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Abstract

Depopulation, especially, but not only, rural, has become a major concern across many countries. As one type of place-based policy, irrigation has been claimed to contribute to resettling populations and reducing outward migration, by increasing agricultural output, productivity, and competitiveness and, consequently, employment and living standards. This paper aims to elucidate on the relationship between irrigation and population for Spain, historically and currently the most irrigated country and one of the most depopulated countries in Europe. We use municipal-level data over the period 1910-2011 and exploit a staggered difference-in-differences design. Overall, we find an effect on population only for irrigation developments that started in the relatively distant past. In any case, effects are temporary or tend to level off. We also consider trade-offs. We discuss the policy implications of the findings in light of current policies, and in terms of environmental and economic costs of increasing the intensity of irrigation.

JEL Codes: J11, Q15, Q25, R11, N54, N94
Keywords: Depopulation, place-based policies, irrigation programs, long-term view, staggered DiD, Spain

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1. Introduction

There has been growing interest in depopulation in a number of advanced and developing countries, especially, but not exclusively, of rural areas (e.g., Haase et al., 2014; Li et al., 2019; Rodríguez-Soler et al., 2020). Of course, it could be argued that there is nothing, or little, to be done, as depopulation is a long-term and inevitable process. Besides, individuals' places of residence must be a matter of choice. However, depopulation has been considered a major concern. This is so because shrinkage poses a severe threat to local economies, not only limiting the opportunities for economic growth and complicating the provision of public services, but also potentially causing environmental problems (e.g., Hoggart and Paniagua, 2001; Carr and Kefalas, 2009; Rodríguez-Soler et al., 2020; Lloret et al., 2024). Spatial inequality may also be behind the rise in popular discontent and territorial-based populism (De Ruyter et al., 2021).

Within the scope of public intervention, the *equity* motivation relies on addressing spatial disparities in well-being, by means of the redistribution of jobs and income. Whereas the *efficiency* motivation is based on market failures of a spatial nature. Depopulation is often associated with long periods of decay that lead to low-income traps (Rodríguez-Pose, 2018; Copus et al., 2020). Shrinking areas are then unable to provide opportunities, because of difficulties in adapting to changes in the economy. Intense and selective outward migration and demographic imbalances may also contribute to a decrease in human capital and investment. Evidence for both equity and efficiency justifications has produced mixed results (Neumark and Simpson, 2015; Duranton and Venables, 2018; McCann, 2023).[1] But an emerging—and empirical—consensus is that the extent of the agreement varies for each type of place-based policy, and that to guide action research needs

[1] Positive findings include the effect of the Tennessee Valley Authority on industrialization (Kline and Moretti, 2014), and the effects of European Union regional policy on various economic domains (Blouri and Ehrlich, 2020). The debate has sometimes been redirected towards the targeting of people in preference to places (Glaeser and Gottlieb, 2008; cf. Barca et al., 2012).

to properly isolate specific interventions and targets (Neumark and Simpson, 2015; Grover et al., 2022). Furthermore, one characteristic of the literature on place-based policy evaluation is the lack of research on long-term effects. Thus, a much stronger case for the support of certain actions would exist if not only an immediate gain, but also a long-lasting impact were found (Moretti, 2010; see also Bartik, 2020).

The contributions of this article are twofold. First, it underlines the importance of using the past to understand the present. We aim to engage with a recent literature that has turned to the use of historical data to analyze regional and urban processes, as long-term databases can offer better insights than modern data alone (see Hanlon and Heblich, 2022; and Nagy, 2022). We use a highly spatially disaggregated database that provides a large number of observations and helps us to better identify the causal effect. Do irrigation projects help to reduce population decline?

In relation to the aforementioned, the second contribution of this article concerns the direction of causality. The effect of population growth on irrigation development has been extensively studied, mainly in developing countries—given the unquestionable importance of food security (among many others, see Simon, 1975; and De Wrachien et al., 2021). However, the opposite effect has been largely overlooked. There are assessments of irrigation projects in developing countries in relation to internal migration (e.g., Oberay, 1987).[2] But, to the best of our knowledge, only a few, recent, studies analyze the long-term causal effect of irrigation on population. Very briefly, for the Ogallala Aquifer in the US, Hornbeck and Keskin (2015) find a moderately positive one. For India, clearer effects on population are found by Asher et al. (2023) and, only for villages not towns, by Blakeslee et al. (2023) and Boudot-Reddy and Butler (2023).

[2] Different social sciences, such as History and Geography, have also looked at population settlement patterns combined with water diversion and storage schemes since the dawn of human societies. On a related note, see Allen et al. (2023).

