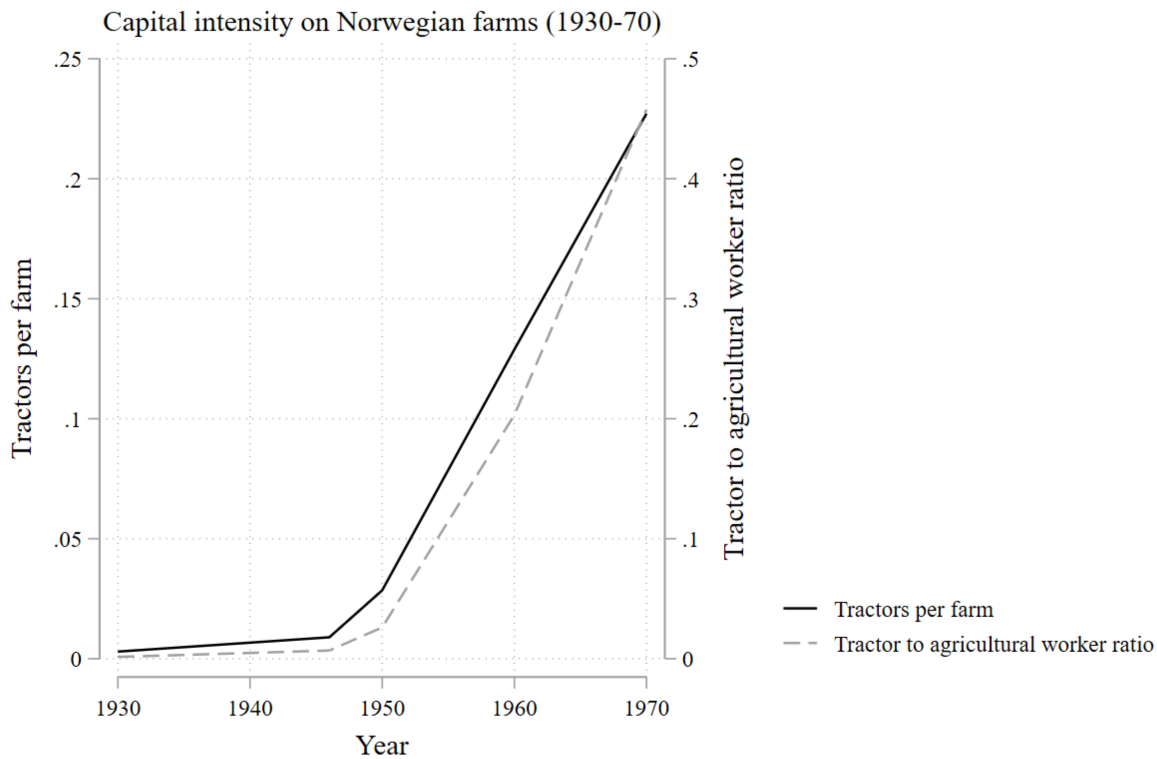




Note.— This figure plots estimates for the short-term effects of milking machines from the specifications described in the text above. Black is for the effect on women, and green is for the differential effect on women vs. men. The sample is a panel of 18,014 women and men born in rural municipalities who turned 16 in 1970 and their incomes over 25 years, from 1970 to 1995 (N=450,350). In Panels (c) and (d), the sample is restricted to positive incomes and to individuals employed at age 16, respectively. Standard errors are clustered by municipality; 95% confidence intervals.

A.2 Appendix figures and tables

Figure A.2: 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 A.3: 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 A.4: Labor input on agricultural holdings (1928–29 to 1965–66)

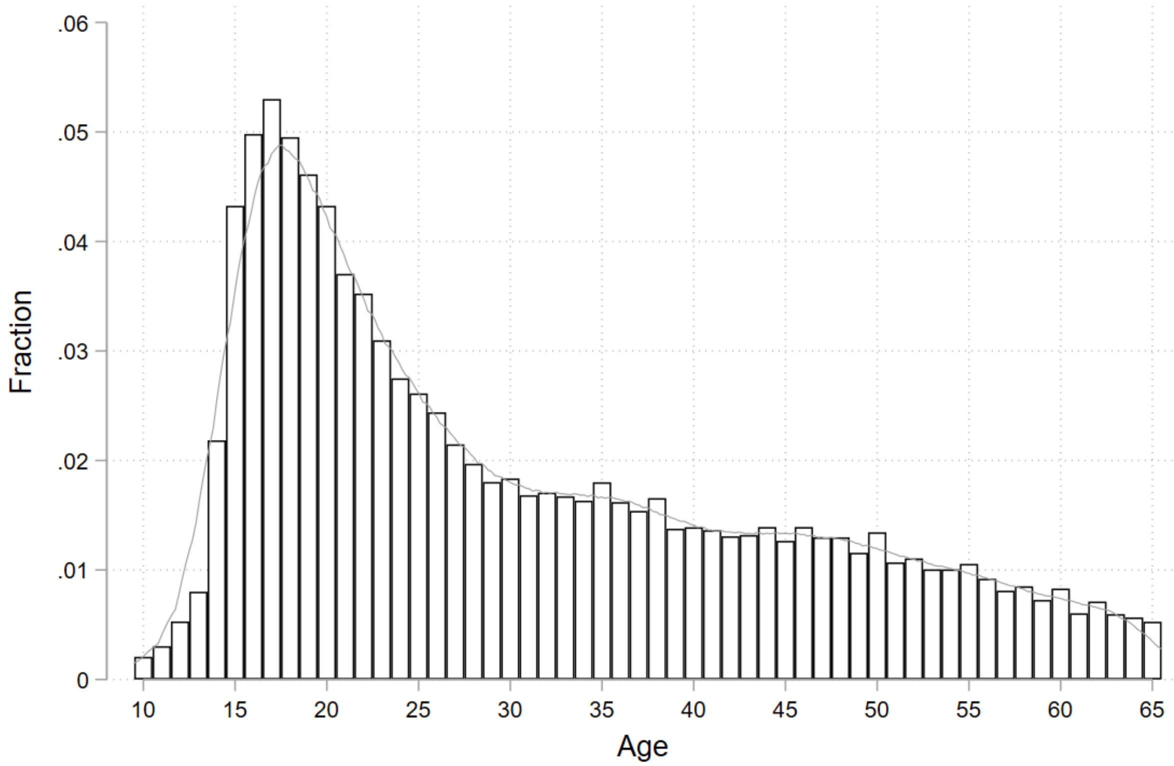
Tabell 78. Arbeidskraft på brukene. Årsverk.
Labour input on holdings. Man-years.

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.*

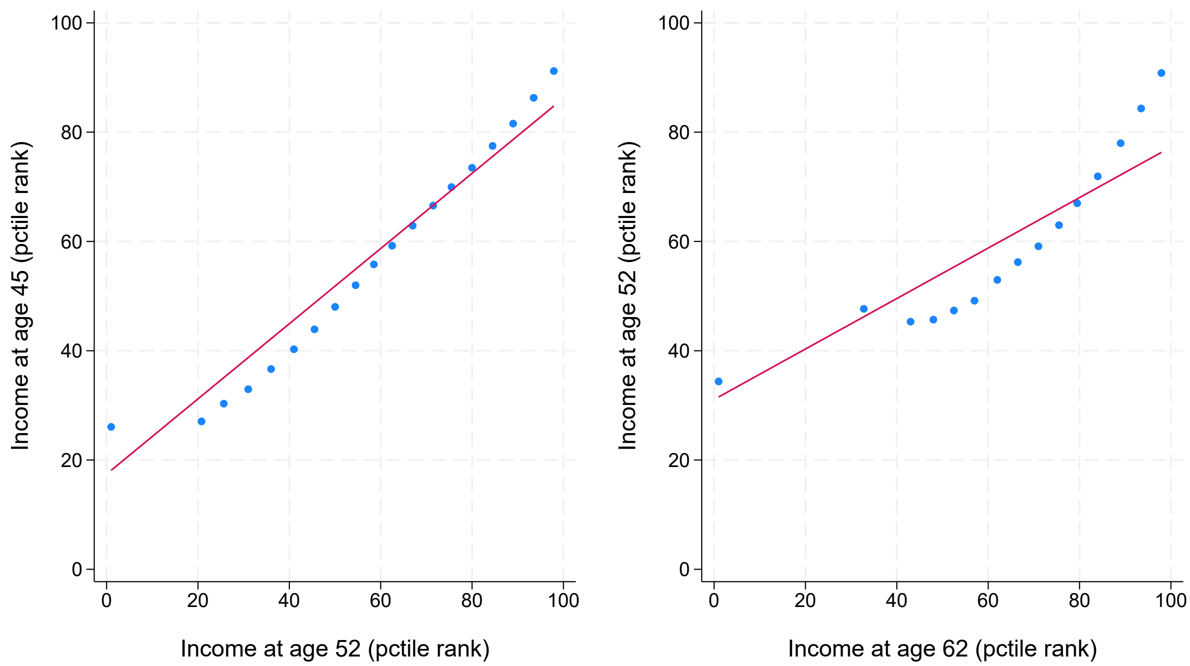
NOTE.— This figure shows the labor input on farms by gender and by type of worker (holders and spouses, other family members, and hired workers) for the years 1928-29 to 1965-66. Source: Central Bureau of Statistics of Norway (1968, Table 78).

Figure A.5: Distribution of milkmaids by age in 1910



Note.— This figure shows the distribution of milkmaids (livestock and dairy farm workers identified by variable ISCO68A code 624 and 625 in IPUMS-I (Minnesota Population Center, 2020)) in 1910 by age. Source: Census of Norway in 1910.

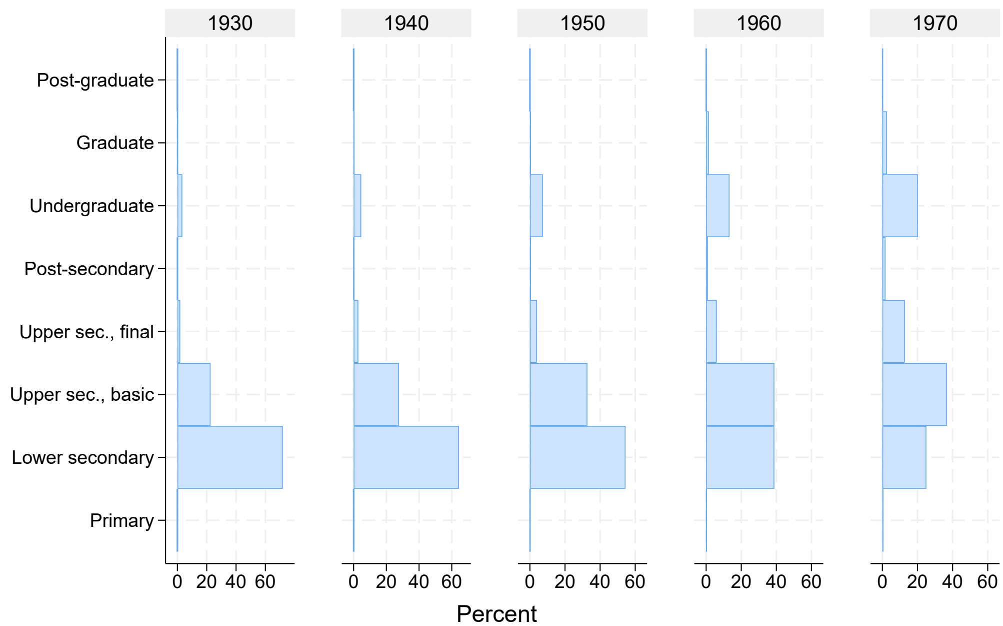
Figure A.6: Comparison of income ranks based on income at ages 45, 52, and 62



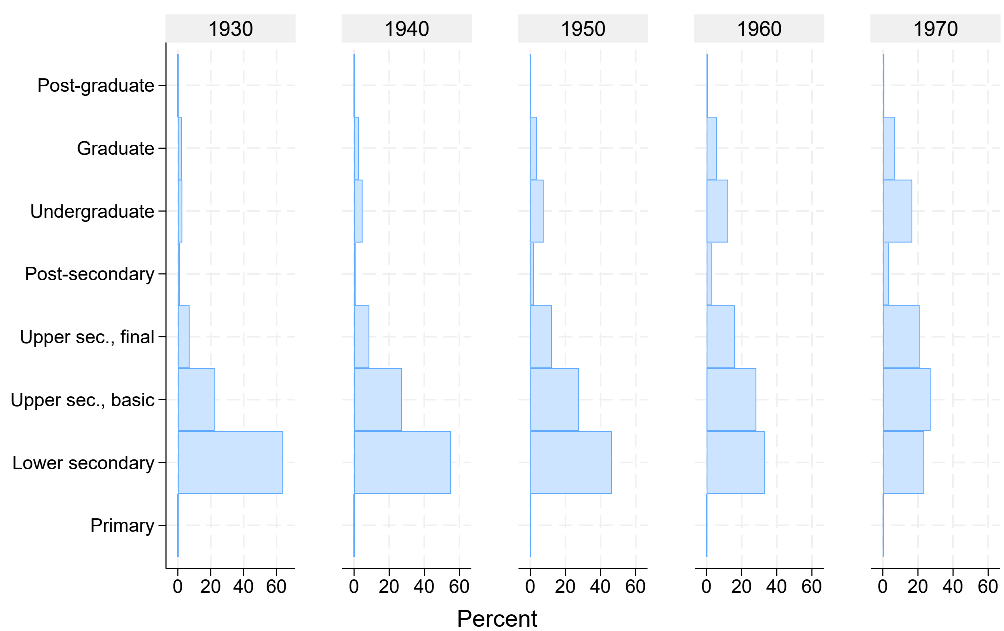
Note: Income ranks calculated over birth-year cohorts for all women in our baseline sample with income data at ages 45, 52, and 62.

Figure A.7: Education distribution over time (1930–1970)

(a) Women



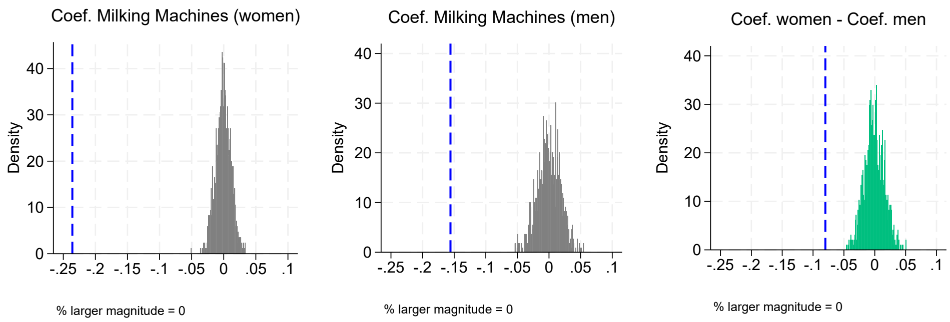
(b) Men



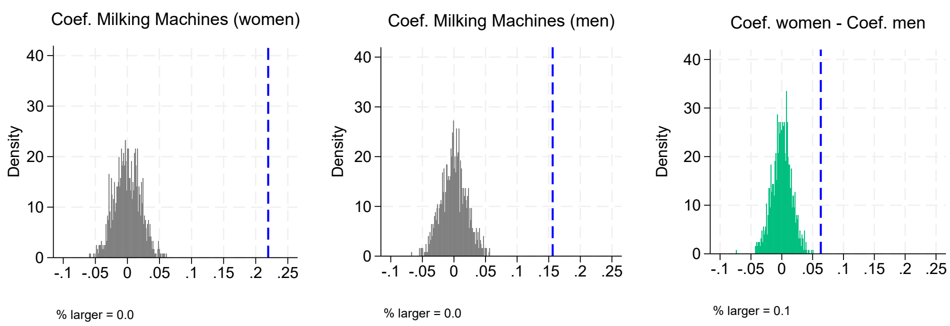
Note.— This figure plots the education distribution of rural women and men aged 16–25 in 1930, 1940, 1950, 1960, and 1970.

Figure A.8: Permutation tests

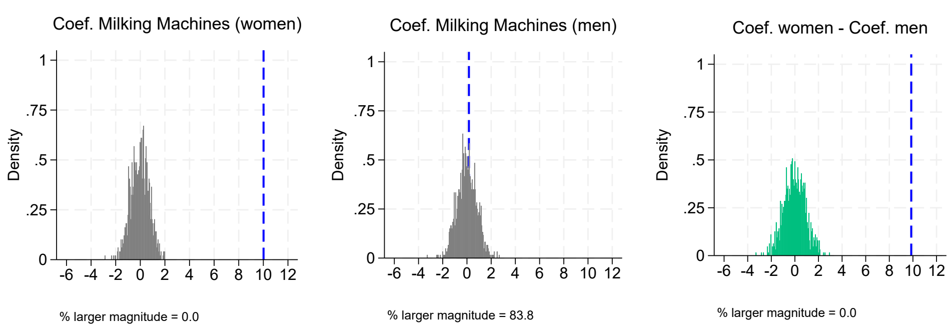
(a) Dep. Var.: Employment in agriculture



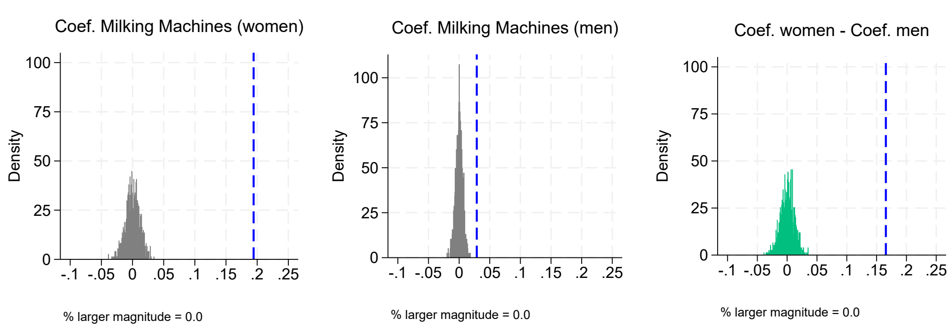
(b) Dep. Var.: Migration



(c) Dep. Var.: Income pctle rank



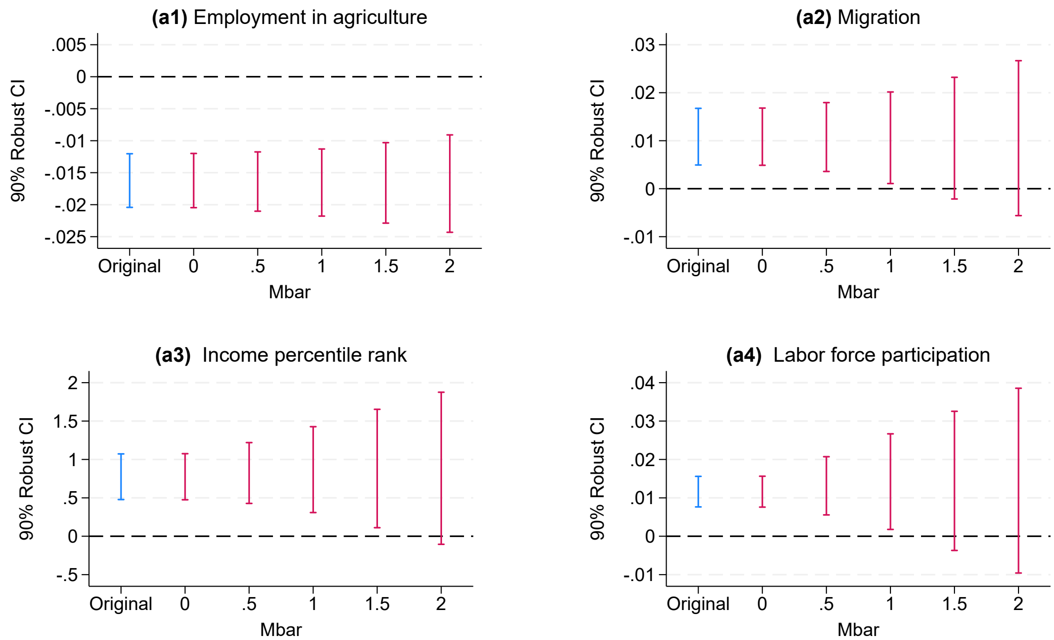
(d) Dep. Var.: Labor force participation



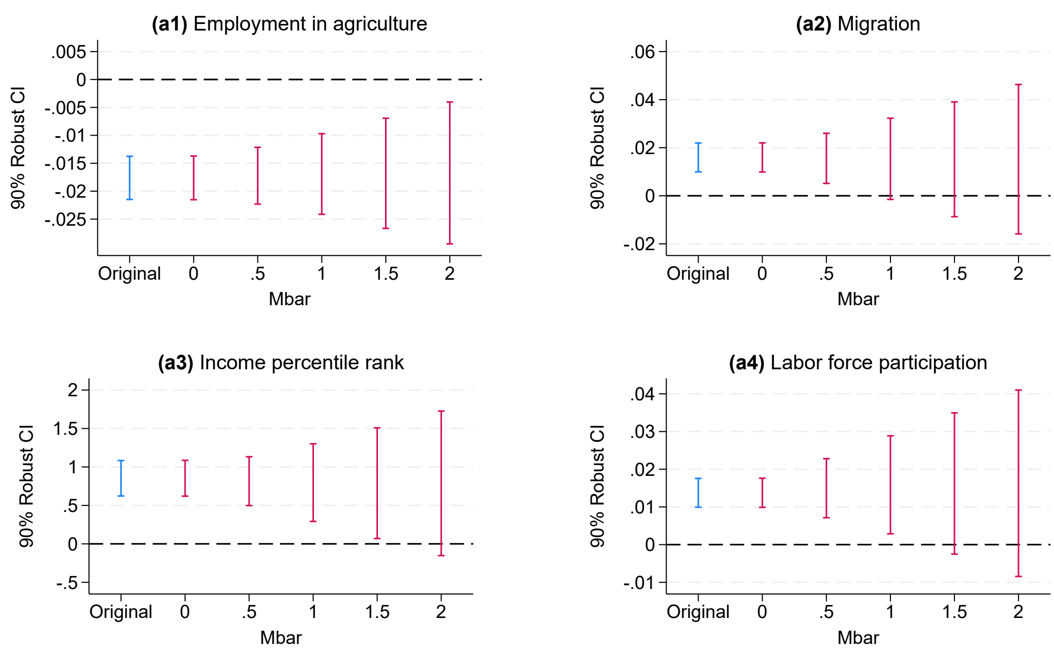
NOTE.— This figure plots 1,000 coefficients from the reduced-form version of equation (3), where we reshuffle the number of milkcows per farm. The left column displays the results for women, the middle column for men, and the last column refers to women-men differences. Dependent variables, samples, and flexible trends are defined as in Tables 2 and 3. Vertical dashed lines indicate baseline (non-permuted) coefficients.

Figure A.9: Rambachan and Roth's "Honest DiD" sensitivity analysis

(a) Difference-in-difference specification

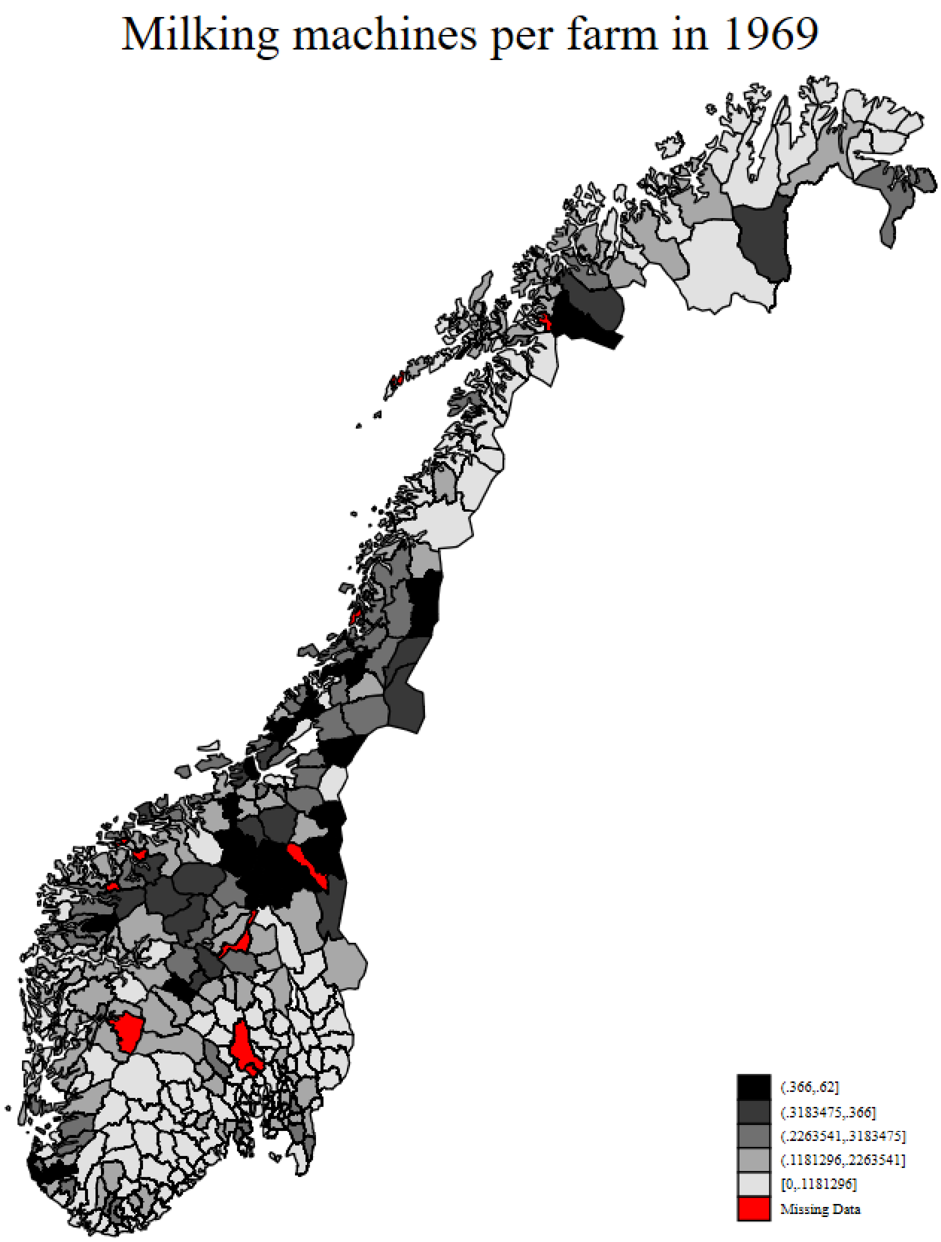


(b) Difference-in-difference specification with flexible trends and county-by-cohort FE



NOTE.— This figure performs the "Honest DiD" sensitivity analysis by Rambachan and Roth (2023). It plots estimates and 90% robust confidence sets for the treatment effect of milking machines for cohorts age 16-25 in 1950–70, assuming that the violation of parallel trends is equal to some constant $\hat{M}$ times the maximum violation of parallel trends in the pre-treatment period, i.e., for cohorts age 16-25 in 1930–1940.