Spain offers a fortuitous setting for the comprehension of the effect of irrigation, as depopulation is an acute issue and irrigation projects have been in place for an extensive period. As a result of an enduring process of migration and its subsequent impact on the demographic system, Spain has become one of, if not, the most depopulated country in Europe, according to a report by the Spanish central bank (Banco de España, 2021; see also Gutierrez et al., 2023). In short, the Spanish population tends to live far more densely concentrated in the territory than that of other European countries. In this regard, four Spanish inland (NUTS-2) regions are among the twenty least populated European regions (Eurostat, 2023). Viewed from another angle, 72.2 percent of Spanish municipalities have less than 2,000 inhabitants.[3]

In light of the situation, it is more than likely not by chance that Spain could very well be the country with the highest degree of commitment to reducing depopulation (Dax and Copus, 2022). At several institutional levels, different types of policies have been implemented or proposed for the development of shrinking, particularly rural, areas (Alloza et al., 2021; Goerlich et al., 2021; Pinilla, 2023). Intended to support the technological modernization of farms, one of these policies is irrigation. In fact, the irrigation of land is far more than just another policy in Spain. As a Mediterranean country, Spain has traditionally been characterized by severe environmental constraints on agricultural performance. Scarce, irregular rainfall coupled with seasonal drought is a key factor in explaining low historical output and productivity records. Irrigation as a systematic public intervention in Spain started at the beginning of the twentieth century. Today, Spain, together with Italy, is the EU country with the largest irrigated area, volume of irrigation water, and water consumption per unit of irrigated area (Rossi, 2019).

Irrigation has historically been considered a response to depopulation, by way of improving living conditions; augmenting employment requirements as a result of increasing

[3] Year 2020. Data belong to the population dataset introduced in Section 3.1.

cropland; and fostering agricultural competitiveness, sometimes by changing the crop mix (Silvestre and Clar, 2010). Within political and academic spheres, with some variations, this argument has been repeated right up until the present time. However, there does not seem to be a provision for comprehensive evaluation.

Overall, we find a positive and significant effect on population only for irrigation developments that started in the relatively distant past. At the same time, we find stronger effects in the smallest municipalities and municipalities farther away from cities, the latter less influenced by urban agglomeration externalities. In any case, effects are temporary or tend to level off. The results also show that one way of overcoming diminishing returns of irrigation over time is to greatly increase its intensity, by which we mean the extent of the irrigated area. However, there are trade-offs. As a whole, our findings would tend to temper a recent public zeal for extending irrigation to a wide range of areas, especially when carried out without due regard to the environmental and economic costs of increasing the intensity of irrigation.

The rest of the article is organized as follows. Section 2 describes the historical background, with respect to depopulation and irrigation. Section 3 presents the data and the empirical strategy. Section 4 provides analyses of the effect of irrigation on population, and Section 5 adds several robustness checks. Section 6 tests the plausibility of our assumptions and guarantee valid inference. Section 7 discusses the policy implications of our results in light of current policies and sets out the conclusions.

2. Historical background: depopulation and irrigation in Spain

2.1. Depopulation

Predominantly rural areas in Spain, as in other parts of Europe, played the role of a demographic reserve throughout the industrialization processes of the last two centuries (Collantes and Pinilla, 2019). Depopulation before the 1980s was primarily driven by migration. Outward

(mainly international) migration goes back to the mid-nineteenth century. Migration intensified over the following century. First, during its first third, when the pull of domestic industrial and some urban areas tended to increase. Then, and principally, between the 1950s and the early 1970s, which represents the high point of out-migration, both internal and international, in connection with the modernization process. Rural outward migration continued afterwards, but with less intensity (Banco de España, 2021; Pinilla, 2023). While cities' populations decrease or increase has varied considerably since the 1950s—relative to their initial size (Goerlich and Mollá, 2021; Fernández and Hartt, 2022).

Depopulation over the last few decades has basically been determined by a negative natural growth, that is to say, deaths outnumbering births. By way of a feedback mechanism, depopulation has continued as a consequence of the impact of previous migration on total fertility and ageing. With one exception, the 2000-2008 period, due to the arrival of international immigrants (Collantes et al., 2014). The endurance of recent inflows into depopulated areas during the COVID-19 pandemic is still an open question, although the evidence also points to a temporary effect (González-Leonardo et al., 2023).

2.2. Irrigation

The construction of large irrigation projects in Spain was held back until the twentieth century, due to technological difficulties, a lack of sufficient private capital, and the minor role played by the state in the largely unregulated economy. A call for state intervention gained traction at the turn of the century, when the competition effects of the first globalization era put pressure on Spanish agriculture. Since then, without overlooking the role played by the private sector, the initiative has mostly been from public institutions (e.g., Gil-Olcina, 2001; Gómez-Limón, 2008; Albiac et al., 2023). One recent example being the (EU-environmental-principles-based) subsidies

granted for the modernization of irrigation infrastructure and technology (Lopez-Gunn et al., 2012; Berbel et al., 2019).