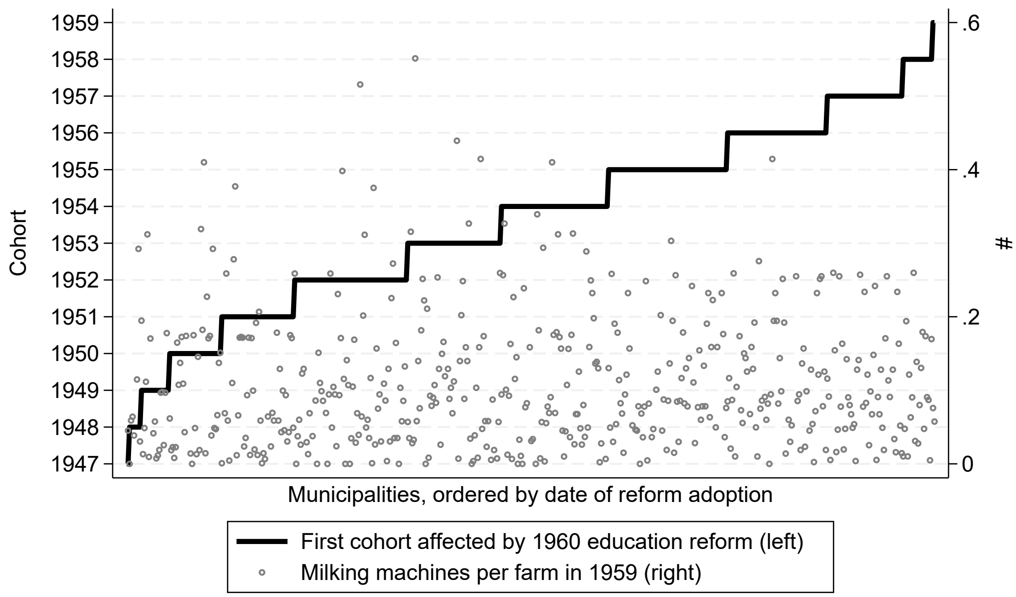
Figure A.10



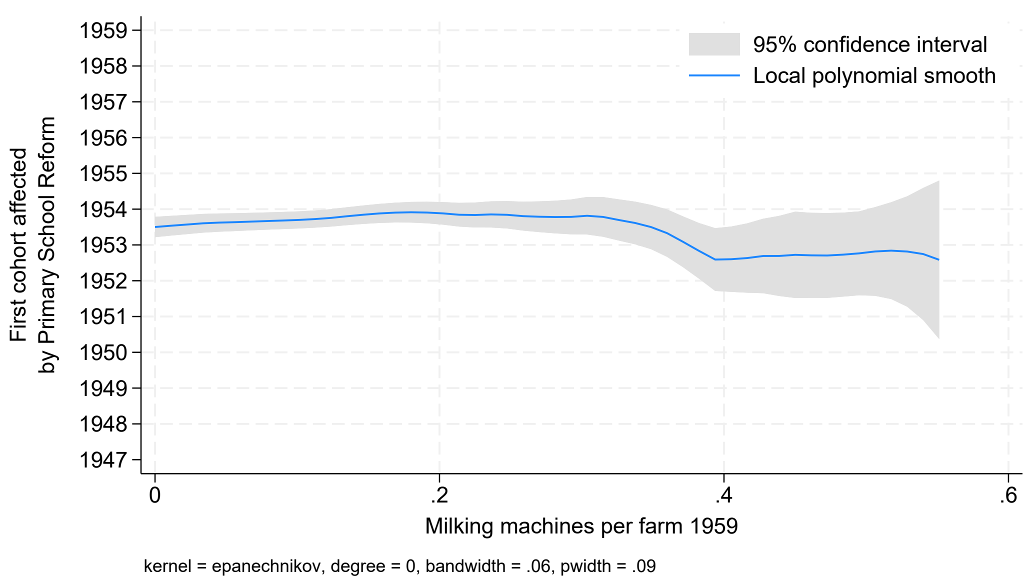
Note.— This figure shows the distribution of milking machines per farm in 1969 across Norwegian municipalities. A darker color refers to higher values of milking machines per farm. Red polygons denote missing observations. Source: Census of Agriculture (own calculations).

Figure A.11: The roll-out of the Primary School Reform and the diffusion of milking machines across municipalities

PANEL A. Scatter plot



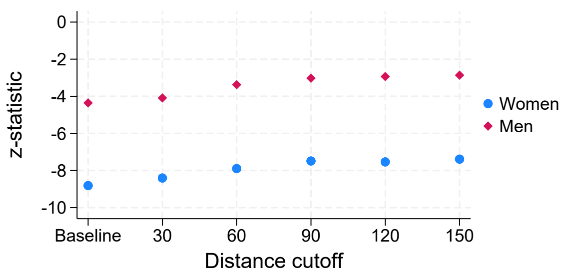
PANEL B. Local polynomial smooth



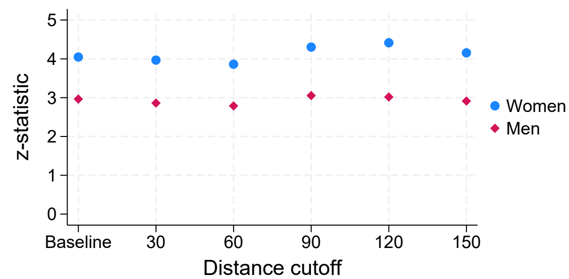
NOTE.— The sample consists of 497 municipalities based on their 1960 borders, with at least one farm in 1929. Data on the first cohort affected by the Primary School Reform in each municipality is from Black et al. (2005).

Figure A.12: Conley Standard Errors with different distance cutoffs

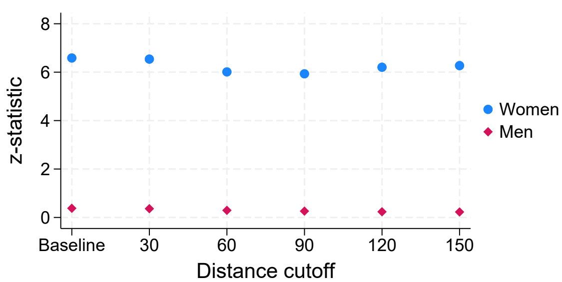
(a) Employment in agriculture (Table 2, col. 2)



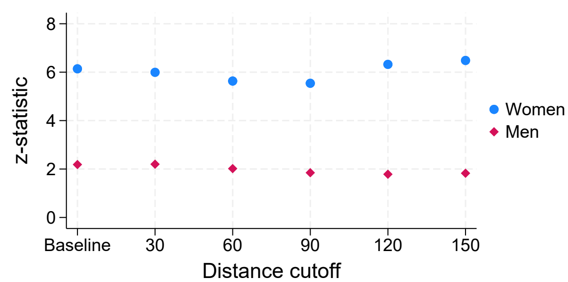
(b) Migration to city (Table 3, col. 1)



(c) Income percentile rank (Table 3, col. 2)

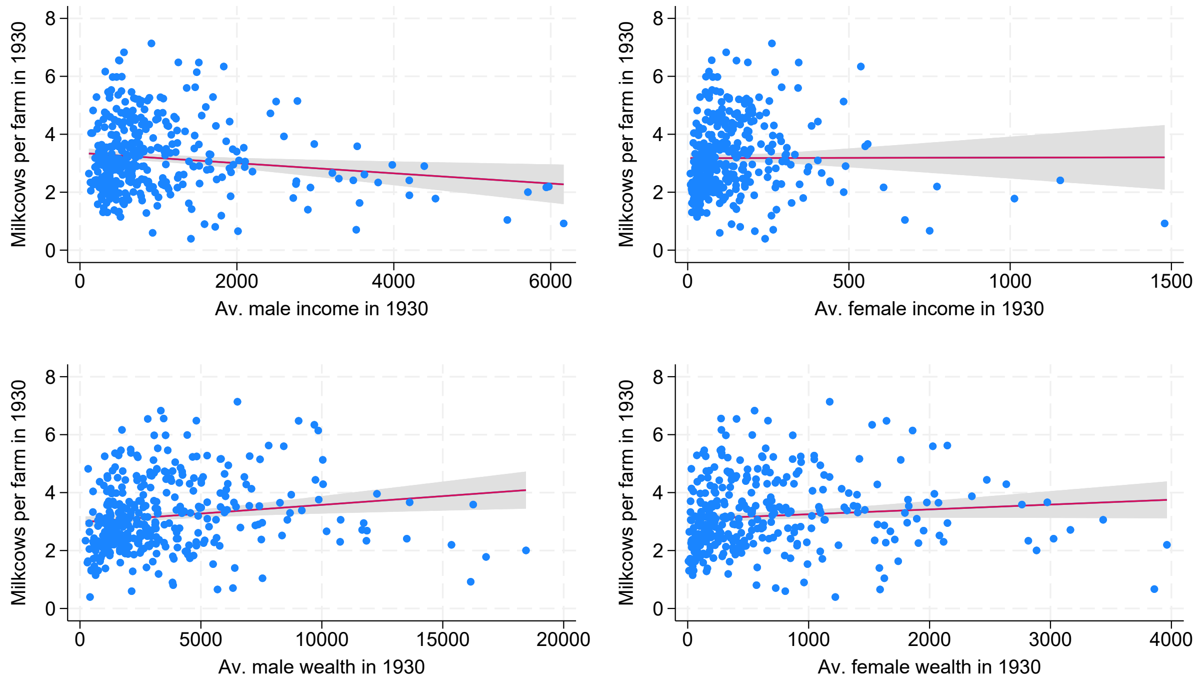


(d) Labor force participation (Table 3, col. 3)



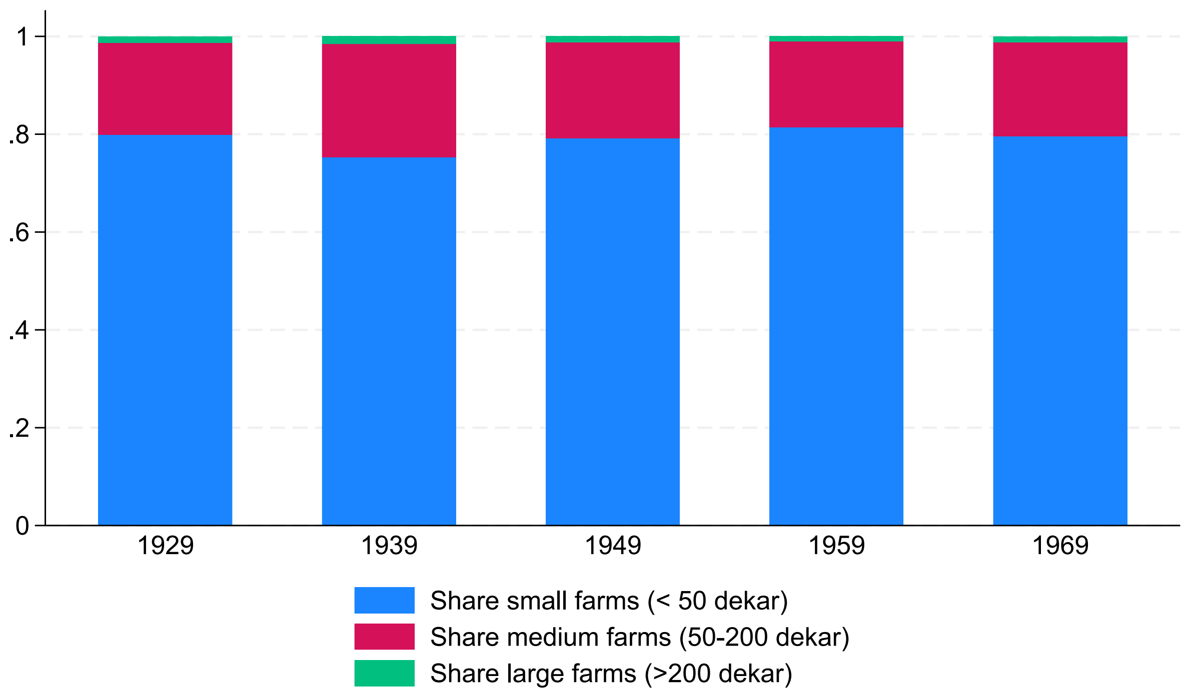
NOTE.— This figure shows spatially-adjusted z-statistics for the effect of milking machines per farm on the main long-term outcomes for women and men. Z-statistics are based on our baseline IV specifications with the full set of FE and controls, using the full sample (see Tables 2 and 3 for further details). The distance cutoff is the point at which the spatial error correlation is assumed to be 0. Spatially-adjusted z-statistics calculated using `acreg` Colella et al. (2019). Baseline z-statistics allow for spatial correlation within municipalities; i.e., are based on standard errors clustered by municipality.

Figure A.13: Milkcows per farm, income, and wealth by 1930



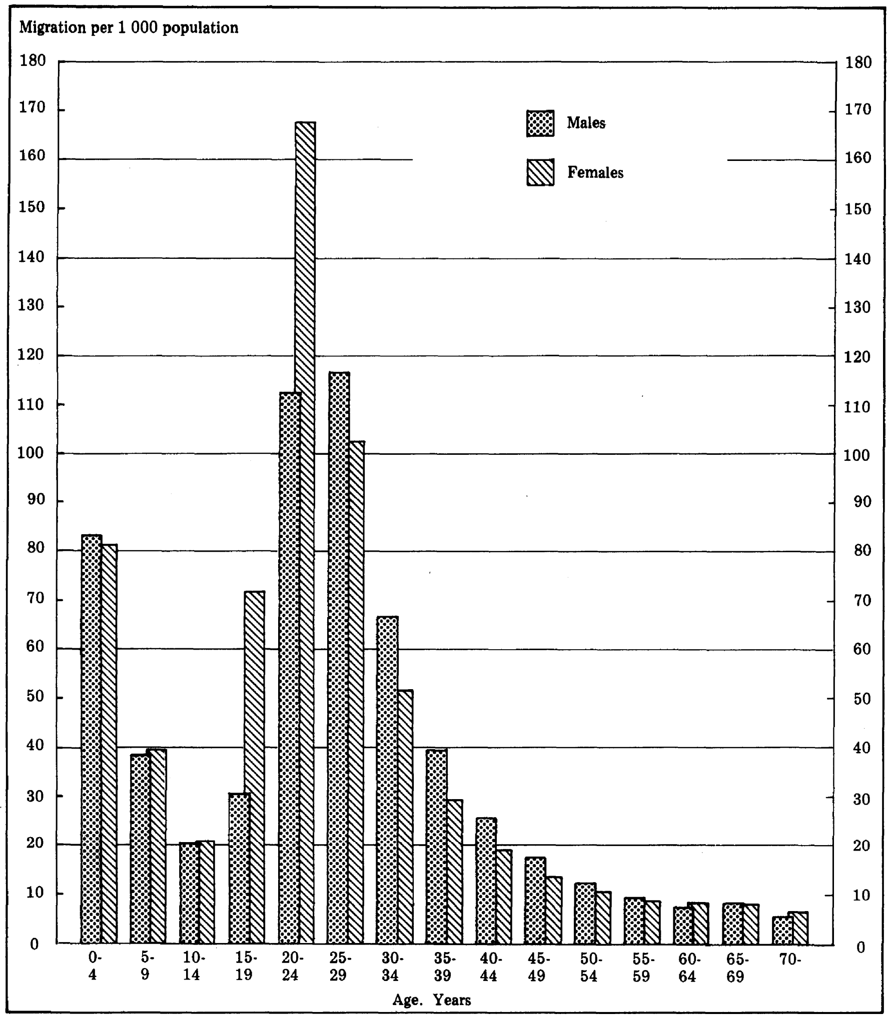
Note: Income and wealth data based on F.O.B. 1930 data digitized from Statistics Norway archives. The figure excludes outlier municipalities with male and female incomes above, respectively, 10,000 and 2,000 NOK, and with male and female wealth above, respectively, 20,000 and 5,000.