A number of plans began to take shape during the first third of the century. Works included dams and main and secondary canals (Pinilla, 2006). However, it was not until the middle of the century when hydraulic efforts started to become prevalent (López Ontiveros, 2003; Cazcarro et al., 2015). The Franco dictatorship, which resulted from the Spanish Civil War (1936-1939), became concerned about water policy. The main elements of the national infrastructure, comprising water regulation schemes (basically dams) and irrigation projects, were built between the 1950s and the early 1970s (which is in line with other countries; see Angelakis et al., 2020). The territorial reorganization of the state after the end of the dictatorship in 1975 implied, at least to a certain extent, the regional decentralization of irrigation policies, which also had to be adapted to European Union principles by 1986 (Paniagua and Rodríguez, 1989). Irrigation developments since then have continued on a large scale, most notably from 1990 to 2012 (Berbel and Espinosa-Tasón, 2020; Serrano et al., 2024).

2.3. Irrigation as a response to population decline

At least since the mid-nineteenth century, irrigation has been seen as a solution to economic and social problems.[4] These arguments gathered momentum with the turn of the century's Regenerationist movement, whose ideas on population retention permeated the initial public intervention during the first third of the twentieth century (e.g., Fernández-Clemente, 1990; Gómez-Mendoza, 1992; Driever, 1998; Swyngedouw, 1999). One distinguished member stated that: "The development of water sources, and consequently of irrigation, should produce the

[4] An early example is Caballero (1864).

following immediate results: (...) to contain emigration, and to encourage those who have already emigrated to return to their homeland" (Costa, 1911: 6-7).[5]

Between 1939 and the early 1950s, in the context of the inward-looking (and unsuccessful) economic development model adopted during the first part of the Franco dictatorship, the idealization of rural life informed (Fascist-inspired) legislation in several realms (Paniagua, 1992; Gómez-Benito, 1995). As stated by the Director-General for Colonization: "Water is an indispensable factor to raise the level of agriculture, to feed the population, to make the country independent from the exterior and also to achieve full employment of its means of production (…)" (Torrejón, 1953: 62-63).

Fostered by economic and institutional reforms since the early 1950s, Spain began to experience profound economic growth, accompanied by industrialization and urbanization. The objectives of irrigation policies, although they had to adapt to the new circumstances, echoed previous efforts to, at the very least, reduce outward migration, which was now on the rise and considered inevitable (Paniagua, 2016; Camarero, 2020).[6] The state also incentivized the irrigation of newly colonized lands—an ongoing issue since the eighteenth century (Monclús and Oyón, 1988)—with financial and technical assistance. According to one estimate, 44 percent of land-settlement programs explicitly referred to the potential demographic impact of irrigation (Paniagua, 1992: 97; see also Albertus, 2023).

After the dictatorship was over (in 1975), at different and sometimes new institutional levels, irrigation still had a role to play in promoting balanced territorial development and sustaining populations (Paniagua and Rodríguez, 1989). Enthusiasm for this idea has grown in recent decades. The National Irrigation Plan for the 2002-2008 period referred to the creation of

[5] See also Mallada (1890: 11-12).

[6] As an example, see the lecture addressed to agricultural engineers by the Minister of Agriculture, Rafael Cavestany y de Anduaga (1955).

employment and fixation of population (Ministerio de Agricultura, Pesca y Alimentación, 2001: 5-6).[7] More recently, the Ministry of Agriculture, Fisheries and Food has made similar proclamations (Ministerio de Agricultura, Pesca y Alimentación, 2023). Established in 2020, the Ministry for the Ecological Transition and the Demographic Challenge in its *Recovery plan. 130 measures to meet the demographic challenge*, also invokes irrigation as a "fundamental tool against depopulation", given that, for example, it "has a great capacity to generate direct and indirect employment" (Ministerio para la Transición Ecológica y el Reto Demográfico, 2021: 37-38).

Moreover, the National Irrigation Board was created in 2022 to assist the progress of irrigation policy, encompassing five ministries, regional governments, river basin authorities, irrigation and farmers' associations, and scientific and environmental organizations. The advisory board considers irrigation to be "a fundamental axis within rural development policies, both for its contribution to the fight against depopulation and to the generation of employment and added value in rural areas" (Gobierno de España, 2022: 139046). In essence the same statements can be found in the programs initiated by several regional (Autonomous Communities) governments.[8] These concepts are supported by the Spanish Federation of Irrigation Communities (FENACORE), which holds the maintenance or even growth of population as a positive externality generated by irrigation (del Campo García, 2017; Melián and Melgarejo, 2020).[9]

In spite of the interest in the irrigation-population nexus over time, no evaluation of the causal effect of the former on the latter has been conducted to date. The National Irrigation Plan for the 2002-2008 period included an analysis of population trends for the 1970-1999 period

[7] See also the 2004 Water Plan (Ministerio de Medio Ambiente, 2004: 41), and the Irrigation Shock Plan for the 2006-2007 period (Gobierno de España, 2006).

[8] See, for example, Gobierno de Aragón (2017) and Gobierno de Castilla-La Mancha (2021).

[9] Water legislation confers a prominent role on water management to irrigation communities (Albiac et al., 2023).