Figure A.14: Farm size distribution over time (1929–1969)



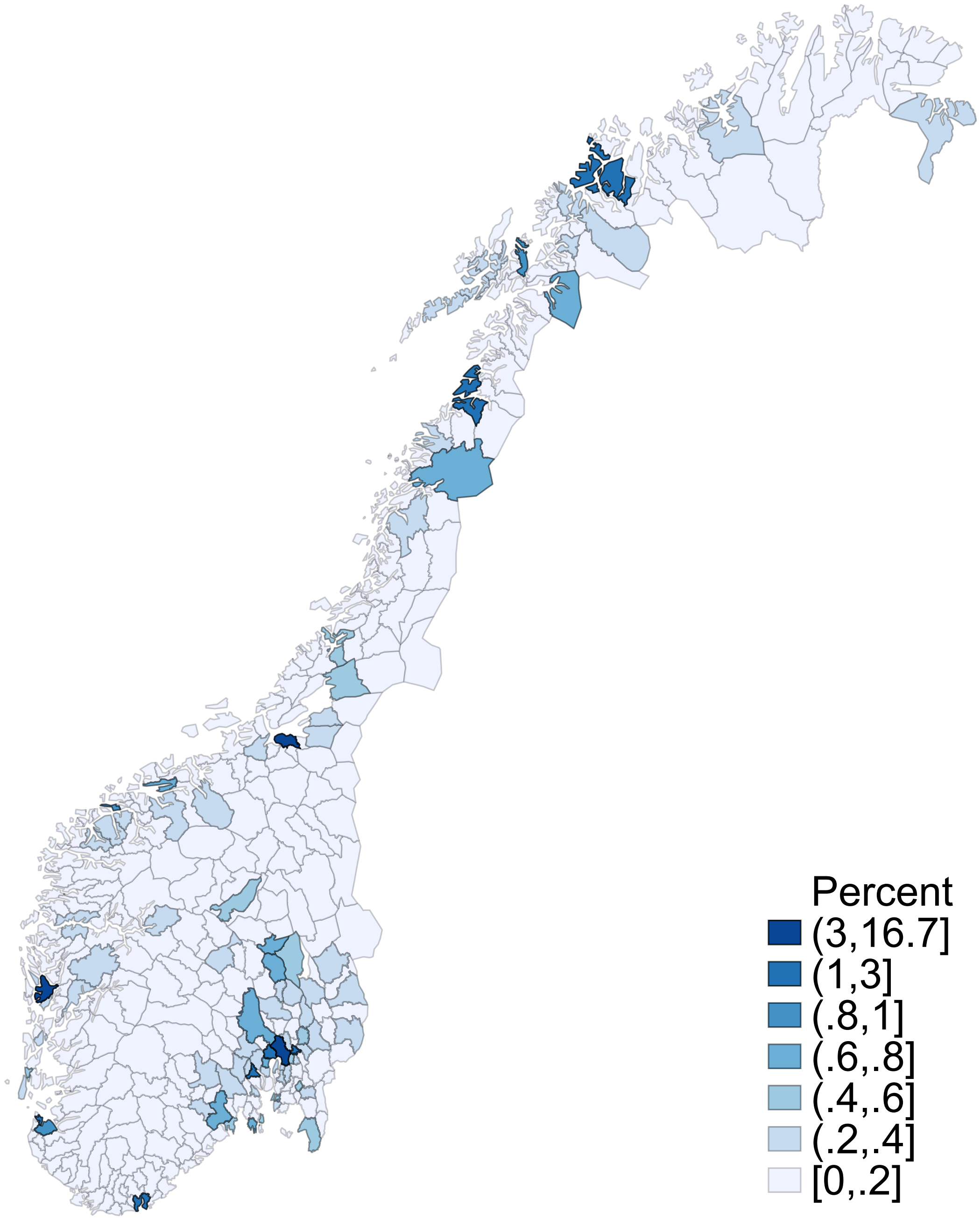
Note: This figure plots the distribution of farms by size (below 50 dekar, 50-200 dekar, and above 200 dekar). Source: Census of Agriculture (own calculations).

Figure A.15: Mobility for males and females in different groups, per 1,000 (1976–1980)



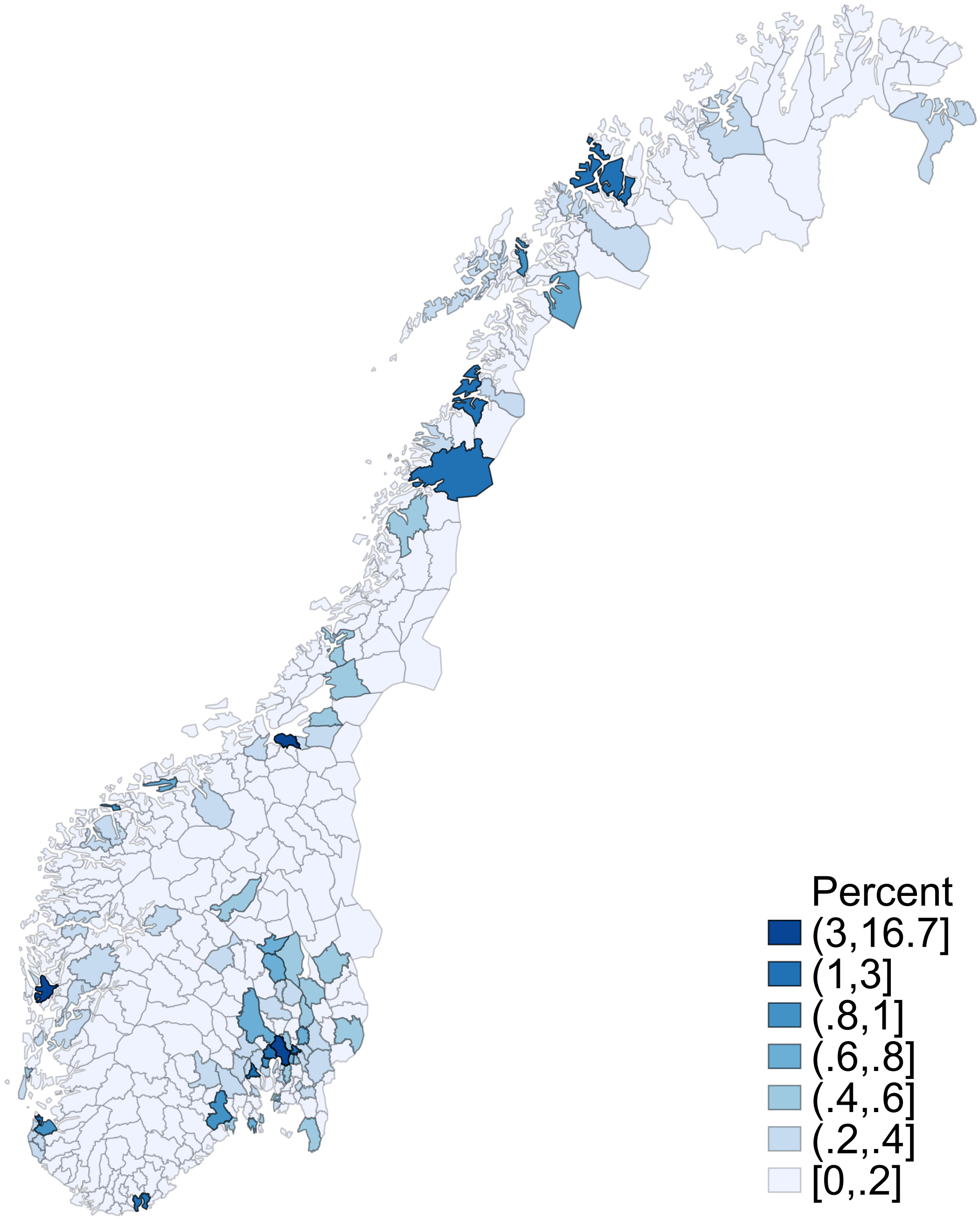
Source: Lian (1981), p. 33. Mobility is the number of internal migrations as per 1 000 of the mean population within each age group.

Figure A.16: Percent of rural female migrants, by destination (1960 census)



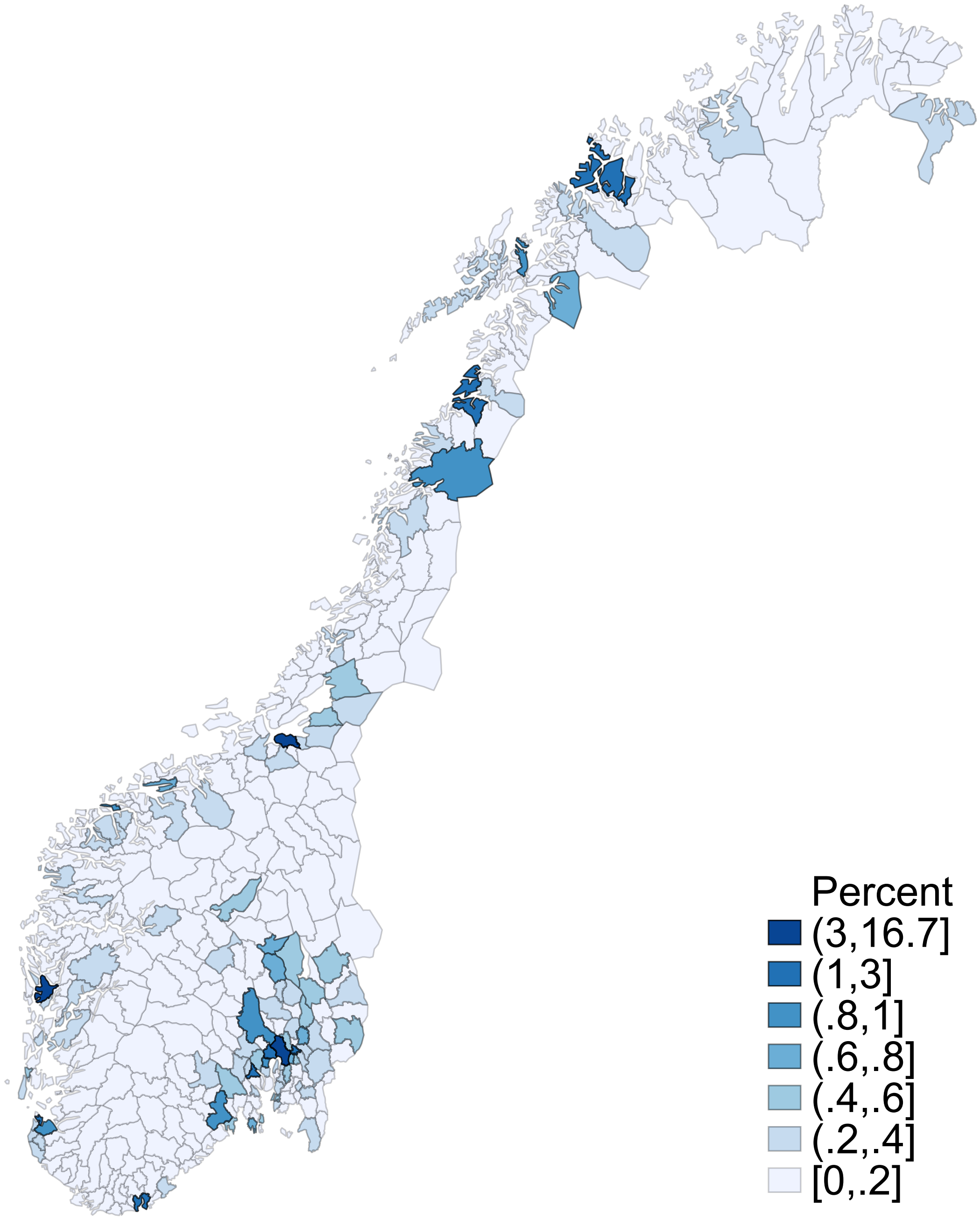
Note.— This figure reports the share of female migrants by municipality of destination. The sample comprises women in our baseline sample who migrated out of their (rural) birthplace in 1960. Municipality borders fixed at 1980 borders.

Figure A.17: Percent of rural female migrants, by destination (1970 census)



Note.— This figure reports the share of female migrants by municipality of destination. The sample comprises women in our baseline sample who migrated out of their (rural) birthplace in 1970. Municipality borders fixed at 1980 borders.

Figure A.18: Percent of rural female migrants, by destination (1980 census)



Note.— This figure reports the share of female migrants by municipality of destination. The sample comprises women in our baseline sample who migrated out of their (rural) birthplace in 1980. Municipality borders fixed at 1980 borders.