(Ministerio de Agricultura, Pesca y Alimentación, 2001: 52). However, it mostly consisted of summary statistics of population data for irrigated areas compared to the country as a whole. An even more basic comparison was established by the Ministry of Environment (Ministerio de Medio Ambiente, 2004: 81). Similarly, the existing literature compares different irrigated and non-irrigated areas in Spain, for relatively short periods, to make the claim that there is a positive effect of irrigation on population (Sancho Azak, 2002; Gómez-Limón et al., 2007; Gutiérrez-Martín and Montilla-López, 2018; Berbel and Espinosa-Tasón, 2020). Although it has been argued more cautiously for more recent times (Gómez-Limón, 2008: 99). Clar and Ayuda (2023) use cross-section regressions at the provincial level (including 50 or 100 observations) to find a strong positive effect of irrigation on inward migration to rural areas for 1960-1980. The only study referring to a longer period (1900-2011) results in mixed evidence (Silvestre and Clar, 2010).

3. Data and empirical strategy

3.1. A long-term highly spatially disaggregated database

Our database consists of information at the eleven census dates between 1910 and 2011. We omitted the year 1900 due to potential flaws in some irrigation values.[10] Complete and consistent data are not yet available for the most recent date of 2021. The data are disaggregated at a high spatial level: i.e. the 8,122 Spanish municipalities. A few municipalities were excluded in different specifications due to the outcome or explanatory variables which are in some cases missing. These municipalities are of a very small size and do not show a discernible spatial pattern.

The outcome of interest is that of total population. A fundamental feature of long-term population datasets is the homogenization of spatial units, since administrative boundaries may

[10] Siebert et al. (2015), introduced below, as the main source used, provided unreasonably high or low (sometimes, zero) values for some spatial units.

have changed over time as a result of (in the case of Spain, predominantly) annexations and (often more recently) segregations of usually neighboring municipalities. We use municipality data homogenized by Goerlich et al. (2015), based on GIS tools and the 2011 census as reference. A pertinent question would be if the focus should be rural, instead of total, population. However, in a number of big municipalities, often surpassing the standard historical urban threshold in Spain of 10,000 inhabitants (Tafunell, 2005), a significant part of the population has been employed in the agricultural sector (López-Ontiveros, 1994; Reher, 1994). In these "agro-towns", usually located in the south of the country, irrigation has been widespread indeed (Ayuda et al., 2022). According to our dataset, in 2011, 37 percent of the total irrigated area corresponds to urban (>10,000 inhabitants) municipalities.

In the empirical analysis, population was transformed using the natural logarithm, as often appeared in research. Models using the log of population can satisfy the normality assumption closely (Wooldridge, 2020: 187). In our case, as shown in Figure A.1 (in the Appendix), high skewedness is, essentially, eliminated. The semi-log model also reduces the impact of outliers, i.e., very big cities. It also has an appealing interpretation, as it relates to the percentage change or growth rate. Such transformation is feasible with our empirical strategy (Roth and Sant'Anna, 2023: 745).

There are two potential limitations to our outcome variable. Firstly, rather than total population, population density cannot be estimated. The spatial homogenization of municipalities uses the area provided by the 2011 census as reference and, therefore, leads to a single value for the entire period (see Goerlich et al., 2015). Within a difference-in-differences framework, changes in the log of total population and changes in the log of population density (taking that constant value of area as denominator for population) yield identical results. In a robustness check, we got as close as possible to the optimal solution adding the area of the municipality as a control variable. Secondly, population data at this level of disaggregation do not enable us to distinguish between

migration and natural growth. Still, the big picture of a two-phased process in which migration, first, and natural growth, second, have been the primary determinants in the behavior of the population is clear, as argued in Section 2.1.

The treatment variable starts from the area equipped for irrigation (AEI) relative to total cultivated land.[11] Long-term, municipality-level, statistical information of the afore mentioned variable does not exist for Spain. However, we can estimate the extent of irrigation (the numerator) between 1910 and 2001 at such a degree of spatial disaggregation thanks to the data set out by the Historical Irrigation Dataset (HID) (Siebert et al., 2015). HID is based on a combination of international, national and sub-national statistics (mostly provided by the Spanish Statistical Office—INE) with geographic data delineating the administrative boundaries; the data are then downscaled following a series of steps to fill in historical gaps. For the most recent date of 2011, the series is completed on the basis of data set out by the Global Irrigated Area (GIA) database (Meier et al., 2018), which carries on from HID and the Spanish Statistical Office. Total cultivated land (the denominator) is estimated from the History Database of the Global Environment (HYDE) (Klein Goldewijk et al., 2017), again based on a combination of statistics of a different nature and allocation methods that derive land use maps for the past.

A feature of the chosen estimator, as introduced in the next section, is that the treatment needs to be a binary variable. This is a strong premise in our setting, since the effect on population may, presumably, vary as a function of the extent of irrigated hectares. However, by establishing a threshold, we are able to convert a continuous *in nature* variable into a binary variable. In our main specifications a municipality is considered to be treated if more than 20 percent of its total

[11] The area equipped for irrigation (AEI), which includes infrastructure to provide water for crops, departs from the narrower definition of the (actual) irrigated surface (IS). Table A.1 reports a comparison of both estimates at the national level.

cultivated land is irrigated. This is not an arbitrary rate, as it is established in accordance with the criteria laid out in the elaborate National Irrigation Plan for the 2002-2008 period (Ministerio de Agricultura, Pesca y Alimentación, 2001: 52). Additionally, we also gradually increased the threshold by increments of 10 percent until we reached 90 percent, which provides a much more thorough account and allows us to evaluate the sensitivity of the findings to irrigation intensity (No municipalities are 100 percent irrigated).

Figure 1 contrasts the evolution of total population and the area equipped for irrigation in absolute terms. Irrigation underwent sharp increases during two (census dates) periods, 1950-1970 and 1990-2011 (as explained in Section 2.2). While the evolution of population is smoother. Figures A.2 and A.3 illustrate in more detail the outcome and treatment variables at selected dates.

[Insert Figure 1 around here]

Covariates allow for determinants of population behavior other than irrigation. A range of variables have been constructed or collected, following a strategy akin to that of Hornbeck and Keskin (2014, 2015), Asher et al. (2023), Blakeslee et al. (2023) and Boudot-Reddy and Butler (2023). The empirical approach adopted requires the inclusion of pre-treatment, but not post-treatment covariates, as these can be affected by the treatment (Callaway and Sant'Anna, 2021).[12]

Climatic and geographic variables first refer to the Standardized Precipitation Evapotranspiration Index (SPEI). The SPEI is a multi-scalar drought index that represents a climatic water balance (Vicente-Serrano et al., 2010; Beguería et al., 2014). It uses the monthly (or weekly) difference between precipitation and evapotranspiration and, among other components,

[12] In practice, the econometric package sets the values of time-variant covariates to be equal to their values in different "base periods", for both pre- and post-treatment periods.

incorporates temperature.[13] Two further indicators of productive activity, especially in historical contexts, are ruggedness, measured as the standard deviation of altitude, and distance to nearest (of any size) river.[14]

Economic and political variables include employed population by sector. Classification criteria are taken from the 1991 Spanish census and the European Nomenclature of Economic Activities (NACE).[15] The resulting seven population share categories constructed are as follows: agrarian; manufacturing; mining and quarrying; energy supply; construction; trade, accommodation and food services; and other services activities. By reason of data availability and consistency, at such level of disaggregation, the construction of this indicator is only possible from population censuses since 1950. Therefore, our specifications will refer to two periods, 1950-2011 or, in a robustness check, 1910-2011, the former being not only the period for which we are able to control for structural change, but also that of more intense irrigation and change in population. An additional variable, which is applicable to the longer, 1910-2011, period, reflects the rural/urban character of municipalities. We apply an accepted classification in rural studies, in agreement with

[13] The replacement of the SPEI with measures of temperature and rainfall led to very similar results. Data for the SPEI are available at https://spei.csic.es/database.html.

[14] Ruggedness (and distance measurements introduced below) have been kindly provided by Francisco J. Beltrán-Tapia. Distance to nearest river was estimated applying GIS methods to the municipality shapefile information available at https://www.miteco.gob.es/es/cartografia-y-sig/ide/descargas/agua/red-hidrografica.html.

[15] Original data from population censuses are available at https://www.ine.es/. Data for the census carried out in 1981 were completed with information provided by the Spanish Statistical Office. NACE information is available at https://nacev2.com/en. From this point onwards, the estimation of population share categories for some (especially, small) municipalities involved downscaling methods based on further (e.g., business) data and interpolation.

the number of inhabitants: rural<2,000; intermediate 2,000-10,000; urban>10,000 (Ministerio de Medio Ambiente y Medio Rural y Marino, 2009: 1; see also Instituto Nacional de Estadística, 1954, p. x).

Two final economic and political indicators are distances. Distance to coast is employed to capture the long-term tendency of the Spanish population to concentrate (highly) in coastal areas—with some notable exceptions, such as Madrid, the capital city—following economic development (Ayuda et al., 2010; Beltrán et al., 2018; Goerlich and Mollá, 2021). Distance to the provincial capital is used as a proxy for political influence, at least for a significant part of the period under study (González-Val and Silvestre, 2023).

Table 1 provides summary statistics. Correlations between covariates, unreported, are fairly low, with the exception of those between the SPEI and the share of agrarian population (0.61), the shares of agrarian population and trade, accommodation and food services population (-0.71), and the shares of agrarian population and other services activities population (-0.75). Stepwise regressions led to, fundamentally, the same results.