Table A.2: Summary statistics for individuals in baseline sample

	Mean	Standard deviation	Observations
Technology diffusion in municipality of birth:			
Milking machines per farm	0.071	0.104	726,537
Milking machines per farm (cohort 16-25 in 1930)	0.000	0.000	72,581
Milking machines per farm (cohort 16-25 in 1940)	0.003	0.008	141,897
Milking machines per farm (cohort 16-25 in 1950)	0.018	0.035	151,571
Milking machines per farm (cohort 16-25 in 1960)	0.110	0.097	161,552
Milking machines per farm (cohort 16-25 in 1970)	0.153	0.125	198,936
Milkcows per farm in 1930	3.089	1.242	726,537
Share women in farming (milkmaids) 1930	0.064	0.036	726,537
Outcomes for women in baseline sample:			
Employment in agriculture (after age 25)	0.091	0.288	379,366
Migration anywhere (ever)	0.689	0.463	379,366
Migration to city (ever)	0.257	0.437	379,366
Migration to town with higher-education institution (ever)	0.327	0.469	359,943
Migration outside county of birth (ever)	0.398	0.490	379,366
Migration inside county of birth (ever)	0.291	0.454	379,366
Distance to migration destination in km | migrating (1960)	79.45	202.50	370,126
Distance to migration destination in km | migrating (1970)	117.13	248.88	375,843
Distance to migration destination in km | migrating (1980)	126.62	259.05	376,984
Income at age 45† in NOK	65,016	82,474	342,792
Labor force participation (age 45)	0.781	0.413	271,450
Undergraduate education or more	0.099	0.298	379,366
Outcomes for men in baseline sample:			
Employment in agriculture (after age 25)	0.176	0.381	347,171
Migration anywhere (ever)	0.580	0.494	347,171
Migration to city (ever)	0.227	0.419	347,171
Migration to town with higher-education institution (ever)	0.281	0.449	333,345
Migration outside county of birth (ever)	0.351	0.477	347,171
Migration inside county of birth (ever)	0.229	0.420	347,171
Distance to migration destination in km | migrating (1960)	60.93	179.985	338,703
Distance to migration destination in km | migrating (1970)	98.89	235.67	343,600
Distance to migration destination in km | migrating (1980)	110.72	249.36	344,571
Income at age 45† in NOK	127,630	129,785	344,829
Labor force participation (age 45)	0.955	0.208	277,608
Undergraduate education or more	0.097	0.296	347,171
Outcomes for women in non-agriculture occupation:			
High-skill occupation	0.125	0.330	344,658
Mid-skill occupation	0.183	0.387	344,658
Low-skill occupation	0.343	0.475	344,658
Outcomes for men in non-agriculture occupation:			
High-skill occupation	0.272	0.445	286,086
Mid-skill occupation	0.562	0.496	286,086
Low-skill occupation	0.078	0.268	286,086
Municipality-level controls:			
Share improved farmland in 1929	0.704	0.241	726,537
Farms p.c. in 1930	0.132	0.037	726,537
Early-tractor adoption by 1930 (0/1)	0.456	0.498	726,537
Ratio large to small farms (in 1929)	0.119	0.239	726,537
Ratio large to small farms (contemporaneous)	0.065	0.253	723,766
Hydropower potential	0.433	0.780	698,324
Hydropower status in 1900-1910	0.071	0.258	701,787

NOTE.— This table shows summary statistics for our baseline sample: women and men born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1930–70. †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 A.3: Determinants of milking machine diffusion (1929–69)

	(1)	(2)	(3)	(4)	(5)	(6)
	Dep. Var.: Milking machines per farm					
	OLS		LASSO	OLS		LASSO
Milkcows per farm in 1930	0.031***	(0.003)	X	0.031***	(0.003)	X
Share milkmaids in 1930	-0.346	(0.226)		-0.351	(0.231)	
Share females in agriculture in 1930	-0.015	(0.127)		-0.016	(0.130)	
Female labor force participation in 1930	0.132*	(0.070)		0.134*	(0.071)	
Female net-migration rate in 1930	-0.027	(0.020)		-0.027	(0.020)	
Population density in 1930	0.241***	(0.075)		0.241***	(0.077)	
Farms per capita in 1930	0.399***	(0.073)	X	0.401***	(0.075)	X
Share improved farmland in 1930	0.070***	(0.011)	X	0.070***	(0.012)	X
Tractor dummy in 1930	-0.008	(0.005)		-0.008	(0.006)	
Share females age 15-19 in 1930	-0.415**	(0.206)		-0.392*	(0.211)	
Share females age 20-39 in 1930	-0.177	(0.121)		-0.170	(0.123)	
Share females age 40-59 in 1930	-0.094	(0.131)		-0.092	(0.134)	
Share females 60+ in 1930	-0.158	(0.126)		-0.151	(0.128)	
Share manufacturing workers in 1930	-0.022	(0.019)		-0.022	(0.019)	
Capital-labor ratio in 1930	0.555	(1.060)		0.571	(1.082)	
Land area in 1930	0.000**	(0.000)		0.000*	(0.000)	
Ratio large to small farms in 1930	0.020**	(0.008)	X	0.020**	(0.009)	X
Avg. income males in 1930	-0.000	(0.000)		-0.000	(0.000)	
Avg. income females in 1930	0.000*	(0.000)		0.000*	(0.000)	
Avg. wealth males in 1930	-0.000	(0.000)		-0.000	(0.000)	
Avg. wealth females in 1930	-0.000	(0.000)		-0.000	(0.000)	
Crude birth rate in 1930	0.001	(0.000)		0.001	(0.000)	
Crude death rate in 1930	-0.001	(0.001)		-0.001	(0.001)	
Marriage rate in 1930	0.002**	(0.001)		0.002**	(0.001)	
Observations	1,449			1,449		
R-squared	0.6124			0.707		
County FE	Y			Y		
Cohort FE	Y			Y		
County × year FE	.			Y		

Note.— Column (1) regresses milking machines per farm on municipality characteristics in 1930 and fixed effects for census year and county. Column (2) shows the selected controls by the Lasso procedure. Columns (3) and (4) show the corresponding results including county-by-census year fixed effects. Controls marked by "X" are selected by the Lasso procedure. The share of milkmaids is negatively associated with milking machine diffusion, conditional on the number of milkcows per farm (see Panel C of Table A.8 for the unconditional positive association between share milkmaids and milking machines). Standard errors (in parentheses) clustered at the municipality level; *p<.05; **p<.01; ***p<.001.

Table A.4: Main results conditional on reporting an occupation

	(1) Employed agriculture	(2) Migration	(3) Income pctile rank	(4) Labor force participation
Panel A. IV				
Milking machines per farm (women)	-0.053***	0.048***	2.338***	0.046***
	(0.007)	(0.009)	(0.342)	(0.007)
Milking machines per farm (men)	-0.028***	0.029***	-0.132	0.004*
	(0.008)	(0.009)	(0.360)	(0.002)
p-value (women = men)	0.000	0.003	0.000	0.000
Panel B. Reduced form				
Cows per farm 1930 × National rollout (wom)	-0.048***	0.043***	2.124***	0.039***
	(0.005)	(0.008)	(0.302)	(0.006)
Cows per farm 1930 × National rollout (men)	-0.025***	0.026***	-0.118	0.003**
	(0.007)	(0.008)	(0.326)	(0.001)
p-value (women = men)	0.000	0.002	0.000	0.000
Panel C. OLS				
Milking machines per farm (women)	-0.017***	0.013***	0.838***	0.015***
	(0.003)	(0.004)	(0.153)	(0.003)
Milking machines per farm (men)	-0.010**	0.007*	-0.220	0.000
	(0.004)	(0.004)	(0.150)	(0.001)
p-value (women = men)	0.068	0.077	0.000	0.000
Municipality and birth year FE	Y	Y	Y	Y
Flexible trends (Lasso)	Y	Y	Y	Y
County-by-byear FE	Y	Y	Y	Y
Mean dep. variable	0.16	0.38	54.10	0.91
F-stat first stage (women)	105.4	105.4	104.6	85.8
F-stat first stage (men)	100.1	100.1	100.0	80.4
Observations	603,816	603,816	594,999	476,047

NOTE.— This table shows IV, reduced-form, and OLS estimates for the long-term effect of milking machines based on equations (3) and (3), conditional on a sample of women and men reporting an occupation. The sample includes all women and men who report an occupation in the censuses after age 25, who were born in rural municipalities with at least one farm in 1930, and who were aged 16–25 in the census years 1930–1970. Dependent variable and flexible trends are defined as in Table 2 and 3. Independent variables are normalized to have a mean of zero and an SD of one. Standard errors (in parentheses) clustered at the municipality level; *p<.05; **p<.01; ***p<.001.

Table A.5: Alternative definitions of labor force participation (LFP)

	Dep. Var.: = 1 if > income in tax registry		Dep. Var.: = 1 if occupation in Census (after age 25) and > income in tax registry	
	at age 45 (baseline) (1)	at age 45, 52, 62 (2)	at age 45 (3)	at age 45, 52, 62 (4)
Panel A. IV				
Milking machines per farm (women)	0.038***	0.029***	0.043***	0.032***
	(0.007)	(0.005)	(0.007)	(0.006)
Milking machines per farm (men)	0.006**	0.007***	0.006**	0.006***
	(0.002)	(0.002)	(0.002)	(0.002)
p-value (women = men)	0.000	0.000	0.000	0.000
Panel B. Reduced form				
Cows per farm 1930 × National rollout (wom)	0.032***	0.026***	0.036***	0.028***
	(0.005)	(0.004)	(0.006)	(0.005)
Cows per farm 1930 × National rollout (men)	0.005***	0.006***	0.005**	0.006***
	(0.002)	(0.001)	(0.002)	(0.002)
p-value (women = men)	0.000	0.000	0.000	0.000
Panel C. OLS				
Milking machines per farm (women)	0.011***	0.010***	0.013***	0.011***
	(0.003)	(0.002)	(0.003)	(0.003)
Milking machines per farm (men)	0.001	0.002**	0.002*	0.003**
	(0.001)	(0.001)	(0.001)	(0.001)
p-value (women = men)	0.000	0.000	0.001	0.003
Municipality and birth year FE	Y	Y	Y	Y
Flexible trends (Lasso)	Y	Y	Y	Y
County-by-byear FE	Y	Y	Y	Y
Mean dep. variable	0.87	0.89	0.79	0.81
F-stat first stage (women)	81.8	95.8	81.8	95.8
F-stat first stage (men)	79.8	98.5	79.8	98.5
Observations	549,058	651,670	549,058	651,670

NOTE.— This table shows IV, reduced-form, and OLS estimates based on Equation (4) for alternative definitions of labor force participation. Our baseline measure (col. 1) is an indicator variable equal to one if an individual reported a positive income at age 45. Because the income registry only starts in 1967, this measure excludes the cohorts aged 16-25 in 1940 and 1930. In col. 2 we consider an indicator variable equal to one if an individual reported a positive income at age 45 (for cohorts aged 16–25 in 1950 to 1970), at age 52 (for cohorts aged 16–25 in 1940), and at age 62 (for cohorts aged 16–25 in 1930). In col. 3, we consider an indicator variable equal to one if an individual reports a non-missing occupation in the Census conducted after age 25 and a positive income in the tax registry at age 45. In col. 4, we consider an indicator variable equal to one if an individual reports a non-missing occupation in the Census conducted after age 25 and a positive income in the tax registry at age 45 (for cohorts aged 16–25 in 1950 to 1970), at age 52 (for cohorts aged 16–25 in 1940), and at age 62 (for cohorts aged 16–25 in 1930). Independent variables and flexible trends are defined as in Table 3. The sample includes women and men born in rural municipalities with at least one farm in 1930, who were aged 16–25 in the census years 1930-70, and with no missing information on income at the relevant age. Standard errors (in parentheses) clustered at the municipality level; *p<.05; **p<.01; ***p<.001.

Table A.6: The diffusion of milking machines and income at ages 40–45

	(1)	(2) Income at age 40	(3)	(4)	(5) Income at age 45	(6)
	Percentile rank	$1(income > 0)$	$log\ (income{+}1)$	Percentile rank	$1(income > 0)$	$log\ (income{+}1)$
Panel A. IV						
Milking machines per farm (women)	1.200***	0.031***	0.322***	1.495***	0.030***	0.347***
	(0.392)	(0.008)	(0.078)	(0.347)	(0.006)	(0.067)
Milking machines per farm (men)	0.261	0.001	0.032	0.253	0.007***	0.081**
	(0.380)	(0.002)	(0.026)	(0.423)	(0.002)	(0.034)
p-value (women = men)	0.063	0.001	0.000	0.013	0.000	0.000
Panel B. Reduced form						
Cows per farm 1930 × National rollout (wom)	0.967***	0.025***	0.259***	1.204***	0.025***	0.280***
	(0.321)	(0.007)	(0.063)	(0.277)	(0.005)	(0.053)
Cows per farm 1930 × National rollout (men)	0.211	0.001	0.026	0.205	0.005***	0.066***
	(0.302)	(0.002)	(0.021)	(0.333)	(0.002)	(0.024)
p-value (women = men)	0.078	0.001	0.000	0.022	0.000	0.000
Panel C. OLS						
Milking machines per farm (women)	0.426***	0.014***	0.140***	0.428***	0.010***	0.107***
	(0.155)	(0.003)	(0.029)	(0.148)	(0.003)	(0.027)
Milking machines per farm (men)	0.250	0.001	0.028**	0.152	0.001	0.020
	(0.164)	(0.001)	(0.014)	(0.172)	(0.001)	(0.014)
p-value (women = men)	0.379	0.000	0.000	0.178	0.002	0.002
Municipality and birth year FE	Y	Y	Y	Y	Y	Y
Flexible trends (Lasso)	Y	Y	Y	Y	Y	Y
County-by-byear FE	Y	Y	Y	Y	Y	Y
Mean dep. variable	50.59	0.85	9.43	51.51	0.89	10.08
F-stat first stage (women)	68.8	68.8	68.8	68.8	68.8	68.8
F-stat first stage (men)	67.1	67.1	67.1	67.1	67.1	67.1
Observations	504,373	504,373	504,373	504,373	504,373	504,373

NOTE.— This table shows IV, reduced-form, and OLS estimates for the effect of the diffusion of milking machines on women's income at the age of 40 and 45, based on equations (3) and (3). The sample includes women and men born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1950–1970, and whose income at age 45 is listed in the tax registry (1967–2010). The dependent variable is the income percentile rank at age 40 (Column 1) or 45 (Column 4), a dummy variable equal to 1 if a woman reported any income at age 40 (Column 2) or 45 (Column 5), and log(income +1) at age 40 (Column 3) and at age 45 (Column 6). In cols. 1-3, we assign income 45 values to two cohorts (born 1925 and 1926) who where older than 40 when income registry started in 1967. Independent variables are normalized to have a mean of zero and an SD of one. Flexible trends are defined as in Table 2. Standard errors (in parentheses) clustered at the municipality level; *p<.05; **p<.01; ***p<.001.

Table A.7: Decomposition of the income effect by mover status

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Income at age 40			Income at age 45			
	Percentile rank	$1(y>0)$	$log\ (y+1)$	Percentile rank	$1(y>0)$	$log\ (y+1)$	High-skill occupation
Panel A. Women							
Stayers (omitted)	-	-	-	-	-	-	-
Migrates to rural	2.178***	0.022***	0.266***	2.606***	0.018***	0.270***	0.039***
	(0.245)	(0.004)	(0.039)	(0.235)	(0.003)	(0.033)	(0.002)
Migrates to urban	7.705***	0.073***	0.907***	7.814***	0.051***	0.749***	0.089***
	(0.293)	(0.004)	(0.047)	(0.282)	(0.003)	(0.039)	(0.002)
p-value (to rural = to urban)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mean dep. variable	33.09	0.74	7.88	36.72	0.82	9.00	0.12
Observations	248,859	248,859	248,859	248,859	248,859	248,859	344,658
Panel B. Men							
Stayers (omitted)	-	-	-	-	-	-	
Migrates to rural	6.632***	0.002	0.181***	6.908***	0.004***	0.210***	0.129***
	(0.320)	(0.001)	(0.016)	(0.327)	(0.001)	(0.018)	(0.005)
Migrates to urban	10.622***	-0.000	0.259***	10.918***	-0.000	0.267***	0.195***
	(0.411)	(0.001)	(0.021)	(0.405)	(0.001)	(0.022)	(0.005)
p-value (to rural = to urban)	0.000	0.049	0.000	0.000	0.000	0.000	0.000
Mean dep. variable	67.64	0.96	10.94	65.91	0.95	11.13	0.27
Observations	255,514	255,514	255,514	255,514	255,514	255,514	286,086
Municipality FE	Y	Y	Y	Y	Y	Y	Y
Birth cohort year FE	Y	Y	Y	Y	Y	Y	Y
Flexible trends (Lasso)	Y	Y	Y	Y	Y	Y	Y
County-by-byear FE	Y	Y	Y	Y	Y	Y	Y

NOTE.— This table decomposes the income effect by mover status. 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. Sample and dependent variables defined as in Appendix Table A.6 (columns 1-6) and as in Table 4 (column 7); Flexible trends defined as in Table 2. Standard errors (in parentheses) clustered at the municipality level; *p<.05; **p<.01; ***p<.001.