[Insert Table 1 around here]

3.2. Empirical strategy: staggered difference-in differences

With observational data, the key issue is to draw more solid inference about the causal effect of irrigation on municipal population. Given the nature of our setting, in which irrigation has been introduced in municipalities at different times during the 1910-2011 period, an appropriate option is a staggered difference-in-differences approach. The traditional two-way fixed effects (TWFE) model has often been shown not to provide valid estimates of the causal estimand of interest (e.g., Baker et al., 2022). This is particularly so when not only heterogeneity in treatment effects across time ("time since treatment") is present, but also heterogeneity in treatment effects across units (cohorts) (Goodman-Bacon, 2021; Sun and Abraham, 2021; de Chaisemartin and

D'Haultfoeuille, 2023). Several alternative estimators have been proposed (as reviewed in Callaway and Sant'Anna, 2021; Baker et al., 2022; de Chaisemartin and D'Haultfoeuille, 2023; and Roth et al., 2023). We chose the estimator proposed by Callaway and Sant'Anna (2021). As compared to "perhaps the closest" by de Chaisemartin and D'Haultfoeuille (2023) and Sun and Abraham (2021), and in relation to our setting, Callaway and Sant'Anna's (2021: 202) methodology seems to give particular consideration to treatment effect *dynamics*, rather than to an instantaneous effect; and permits a more comprehensive approach to a conditional on covariates design. The adopted methodology can be complemented with the sensitivity analysis proposed by Rambachan and Roth (2023).

The estimation of the average treatment effect for the treated subpopulation (ATT) entails making three important identification assumptions. Firstly, the parallel trends assumption holds if the average outcomes for the treated and comparison groups would have followed parallel paths over time, had the treated group not received treatment. Parallel trends may hold only if conditional on observed covariates, measured prior to the treatment (Roth et al., 2023). Secondly, the no anticipation assumption means that treatment has no impact before its implementation. In other words, the treatment is not known a priori, or units cannot choose treatment status. This is likely to be unreasonable in our case, as some municipalities at some point may have known if they were part of irrigation plans or have had decision-making power, at least to a certain extent. Fortunately, the estimation method allows for anticipation behavior. Thirdly, the difference-in-differences framework implicitly encodes stable unit treatment value assumption (SUTVA): a unit's outcome does not depend on the treatment status of the other units, which would rule out spillover effects (Roth et al., 2023). In any case, we will consider two potential linkages.

There are four types of units, i.e., municipalities, depending on their treatment status. *Always-treated* municipalities have been irrigated since the beginning of our period, these are consequently not included. *Never-treated* municipalities have never been irrigated. In our main

specifications, never-treated municipalities are the preferred comparison group to the irrigated municipalities, because they are sufficiently numerous, and the economic environment has changed considerably over time (Callaway and Sant'Anna, 2021). *Not-yet-treated* municipalities are those that started to be irrigated at different times. In additional specifications, they also act as comparison group. In this respect, comparisons between units that receive treatment at different times are admissible as long as those between late treated units to early treated units are excluded (Goodman-Bacon, 2021; Baker et al., 2022). In a fourth group of *on/off-treated* municipalities, the treatment can be turned off. Callaway and Sant'Anna's (2021) estimator considers treatment to be an absorbing state, or irreversible. Therefore, this group needs to be removed. The group of on/off municipalities may reach percentages slightly below ten percent of the total of municipalities in different subsamples (when using the irrigation threshold of 20 percent of total cultivated land). However, they only account for around two percent of the total irrigated area and represent around five percent of the population. They tend to be very small municipalities in which irrigated agriculture is ultimately abandoned. At selected irrigation thresholds, Table A.2 reports the distribution of municipalities according to their irrigation status.

4. Main results, 1950-2011

As discussed in Section 3.1, our main specifications refer to the 1950-2011 period, with the 1910-2011 period considered in a robustness check. Unless stated otherwise, the comparison group is never-treated municipalities and no anticipation effects are allowed. The estimand is based on double-robust methods (Sant'Anna and Zhao, 2020). Pre-treatment effects are obtained using a universal base period, as proposed by Roth (2024). Standard errors are clustered at the panel level.

In order to feature different aspects of treatment heterogeneity, we report results using two, complementary, partial aggregations of the group-time average effects (Callaway and

Sant'Anna, 2021). *Group-specific* effects refer to the estimation of the ATT for each irrigation-status group, across all periods. How does the effect vary across groups of municipalities according to the (census) year in which they started to be irrigated? *Event-study* effects refer to the estimation of the ATT for each period relative to the period of first treatment, across all irrigation-status groups. In other words, the effect *n* years after the adoption of irrigation—or the effect by length of exposure to irrigation.

4.1. Irrigation threshold: 20 percent of total cultivated land

First of all, Figure 2 graphically shows the effect of irrigation on population assuming that the parallel trends assumption would hold unconditionally, in Panel A, and conditional on our set of climatic and geographic, and economic and political variables, in Panel B. Figures include pre-treatment estimates (on the left side). They are used to "pre-test" the parallel trends assumption, that is to say, to check if the parallel trends assumption holds in pre-treatment periods. Pre-treatment estimates are also used to pre-test effects in post-treatment periods (reported on the right side). The shaded area represents the 95% confidence interval of the event-study estimated coefficients.

In Panel A, unreported significance indicates that all but one of effects for pre-treatment periods are significant at the usual levels. Whereas, in Panel B all pre-treatment effects are not significant. Thus, to enhance the credibility of the staggered DiD framework applied to our setting, we need to assume that parallel trends hold only if conditional on observed covariates (Callaway and Sant'Anna, 2021). Hereafter, we will present results assuming parallel trends conditional on characteristics of municipalities, as in Panel B, based on the understanding that, historically, they

have contributed to the settlement and evolution of populations.[16] Then, the pattern of estimated coefficients suggests an effect of irrigation on population in post-treatment periods.

[Insert Figure 2 around here]

Table 2, in the first two columns and for comparative purposes, reports the estimated coefficient of a post-treatment dummy variable from a two-way fixed effects specification, and the weighted average (by group size) of all group-time average treatment effects, as obtained from Callaway and Sant'Anna's (2021) estimator. Both coefficients are positive, but the ATT is not significant at the usual levels.

In addition to the aggregation of all group-time combinations, partial aggregations may be of more interest. In the third column, average treatment effects by timing of irrigation, or group-specific effects, indicate that irrigation has a positive and significant effect, at the 5% level, on population only for the group of municipalities that started to be irrigated in 1970 (G1970). The effect is negative for the most recently irrigated group (G2011). The fourth column displays the average treatment effects by length of exposure to irrigation, or event-study effects, which are those represented in Figure 4, Panel B. Before all else, it must be said that the pre-treatment average is not significant. Thereafter, the dynamic effect is positive and significant only between 10 and 30 years after treatment. Moving from no irrigation to irrigation of more than 20 percent of cultivated land increases population by 3.2-5.8 percent, *as per* [100[exp(β)-1]]. The effect then seems to vanish, as also shown by the bending of the curve in Figure 4, Panel B.

[16] Pre-trend tests would support this decision. In Panel B, the null hypothesis that all pre-treatment is equal to zero is not rejected at the 0.1% significance level. Whereas in Panel A the null hypothesis is rejected. Even so, the interpretation of these tests should be carried out with caution, hence the implementation, in section 6, of the method proposed by Rambachan and Roth (2023).

[Insert Table 2 around here]

To confirm our findings so far, we separately performed three additional analyses.[17] Firstly, we replaced the never-treated municipalities with the not-yet-treated municipalities as the comparison group, to obtain largely similar results. Secondly, we allowed for one (census) date of treatment anticipation behavior, and results were again very similar in sign and magnitude.[18] Finally, the sample was "balanced" or restricted to groups of municipalities that have been exposed to the treatment for a fixed number of time periods. This is to avoid the potential bias resulting from the combination of groups with different durations of exposure. We concentrated on the period around which the most important changes in irrigation occurred, corresponding to the three census years of 1960, 1970 and 1981. Therefore, we removed G1991, G2001 and G2011 from the sample. The pattern of significant group-specific and event-study coefficients was practically the same.

4.2. Increasing the irrigation threshold

A possible concern with our results is the 20 percent irrigation threshold, although set by the public administration, to be a very narrow criterion. To offset this possibility, we gradually increased the limit by increments of 10 percent until we reached 90 percent. Results in Table 3 are reasonable. Table 3, Panel A reaffirms the positive and significant effect for the group of municipalities that started to be irrigated in 1970. The higher the irrigated land—as percentage of total cultivated land—is, the higher the magnitude of the positive and significant effect tend to be.

[17] All unreported results mentioned in this and following sections are available from the authors upon request.

[18] On the reference period adjusted one date backward, we follow Callaway and Sant'Anna (2021: Supplementary Appendix C).

For example, the effect in population (for G1970) increases from 6.5 percent to 23 percent when the irrigation threshold is pushed from 20 percent to 90 percent. A similar, increasing, pattern is found for G1960. As for event-study effects, Table 3, Panel B, shows that the increase in irrigated land contributes to the overcoming of diminishing returns of treatment over time, as previously suggested in Figure 2 (Panel B) and Table 2. Treatment effects tend to grow in relation to length of exposure. At the bottom-right corner of the table (Tp50 and irrigation threshold= 90 percent), the effect reaches a maximum of a 51.7 percent increase in population. We will discuss such large effects in Section 7.

[Insert Table 3 around here]

5. Robustness checks

We performed a series of robustness checks in relation to characteristics of units of analysis, sub-samples, spillovers, and stability across space and time. All specifications are estimated using the 20 percent irrigation threshold criterion.

5.1. Area and type of municipality

Table A.3, Panel A, reports group-specific effects. The first two columns compare the results of the baseline specification, as first reported in Table 2, with those of adding area of municipality as covariate. The effect of irrigation on population for G1970 is again positive and significant, and greater. For two more groups, G1960 and G2001, there is also a positive and significant effect. However, the level of significance, 5%, is weaker in relative terms. Perhaps more informative is the result of dividing the sample into three sub-samples according to the rural/urban nature of municipalities.[19] The positive and significant effect of irrigation on population in the

[19] Municipalities are assigned to each sub-sample depending on their size in 1950.

smallest, rural, municipalities, that is, those below 2,000 inhabitants, becomes much stronger for G1970 (the increase in population increasing from 7.2 percent to 16.4 percent), and the effect for the previous period (G1960) turns out to be an important one too (Increase in population= 13.1 percent). All of which is in contrast to intermediate and urban municipalities.[20]

Table A.3, Panel B, reports event-study effects. When area of municipality is added as covariate, as in Panel A, two more effects are positive and weakly significant (Tp0 and Tp40). Whereas a consistent pattern of strong, positive and significant effects is found when focusing on rural municipalities, as compared to intermediate and urban ones. However, a further, noteworthy, result would be that the effect in rural municipalities tends to level off 30 years after treatment, in accordance with results for the entire sample (Figure 2, panel B, and Table 2). Supplementary, unreported, specifications combined the addition of area and the focus on rural, intermediate and urban sub-samples, but the results for both group-specific and event-study effects varied slightly.