Table A.8: Results using milkmaid employment shares as treatment-exposure measure

	(1) Employed agriculture	(2) Migration	(3) Income pctile rank	(4) Labor force participation
Panel A. Reduced form				
Share milkmaids 1930 × National rollout (wom)	-0.030***	0.018***	1.078***	0.022***
	(0.003)	(0.005)	(0.202)	(0.005)
Share milkmaids 1930 × National rollout (men)	-0.014**	0.004	0.025	0.004***
	(0.006)	(0.006)	(0.240)	(0.001)
p-value (women = men)	0.002	0.001	0.000	0.000
Panel B. IV second stage				
Milking machines per farm (women)	-0.083***	0.050***	2.969***	0.061***
	(0.018)	(0.016)	(0.811)	(0.020)
Milking machines per farm (men)	-0.039**	0.010	0.068	0.010**
	(0.019)	(0.016)	(0.658)	(0.004)
p-value (women = men)	0.002	0.002	0.000	0.005
Panel C. IV first stage	**Dep. Var.: Milking machines per farm**			
Share milkmaids 1930 × National rollout (wom)	0.358***	0.358***	0.363***	0.362***
	(0.073)	(0.073)	(0.074)	(0.076)
Share milkmaids 1930 × National rollout (men)	0.368***	0.368***	0.366***	0.372***
	(0.074)	(0.074)	(0.074)	(0.076)
Municipality and birth year FE	Y	Y	Y	Y
Flexible trends (Lasso)	Y	Y	Y	Y
County-by-byear FE	Y	Y	Y	Y
F-stat first stage (women)	24.1	24.1	24.3	23.0
F-stat first stage (men)	24.8	24.8	24.8	23.9
Observations	726,537	726,537	687,621	549,058

NOTE.— This table shows IV and reduced-form estimates using the share of women employed as milkmaids in 1930 instead of the number of cows per farm in 1930 in the instrument. Specifically, the instrument is $\frac{\bar{M}_{d(b)}}{\bar{F}_{d(b)}} \times \frac{L_{j,1930}}{P_{j,1930}}$. As before, the first component is the national "shift" in the adoption of milking machines, i.e., the total number of milking machines in Norway, $\bar{M}_{d(b)}$, normalized by the total number of farms in Norway, $\bar{F}_{d(b)}$, at the census year $d(b)$ when birth cohort b was aged 16-25. The second component is the treatment intensity at the municipality level, here the share of women employed as milkmaids: $L_{j,1930}$ denotes the number of young women employed in farming in municipality j in 1930 and $P_{j,1930}$ the total female population in municipality j in 1930. Dependent variables, flexible trends, and samples are defined as in Table 2 (col. 2) and Table 3. Independent variables are normalized to have a mean of zero and an SD of one. Standard errors (in parentheses) clustered at the municipality level; *p<.05; **p<.01; ***p<.001.

Table A.9: Comparing stratified samples

	(1) Employed agriculture	(2) Migration	(3) Income pctile rank	(4) Labor force participation
Panel A. Municipalities with >0 milking machines in 1950				
Cows per farm 1930 × National rollout (wom)	-0.037***	0.037***	1.702***	0.031***
	(0.005)	(0.009)	(0.325)	(0.007)
Cows per farm 1930 × National rollout (men)	-0.026***	0.028***	0.151	0.005***
	(0.008)	(0.009)	(0.405)	(0.002)
p-value (women = men)	0.125	0.096	0.002	0.000
Observations	522,549	522,549	494,548	392,861
Mean dep. variable	0.13	0.37	50.41	0.87
Panel B. Municipalities with no milking machines in 1950				
Cows per farm 1930 × National rollout (wom)	-0.055***	0.029**	1.387***	0.035***
	(0.008)	(0.013)	(0.490)	(0.009)
Cows per farm 1930 × National rollout (men)	-0.024*	0.015	-0.280	-0.000
	(0.014)	(0.012)	(0.469)	(0.004)
p-value (women = men)	0.004	0.203	0.002	0.000
Observations	203,986	203,986	193,070	156,197
Mean dep. variable	0.14	0.38	48.47	0.86
Municipality and birth year FE	Y	Y	Y	Y
Flexible trends (Lasso)	Y	Y	Y	Y
County-by-byear FE	Y	Y	Y	Y

Note.— This table replicates reduced-form estimates on stratified samples. All samples include women and men born in rural municipalities with at least one farm in 1929, who were aged 16–25 in the census years 1930–1970. Panel A considers women and men in municipalities which had adopted milking machines in 1950 (switchers by 1950); Panel B considers women and men in municipalities which had not adopted milking machines in 1950 (non-switchers by 1950). Dependent variables and flexible trends are defined as in Tables 2 and 3. Independent variables are normalized to have a mean of zero and an SD of one. Standard errors (in parentheses) clustered at the municipality level; *p<.05; **p<.01; ***p<.001.

Table A.10: Robustness to excluding migrants to Oslo

	(1) Employed agriculture	(2) Migration	(3) Income pctile rank	(4) Labor force participation
Panel A. IV				
Milking machines per farm (women)	-0.045***	0.027***	1.505***	0.035***
	(0.006)	(0.007)	(0.306)	(0.007)
Milking machines per farm (men)	-0.025***	0.017**	-0.309	0.006**
	(0.009)	(0.007)	(0.371)	(0.002)
p-value (women = men)	0.003	0.093	0.000	0.000
Panel B. Reduced form				
Cows per farm 1930 × National rollout (wom)	-0.040***	0.024***	1.333***	0.029***
	(0.004)	(0.006)	(0.268)	(0.006)
Cows per farm 1930 × National rollout (men)	-0.022***	0.016**	-0.273	0.005***
	(0.007)	(0.006)	(0.334)	(0.002)
p-value (women = men)	0.005	0.098	0.000	0.000
Panel C. OLS				
Milking machines per farm (women)	-0.017***	0.008**	0.475***	0.011***
	(0.003)	(0.004)	(0.130)	(0.003)
Milking machines per farm (men)	-0.010**	0.004	-0.138	0.002
	(0.004)	(0.003)	(0.158)	(0.001)
p-value (women = men)	0.078	0.208	0.001	0.001
Municipality and birth year FE	Y	Y	Y	Y
Flexible trends (Lasso)	Y	Y	Y	Y
County-by-byear FE	Y	Y	Y	Y
Mean dep. variable	0.15	0.30	48.89	0.86
F-stat first stage (women)	103.7	103.7	99.5	80.3
F-stat first stage (men)	97.9	97.9	97.8	78.2
Observations	644,447	644,447	608,398	485,642

NOTE.— This table shows IV, reduced-form, and OLS estimates for the long-term effect of milking machines based on equations (3) and (3), using a sample that excludes women and men who migrated to Oslo. Specifically, the sample includes all women and men who were born in rural municipalities with at least one farm in 1930, who were aged 16–25 in the census years 1930–1970, and who did not migrate to Oslo. Dependent variables and flexible trends are defined as in Table 2 (cols. 2, 4, and 5) and Table 3. Independent variables are normalized to have a mean of zero and an SD of one. Standard errors (in parentheses) clustered at the municipality level; *p<.05; **p<.01; ***p<.001.

Table A.11: Robustness controlling for access to hydroelectric power plants

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Employment in agriculture		Migration		Income pctile rank		FLFP	
Panel A. IV								
Milking machines per farm (women)	-0.045***	-0.045***	0.041***	0.041***	1.906***	1.884***	0.041***	0.040***
	(0.006)	(0.006)	(0.009)	(0.009)	(0.318)	(0.320)	(0.007)	(0.007)
Milking machines per farm (men)	-0.032***	-0.030***	0.030***	0.029***	-0.014	-0.046	0.005**	0.005**
	(0.009)	(0.009)	(0.009)	(0.009)	(0.390)	(0.395)	(0.002)	(0.002)
p-value (women = men)	0.058	0.018	0.043	0.036	0.000	0.000	0.000	0.000
Panel B. Reduced form								
Cows per farm 1930	-0.040***	-0.040***	0.036***	0.036***	1.704***	1.673***	0.034***	0.033***
× National rollout (women)	(0.004)	(0.004)	(0.007)	(0.008)	(0.259)	(0.270)	(0.005)	(0.005)
Cows per farm 1930	-0.029***	-0.027***	0.027***	0.026***	-0.013	-0.041	0.004**	0.004**
× National rollout (men)	(0.007)	(0.007)	(0.008)	(0.008)	(0.348)	(0.351)	(0.002)	(0.002)
p-value (women = men)	0.069	0.024	0.043	0.036	0.000	0.000	0.000	0.000
Panel C. OLS								
Milking machines per farm (women)	-0.017***	-0.017***	0.010**	0.010**	0.609***	0.615***	0.012***	0.012***
	(0.002)	(0.002)	(0.004)	(0.004)	(0.144)	(0.145)	(0.003)	(0.003)
Milking machines per farm (men)	-0.011***	-0.011***	0.007*	0.007*	-0.173	-0.177	0.001	0.001
	(0.004)	(0.004)	(0.004)	(0.004)	(0.156)	(0.156)	(0.001)	(0.001)
p-value (women = men)	0.140	0.115	0.284	0.263	0.000	0.000	0.000	0.000
Municipality and birth year FE	Y	Y	Y	Y	Y	Y	Y	Y
Flexible trends (Lasso)	Y	Y	Y	Y	Y	Y	Y	Y
County-by-byear FE	Y	Y	Y	Y	Y	Y	Y	Y
Hydropower instrument × byear FE	Y	.	Y	.	Y	.	Y	.
Hydropower 1900-10 status	.	Y	.	Y	.	Y	.	Y
Mean dep. variable	0.13	0.13	0.38	0.38	49.90	49.91	0.87	0.87
F-stat first stage (women)	98.7	93.7	98.7	93.7	94.6	89.5	75.8	71.2
F-stat first stage (men)	92.1	87.4	92.1	87.4	92.0	87.2	73.1	69.0
Observations	698,324	701,787	698,324	701,787	661,141	664,319	527,750	530,127

NOTE.— This table shows IV estimates in extended specifications of equations (2) and (3) controlling for different measures of access to hydroelectric power plants. Odd columns control for the hydropower potential × birth year FE; Even columns control for the hydropower status between 1900 and 1910 (early adopters). Dependent and independent variables, flexible trends, and the baseline sample are defined as in Table 2 (cols. 2, 4, and 5) and Table 3. Samples are smaller than in Tables 2 and 3 because of missing hydropower data for some municipalities. Standard errors (in parentheses) clustered at the municipality level; *p<.05; **p<.01; ***p<.001.

Table A.12: Robustness to the roll-out of the Primary School Reform (1960-72)

	(1) Employed agriculture	(2) Migration	(3) Income pctile rank	(4) Labor force participation	(5) Education $\geq$ undergrad
Panel A. IV					
Reform: not treated	ref.	ref.	ref.	ref.	ref.
treated	0.000	0.010	-0.146	0.002	0.005
	(0.004)	(0.008)	(0.253)	(0.003)	(0.004)
missing data	0.034	-0.008	-0.688	-0.007	-0.016
	(0.039)	(0.011)	(0.956)	(0.009)	(0.012)
Milking machines (women)	-0.044***	0.041***	1.893***	0.038***	0.014***
	(0.005)	(0.008)	(0.305)	(0.007)	(0.004)
Milking machines (men)	-0.029***	0.029***	0.031	0.006**	0.006**
	(0.008)	(0.009)	(0.371)	(0.002)	(0.003)
p-value (women = men)	0.015	0.03	0.000	0.000	0.035
Panel B. Reduced form					
Reform: not treated	ref.	ref.	ref.	ref.	ref.
treated	0.002	0.009	-0.196	0.000	0.005
	(0.004)	(0.008)	(0.250)	(0.003)	(0.004)
missing data	0.034	-0.008	-0.682	-0.007	-0.016
	(0.040)	(0.011)	(0.960)	(0.009)	(0.012)
Cows per farm 1930	-0.040***	0.037***	1.693***	0.032***	0.012***
× National rollout (women)	(0.004)	(0.007)	(0.263)	(0.005)	(0.003)
Cows per farm 1930	-0.026***	0.026***	0.028	0.005***	0.005**
× National rollout (men)	(0.007)	(0.007)	(0.331)	(0.002)	(0.003)
p-value (women = men)	0.022	0.035	0.000	0.000	0.044
Panel C. OLS					
Reform: not treated	ref.	ref.	ref.	ref.	ref.
treated	0.001	0.009	-0.180	0.001	0.005
	(0.004)	(0.008)	(0.250)	(0.003)	(0.004)
missing data	0.034	-0.008	-0.676	-0.007	-0.016
	(0.040)	(0.011)	(0.967)	(0.009)	(0.012)
Milking machines (women)	-0.017***	0.011***	0.637***	0.011***	0.005***
	(0.002)	(0.004)	(0.137)	(0.003)	(0.002)
Milking machines (men)	-0.011***	0.007*	-0.115	0.001	0.001
	(0.004)	(0.004)	(0.154)	(0.001)	(0.002)
p-value (women = men)	0.103	0.177	0.000	0.000	0.061
Municipality and birth year FE	Y	Y	Y	Y	Y
Flexible trends (Lasso)	Y	Y	Y	Y	Y
County-by-byear FE	Y	Y	Y	Y	Y
F-stat first stage (women)	105.1	105.1	101.0	81.6	105.1
F-stat first stage (men)	99.1	99.1	99.0	79.6	99.1
Observations	726,537	726,537	687,621	549,058	726,537

NOTE.— This table replicates our estimates of Equation (4) controlling for the Primary School Reform roll-out between 1960 and 1972. The variable Reform is an indicator equal to one if an individual 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. We also report effects for municipalities with missing data on the reform. Dependent and independent variables, flexible trends, and samples are defined as in Table 2 (cols. 2, 4, and 5) and Table 3. Standard errors (in parentheses) clustered at the municipality level; *p<.05; **p<.01; ***p<.001.

Table A.13: Robustness to controlling for the intensity of WW2

	(1) Employed agriculture	(2) Migration	(3) Income pctile rank	(4) Labor force participation
Panel A. IV				
Milking machines per farm (women)	-0.044***	0.041***	1.890***	0.038***
	(0.005)	(0.008)	(0.305)	(0.007)
Milking machines per farm (men)	-0.029***	0.029***	0.034	0.006**
	(0.008)	(0.009)	(0.372)	(0.002)
p-value (women = men)	0.016	0.029	0.000	0.000
Panel B. Reduced form				
Cows per farm 1930 × National rollout (wom)	-0.236***	0.220***	10.017***	0.193***
	(0.024)	(0.043)	(1.558)	(0.033)
Cows per farm 1930 × National rollout (men)	-0.157***	0.156***	0.179	0.029***
	(0.040)	(0.044)	(1.965)	(0.010)
p-value (women = men)	0.023	0.033	0.000	0.000
Panel C. OLS				
Milking machines per farm (women)	-0.017***	0.011***	0.647***	0.012***
	(0.002)	(0.004)	(0.137)	(0.003)
Milking machines per farm (men)	-0.010***	0.006*	-0.122	0.001
	(0.004)	(0.004)	(0.156)	(0.001)
p-value (women = men)	0.095	0.153	0.000	0.000
Municipality and birth year FE	Y	Y	Y	Y
Flexible trends (Lasso)	Y	Y	Y	Y
County-by-byear FE	Y	Y	Y	Y
WW2 investment (0/1) × birth year	Y	Y	Y	Y
Mean dep. variable	0.13	0.38	49.87	0.87
F-stat first stage (women)	105.65	105.65	101.57	82.47
F-stat first stage (men)	99.74	99.74	99.57	80.46
Observations	726,537	726,537	687,621	549,058

NOTE.— This table shows IV, reduced-form, and OLS estimates for the long-term effect of milking machines based on equations (3) and (3), controlling for flexible trends by the intensity of WW2, captured by german investments in industry, airports, and coastal infrastructure. Specifically, we use data from **??** and include the interaction of birth year FE with a dummy variable equal to one if the municipality received German investments in these areas during WW2, and zero otherwise. The sample and flexible trends are defined as in Table 2 and 3. Independent variables are normalized to have a mean of zero and an SD of one. Standard errors (in parentheses) clustered at the municipality level; *p<.05; **p<.01; ***p<.001.

Table A.14: The diffusion of milking machines on younger versus older women, Reduced-form and OLS estimates

	(1) Employed agriculture	(2) Migration	(3) Income pctile rank	(4) Labor force participation
Panel A. Reduced form				
Cows per farm 1930 × National rollout (younger)	-0.058***	0.027***	1.402***	0.029***
	(0.007)	(0.008)	(0.353)	(0.008)
Cows per farm 1930 × National rollout (older)	0.052***	-0.003	0.508	-0.000
	(0.006)	(0.003)	(0.433)	(0.009)
p-value (younger = older)	0.000	0.000	0.156	0.041
Panel B. OLS				
Milking machines per farm (younger)	-0.028***	0.017***	0.577***	0.015***
	(0.004)	(0.004)	(0.191)	(0.004)
Milking machines per farm (older)	0.006*	0.000	0.441**	0.004
	(0.003)	(0.002)	(0.220)	(0.005)
p-value (younger = older)	0.000	0.000	0.681	0.112
Municipality and birth year FE	Y	Y	Y	Y
Flexible trends (Lasso)	Y	Y	Y	Y
County-by-byear FE	Y	Y	Y	Y
Mean dep. variable	0.09	0.20	31.05	0.71
Observations	319,092	319,092	289,187	289,187

NOTE.— This table shows reduced-form and OLS estimates based on equations (3) and (3), where instead of comparing women versus men we compare "younger" versus "older" women. The sample includes women aged 16–25 (younger) and 36–45 (older) living in a rural municipalities in 1950, 1960, and 1970. The number of milking machines per farm is measured at their municipality of residence, based on the 1960 and 1970 census. For younger cohorts, all dependent variables are defined as in Tables 2 and 3. For older cohorts, employment in agriculture and migration are based on the occupation and residency reported in the following census (i.e., for women aged 36–45 in 1950, 1960, and 1970, we look, respectively, into the 1960, 1970, and 1980 census); income rank is defined as before; and FLFP is equal to one if the older cohort in 1950, 1960, and 1970 reported a positive income at, respectively, age 45, 52, and 62. We use different ages because the income registry only starts in 1967 so we do not observe income at age 45 for all the "older cohorts." Similarly, because we do not observe women aged 36–45 before 1950 (e.g., born before 1905) in the registry data, the sample is restricted by construction to young and old cohorts in 1950, 1960, and 1970. Independent variables are normalized to have a mean of zero and an SD of one. Standard errors (in parentheses) clustered at the municipality level; *p<.05; **p<.01; ***p<.001.

Table A.15: Migration decisions and schooling structure, IV estimates

	(1)	(2)	(3)
	Migrates to town with higher-edu.	Long-dist. rural-urban migration	Short-dist. rural-rural migration
Milking machines (women)	0.391***	0.346***	-0.043
× municipality high school in 1963 = NO	(0.081)	(0.072)	(0.038)
Milking machines (men)	0.283***	0.251***	-0.021
× municipality high school in 1963 = NO	(0.071)	(0.074)	(0.038)
p-value (women = men)	0.053	0.081	0.532
Milking machines (women)	0.180**	0.182**	0.110***
× municipality high school in 1963 = YES	(0.089)	(0.083)	(0.041)
Milking machines (men)	0.120	0.089	0.115**
× municipality high school in 1963 = YES	(0.080)	(0.080)	(0.045)
p-value (women = men)	0.324	0.117	0.898
Municipality FE	Y	Y	Y
Birth year FE	Y	Y	Y
Flexible trends (Lasso)	Y	Y	Y
County-by-byear FE	Y	Y	Y
Observations	677,235	703,918	703,918
F-stat women, high schol NO	88.88	90.23	90.23
F-stat women, high schol YES	10.51	11.06	11.06
F-stat men, high schol NO	84.71	85.93	85.93
F-stat men, high schol YES	10.32	10.81	10.81
Mean dep. variable	0.31	0.30	0.11

NOTE.— This table shows IV estimates based on equations (2) and (4). Interactions capture the differential effect of the diffusion of milking machines in municipalities with at least one high-shool (gymnasium) in 1963, and are instrumented with our exposure measure (Equation (1)) × a dummy for municipalities with at least one high-school in 1963. The sample includes women and men born in rural municipalities with at least one farm in 1930, who were aged 16–25 in the census years 1930–1970. In col. 1 the dependent variable is equal to 1 if an individual migrated to one of the 28 towns with a higher-education institution where academic (university) or vocational programmes (høyskole) were offered in 1963. In cols- 2-3, urban (rural) areas are towns with a population above (below) 10,000 in 1929. Independent variables are normalized to have a mean of zero and an SD of one. All specifications are fully-interacted models, where gender dummies are interacted with fixed effects for municipality and birth cohort; flexible trends selected with a LASSO procedure (see Appendix Table A.3) and defined as in Table 2; and county-by-birth cohort fixed effects. Standard errors in parentheses clustered at the municipality level; *p<.05; **p<.01; ***p<.001.

Table A.16: Migration decisions and schooling structure, reduced-form estimates

	(1)	(2)	(3)
	Migrates to town with higher-edu.	Long-dist. rural-urban migration	Short-dist. rural-rural migration
Milkcows × National rollout (women)	0.037***	0.032***	-0.004
× municipality high school in 1963 = NO	(0.007)	(0.006)	(0.004)
Milkcows × National rollout (men)	0.027***	0.024***	-0.002
× municipality high school in 1963 = NO	(0.006)	(0.006)	(0.004)
p-value (women = men)	0.060	0.099	0.540
Milkcows × National rollout (women)	0.022***	0.021***	0.008*
× municipality high school in 1963 = YES	(0.008)	(0.007)	(0.004)
Milkcows × National rollout (men)	0.015**	0.012*	0.008*
× municipality high school in 1963 = YES	(0.007)	(0.007)	(0.005)
p-value (women = men)	0.231	0.108	0.816
Municipality FE	Y	Y	Y
Birth year FE	Y	Y	Y
Flexible trends (Lasso)	Y	Y	Y
County-by-byear FE	Y	Y	Y
Observations	677,235	703,918	703,918
Mean dep. variable	0.31	0.30	0.11

NOTE.— This table shows RF estimates based on equation (4). Interactions capture the differential effect of the diffusion of milking machines in municipalities with at least one high-shool (gymnasium) in 1963. The sample includes women and men born in rural municipalities with at least one farm in 1930, who were aged 16–25 in the census years 1930–1970. In col. 1 the dependent variable is equal to 1 if an individual migrated to one of the 28 towns with a higher-education institution where academic (university) or vocational programmes (høyskole) were offered in 1963. In cols- 2-3, urban (rural) areas are towns with a population above (below) 10,000 in 1929. Independent variables are normalized to have a mean of zero and an SD of one. All specifications are fully-interacted models, where gender dummies are interacted with fixed effects for municipality and birth cohort; flexible trends selected with a LASSO procedure (see Appendix Table A.3) and defined as in Table 2; and county-by-birth cohort fixed effects. Standard errors in parentheses clustered at the municipality level; *p<.05; **p<.01; ***p<.001.

Table A.17: Migration decisions and schooling structure, OLS estimates

	(1)	(2)	(3)
	Migrates to town with higher-edu.	Long-dist. rural-urban migration	Short-dist. rural-rural migration
Milking machines (women)	0.090**	0.108***	0.000
× municipality high school in 1963 = NO	(0.036)	(0.036)	(0.018)
Milking machines (men)	0.062**	0.072**	-0.006
× municipality high school in 1963 = NO	(0.029)	(0.032)	(0.020)
p-value (women = men)	0.328	0.232	0.730
Milking machines (women)	-0.037	0.028	0.110***
× municipality high school in 1963 = YES	(0.043)	(0.042)	(0.025)
Milking machines (men)	-0.040	-0.015	0.109***
× municipality high school in 1963 = YES	(0.035)	(0.034)	(0.024)
p-value (women = men)	0.909	0.164	0.978
Municipality FE	Y	Y	Y
Birth year FE	Y	Y	Y
Flexible trends (Lasso)	Y	Y	Y
County-by-byear FE	Y	Y	Y
Observations	677,235	703,918	703,918
Mean dep. variable	0.31	0.30	0.11

NOTE.— This table shows OLS estimates based on equation (4). Interactions capture the differential effect of the diffusion of milking machines in municipalities with at least one high-shool (gymnasium) in 1963. The sample includes women and men born in rural municipalities with at least one farm in 1930, who were aged 16–25 in the census years 1930–1970. In col. 1 the dependent variable is equal to 1 if an individual migrated to one of the 28 towns with a higher-education institution where academic (university) or vocational programs (høyskole) were offered in 1963. In cols- 2-3, urban (rural) areas are towns with a population above (below) 10,000 in 1929. Independent variables are normalized to have a mean of zero and an SD of one. All specifications are fully-interacted models, where gender dummies are interacted with fixed effects for municipality and birth cohort; flexible trends selected with a LASSO procedure (see Appendix Table A.3) and defined as in Table 2; and county-by-birth cohort fixed effects. Standard errors in parentheses clustered at the municipality level; *p<.05; **p<.01; ***p<.001.

Table A.18: Percent of rural female migrants to 10 largest towns

	(1)	(2)	(3)
	1960 census	1970 census	1980 census
Oslo	16.67	14.86	12.96
Bergen	5.39	5.26	4.73
Trondheim	3.48	3.87	3.87
Stavanger	1.67	1.63	1.64
Bærum (Greater Oslo)	1.88	2.00	1.81
Kristiansand	1.21	1.30	1.20
Drammen	1.19	1.20	1.13
Tromsø	1.13	1.36	1.58
Bodø	1.12	1.30	1.33
Other (urban municipalities)	30.43	32.28	32.61
Other (rural municipalities)	35.85	34.94	37.14

Note.— This table shows the distribution of female rural migrants across the 10 largest cities in Norway. Other urban (rural) municipalities are those with a population above (below) 10,000 in 1969. The sample comprises women in our baseline sample who migrated out of their (rural) birthplace in the census year 1960 (column 1), 1970 (column 2), and 1980 (column 3).

Table A.19: Public-sector occupations, as defined by the *Standard for yrkesklassifisering*

Digit	Description
11	Legislators and senior officials in public administration and interest organisations
1227	Production and operations department managers in public administration
1228	Production and operations department managers in education, health and social security
222	Health professionals
223	Nursing and midwifery professionals
23	Teaching professionals
24	Public service administrative professionals
323	Nursery and Registered Nurses for the Mentally Subnormal (RNMS)
33	Teaching associate professionals
344	Public service administrative associate professionals
345	Police officers
346	Social workers (college-trained), child care officers, etc.
5161	Fire-fighters
5162	Prison guards

NOTE.— This table lists the four-digit occupations included in our variable "Public sector occupation" (Table 4, column 4). Definitions based on the *Standard for yrkesklassifisering* for occupations in the full count Censuses of 1960, 1970, and 1980.

A.3 Model

In this appendix, we develop a simple conceptual framework that links the adoption of milking machines to the displacement of female labor, its reallocation from dairying into the urban sector jobs (e.g., public sector), and the eventual long-term income gains for women. To do so, we combine a task-based production function, which accounts for the gender division of labor in traditional agriculture and for the automation of hand milking (Zeira, 1998; Autor et al., 2003; Acemoglu and Autor, 2011), with the key ideas of comparative advantage, which explain labor reallocation across sectors (Roy, 1951).

A.3.1 Set up

Consider an economy with a large number of municipalities specialized in two sectors: a rural sector (R) and urban sector (U). The rural sector consists of primary industries such as agriculture, dairying, or fisheries, as well as construction and timber industries located in rural municipalities. The urban sector comprises manufacturing, services and, especially, the growing public sector jobs which abounded in urban areas.

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, $\alpha_U(i)$ represents skills demanding more general human capital for white-collar occupations, e.g., skills required in public sector jobs. 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 starting off in the rural sector, for whom supplying labor to the urban sector requires reallocating across occupations and, in most cases, migrating out of rural municipalities. This entails a cost c, which we assume to be a fraction of their earnings (Nakamura et al., 2021). This cost can be thought of as sectoral reallocation costs—e.g., the educational investments necessary to secure employment in the growing public sector—and/or as migration costs[52]—e.g., the economic cost of moving to a new locality and the foregone social ties and rural insurance networks (Munshi and Rosenzweig, 2016). Additionally, for female labor, this cost incorporates barriers to moving across sectors

[52]Although we do not directly observe moving costs, our empirical analysis provides important insights on it. First, we show that migration patterns did not differ across more and less dairy-intensive municipalities in the pre-milking machine era. Second, by using fixed effects for municipalities and county-by-birth cohorts, we account for time-invariant *municipality-specific* and for time-varying *county-specific* moving costs that may have affected women's decisions to migrate and their long-run income gains.

due to traditional norms on the gender division of labor, family ties, larger opportunity costs of having children and, more generally, social norms about the role of women in the labor market.

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:

$$Y_R = y_1^{1-\beta}\ y_2^{\beta}\ . \tag{A.4}$$

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 milking cows, and task y_2 as work traditionally done by men, e.g., cultivating fields, seasonal work in construction or in fisheries. To capture the displacement effects of milking machines, assume that capital (milking machines) M and female labor are perfect substitutes. Formally, the production function of each task is:

$$y_1 = A_R L_R^f + M \quad \text{and} \quad y_2 = A_R L_R^m\ , \tag{A.5}$$

where $L_R^f = \int_{i\in\mathcal{F_R}} \alpha_R(i)di$ and $L_R^m = \int_{i\in\mathcal{M_R}} \alpha_R(i)di$ are female and male labor in the rural sector, and $\mathcal{F_R}$ and $\mathcal{M_R}$ denote the set of female and male rural workers.

This task-based production function encompasses the canonical labor-augmenting technological change (A_R) and 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 production, irrespective of gender. Formally, the production function is:

$$Y_U = A_U L_U\ ,\ \text{where}\ \ L_U = \int_{i\in\mathcal{S_U}} \alpha_U(i)di \tag{A.6}$$

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

A.3.2 Equilibrium

Three main conditions govern the remainder of the equilibrium. The first is that labor markets are perfectly competitive and the economy is small. Therefore, 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 $W_U = A_U P_U$.

The second 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 the labor-augmenting technological change, A_R, and by the labor-saving technological change, captured by the price of machines μ:

$$W_R^f = A_R \mu \ . \tag{A.7}$$

The third condition is worker self-selection among the rural and urban sectors. 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 c of reallocating across sectors, this implies that the marginal female worker, $\imath^*$, is indifferent between remaining in the rural sector and reallocating to the urban sector 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 of female, η_i^f, and of male, η_i^m, workers:

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

The indifference condition is then:

$$\eta_{\imath^*}^f = \eta_{\jmath^*}^m = \frac{1}{1-c} \ . \tag{A.8}$$

Note that this indifference condition 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 Panel (a) of Figure A.19. Female workers with a higher comparative advantage in the urban sector have higher relative earnings in that sector.[53] All women with a comparative advantage above $\tilde{\imath}$ would earn a higher salary in the urban sector. However, the cost of reallocating across sectors implies that all women with a comparative advantage below $\imath^*$ will remain employed in the rural sector, and that only women with a comparative advantage above $\imath^*$ will relocate to the urban sector. Hence, all women between $\tilde{\imath}$ and $\imath^*$ will be "misallocated" and their earnings would increase if they moved to the urban sector. As we will discuss in the next sub-section, a large technology

[53] 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.

shock like milking machines can break this allocative inefficiency and generate long-term income gains for these "misallocated" workers.

A.3.3 Comparative statics

Here we consider the situation at the time of the mechanization of agriculture and derive comparative statics. This exercise helps us a) to identify the compliers of our quasi-experiment; b) to motivate our empirical strategy based on using differences in dairy-farming intensity in the pre-milking machines era; c) to rationalize our main results for the effects of milking machines on displacement from agriculture; and d) to illustrate the mechanisms though which automation can result in long-term income gains.

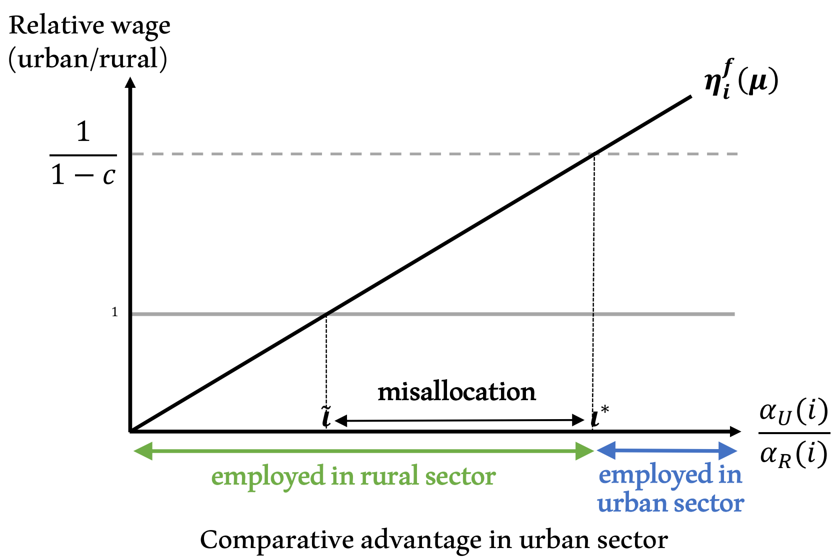
As explained in the main text, the adoption of milking machines automated tasks typically performed by women in rural areas. In our model, this labor-saving technological change is captured by a decline in the price of the machines, M, from μ to μ'. This quasi-experiment is illustrated in Panel (b) of Figure A.19.

The *first comparative-static result* 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 (A.7) that a decline in the price of machines reduces the female wage in the rural sector. That is, $\partial W_R^f/\partial\mu = A_R > 0$, and hence, $\partial\eta^f/\partial\mu = -(A_U P_U/A_R\mu^2)\cdot(\alpha_U(i)/\alpha_R(i)) < 0$. This is illustrated by the relative earnings curve shifting up (red line) in Panel (b) of Figure A.19. 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 that we adopted implies that female workers' decisions to reallocate to the urban sector 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 machines from agricultural jobs in the rural sector, migrate out of rural areas, and reallocate to the urban sector. This rationalizes our main empirical results on employment in agriculture and migration for women exposed to the adoption of milking machines.

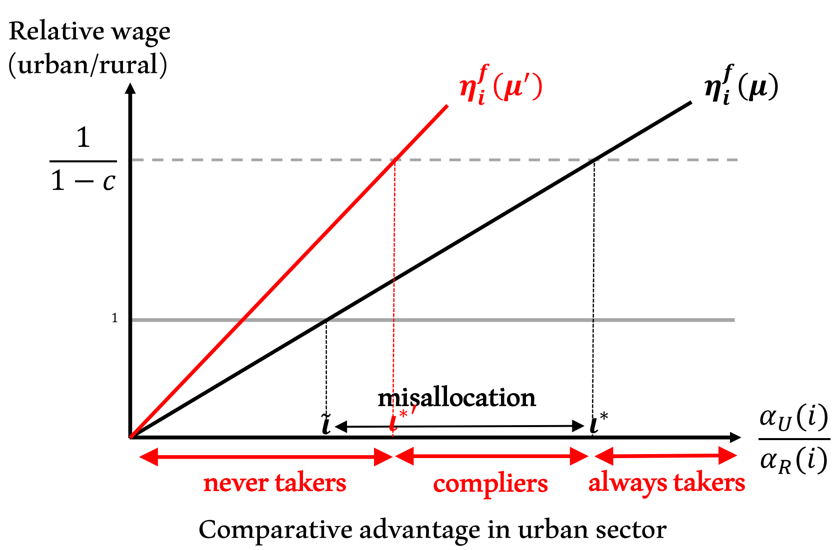
This comparative static result also allows us to identify the compliers of our quasi-experiment. Based on the terminology of Angrist (2004), female workers to the left of $\imath^{*\prime}$ in Panel (b) of Figure A.19 are "never-takers." They have such a strong comparative advantage in the rural sector that they will not reallocate to the urban sector, even after the adoption of milking machines. Female workers between $\imath^{*\prime}$ and $\imath^*$ are "compliers." They will reallocate to the urban sector 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 reallocate, even if their municipality does not adopt milking machines.

Figure A.19

Panel (a) Sorting by comparative advantage (women)



Panel (b) Milking machines' impact on women



NOTE.— For illustrative purposes, we assume that $\alpha_U(i)$ and $\alpha_R(i)$ are uniformly distributed.

The *second comparative-static result* 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 the rural sector only due to the reallocation cost—which we defined above as the costs to upskill, economic costs of moving, family ties, or barriers to the reallocation of labor across sectors due to gender norms. In Figure A.19, 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 substantial 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 the urban sector. This result hinges on the assumption that the reallocation cost c is large enough such that a substantial share of the compliers are misallocated in rural areas prior to the technology shock.

Recent evidence supports the assumption that the reallocation cost c is large. In detail, barriers to migration and moving costs have been shown to be substantial in rural settings similar to our case study (see e.g., Nakamura et al. (2021) and Munshi and Rosenzweig (2016)). In addition, for female labor, barriers to moving across sectors and out of rural areas were even larger due to traditional norms on the gender division of labor and from family ties in rural areas. This is illustrated by the fact that the automation of hand milking also triggered changes in fertility (see Table 5), which were knitted with and necessary to facilitate women's reallocation form the rural to the urban sector.

More generally, the comparative-static result on women's long-term income gains is in line with the prediction of Acemoglu and Restrepo (2019) that automation can benefit displaced workers if employment opportunities in new occupations emerge and labor is reinstated. This process typically requires investments in education and upskilling—which in our simple framework would further suggest a non-negligible reallocation cost c.

The *third comparative-static result* 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 need to extend the model. Let this economy be a collection of rural municipalities $j \in J$. Each municipality operates with the production functions in equations (A.4) and (A.5), 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. Although all municipalities face the same price of milking machines, μ, the degree to which municipalities adopt this technology 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:

$$\frac{\partial ln\theta(j)}{\partial \mu} = \frac{-1}{\mu\beta(j)} < 0 \text{ and } \frac{\partial^2 ln\ \theta(j)}{\partial\mu\partial\beta(j)} = \frac{1}{\mu\beta(j)^2} > 0\ . \tag{A.9}$$

Equation (A.9) 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 $1 - \beta(j)$.

Importantly, we adopt this theoretical insight in our estimation strategy. We capture municipality-level heterogeneity in dairy production prior to the diffusion of milking machines by using the number of milk cows per farm in 1930 (see Section 4). As explained in the main text, this captures both formal and informal employment in the dairy sector, and hence, it is a good proxy for $1 - \beta(j)$ in the model. In detail, in our model the factor shares for female labor, milking machines, and male labor in the rural sector are, respectively, $(1-\beta)\frac{A_R L^f}{A_R L^f + M}$, $(1-\beta)\frac{M}{A_R L^f + M}$, 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 correspondence between our model's $1-\beta$ and the pre-milking machine formal and informal employment of women as milkmaids, which we proxy in our empirical analysis with our cross-sectional measure of exposure to milking machines.

The *fourth comparative-static result* is that the adoption of milking machines will affect women relatively more than men in the long term. In short, this is because milking machines will not only displace women from the rural sector, but will also increase their comparative advantage in the urban sector *relatively more* than men's. As a result, women will reallocate to the urban sector at larger rates than men which, as discussed above, will break allocative inefficiencies and raise long-term incomes for women but not for men.

Formally, let $\dfrac{\eta_i^f}{\eta_i^m}$ be a woman's comparative advantage in the urban sector relative to the comparative advantage of a man endowed with the same skill pair $\alpha_R(i)$ and $\alpha_U(i)$. In equilibrium,

$$\frac{\eta_i^f}{\eta_i^m} = P_R \beta \left(\frac{(1-\beta)^{1-\beta}}{\mu} \right)^{\frac{1}{\beta}} \ , \tag{A.10}$$

which implies that

$$\frac{\partial(\eta_i^f/\eta_i^f)}{\partial \mu} = -P_r(1-\beta)^{\frac{1-\beta}{\beta}} \left(\frac{1}{\mu} \right)^{\frac{1+\beta}{\beta}} \leq 0 \ . \tag{A.11}$$

The partial derivative in Equation A.11 shows that the adoption of milking machines (i.,e., a fall in their price from μ to μ') will increase a woman's comparative advantage in the urban sector relatively to that of a man of similar skill. Hence, this labor-saving technological change will trigger a larger displacement effect and migration out of rural areas for women than for men. This is consistent with the evidence in Section 2 that the rapid mechanization of farming led to the masculinization of agriculture in Norway, as well as with our empirical results that women's employment in agriculture and migration were relatively more affected by the adoption of milking machines than men's.

Note that, under a Cobb-Douglas production technology, machines used in task y_1 and male labor used in task y_2 are q-complements. By construction, this implies that the wage per efficiency unit of male labor in the rural sector will increase with a fall in the price of milking machines. That said, this positive effect for men is smaller than the wage gains for women who reallocate to the urban sector because $\partial W_R^f/\partial \mu$ is larger in magnitude (i.e., in absolute value) than $\partial W_R^m/\partial \mu$, as long as $\mu > P_R(1-\beta)$. This condition is satisfied when milking machines are first introduced, as the pre-adoption price of new technologies, here μ_0, tends to infinity. Importantly, under a more general CES production function that relaxes the q-complementarity between milking machines and male labor, the model can also generate a decline in male wages in the rural sector after the adoption of milking machines, triggering some male migration and reallocation to the urban sector—albeit at a smaller rate than women, as we observe in our empirical results.

Overall, this simple conceptual framework can rationalize our main results that milking machines displaced women from agriculture, pushed them to migrate out of rural areas, and that the effects were stronger than for men, contributing to reduce gender gaps. The model also justifies our exposure design based on using pre-milking machine dairy intensity. Finally, it formalizes the mechanisms described in Section 5.2 on how automation can break-up allocative inefficiencies, reinstate labor into jobs requiring higher skills in the urban sector, and generate long-term income gains.