One final issue deserves attention here. As mentioned briefly in Section 2.3, one characteristic of some municipalities was that they were included in colonization schemes during the Franco dictatorship, aimed at stabilizing or redirecting rural populations. The government claimed to help the landless by providing them with irrigated land. We re-estimated our main specification in Table 2 with the addition of a colonization dummy variable as covariate, set to 1 for 176 municipalities hosting colonization towns from the closest census date onwards.[21] (Unreported) Results were virtually the same. As also suggested by the historical literature, land-settlement programs do not seem to make a difference in demographic terms.[22] The results also

[20] An inspection of the data reveals that the strong positive effect for G1991 and G2001 in the last column may be associated with the expansion of irrigation in agro-towns in the south of the country. We will return to this issue in Section 5.3.

[21] We drew the list of towns from Arcas (2022) and checked it against Villanueva and Leal (1991).

[22] Silvestre and Clar (2010: 318) review a number of studies at national and regional levels.

coincide with those from Albertus (2023), who follows a very similar procedure of assigning colonization towns to municipalities.

5.2. Spillovers

Although in principle the SUTVA assumption in DiD designs would rule out spillover effects, in a setting like ours they may still be important. We acknowledge two potential linkages. On the one hand, irrigation of a municipality could affect population in neighboring municipalities. This spillover would be negative if labor moves to irrigated lands or as a response to the construction of the hydraulic infrastructure. But the spillover could be positive if irrigation also benefits nearby areas. For example, promoting interrelated activities such as agro-industry, an issue to which we will return in Section 7. We therefore propose an alternative definition of the treatment status of a municipality based, not only, on the status of the municipality itself, but also on those of adjacent municipalities. The complete list of occurrences and its meaning is given in Table A.4, Panel A. In short, in relation to the outcome variable, we control for irrigation, or lack thereof, in the adjacent municipalities. In Table A.4, Panel B, overall, changes between the baseline specification (as in Table 2) and an "Adjacent" specification are not clearly telling. Although the pattern of significant group-specific effects points to some population growth via the impact of irrigation in adjacent municipalities for two further groups of municipalities, G1981 and G1991.

On the other hand, proximity to a city may also have changed prospects for farmers and agricultural laborers, especially during periods of vigorous economic growth and urbanization. Here, the spillover could be negative if closer and rising, non-agricultural, economic prosperity fosters out-migration to cities. We also expect this spillover to decay with distance, as the pull of cities decrease and migration costs increase (Paluzie et al., 2009). We separate the samples into

municipalities within or outside 25 km distance of an urban municipality (>10,000 inhabitants).[23] In Table A.4, Panel C, as expected, there is no positive and significant effect of irrigation on municipalities nearer to cities (Column "<25 km."). Furthermore, the results in Table A.4, Panel C, are in line with those obtained when distinguishing between rural and other types of municipalities (Table A.3, Panels A and B). In particular, the pattern of significance of both group-specific and event-study effects for municipalities farther away from cities (Column ">25 km.") is similar to that of rural municipalities (<2,000 inhabitants).

5.3. River basins

Our data cover the entire Spanish territory. We can test the stability of the relationship between irrigation and population by zeroing in on smaller geographical areas. A suitable starting point is the river authorities, the establishment of which began in 1926 (and were known as *Confederaciones Sindicales Hidrográficas*). The creation and interpretation of the responsibilities of river authorities was the cause of debate. Nevertheless, a fundamental criterion was the "unity of the river basin" in relation to the shared physical, geographical and economic characteristics of the areas served by a main river and its tributaries (del Moral and Hernández-Mora, 2016). For this reason, we are confident in the use of the river basin as a spatial unit for the entire period under study. We focus on the six main river basins, according to the extent of the irrigated area and the number of observations available. Together, they represent 77.7 percent of the surface area of all the river basins of the Spanish Iberian Peninsula.

Table A.5 first suggest that variation across space may be important, especially when looking at dynamic effects, in Panel B. Nevertheless, more distinguishable trends seem to emerge when concentrating on the timing of irrigation, in Panel A. As in previous tables, positive and

[23] We experimented with a cutoff point of 50 km. to find a greater impact of distance to city.

significant group-specific effects tend to agglomerate in the municipalities where irrigation was introduced both in 1960 and, particularly, 1970; whereas negative and significant effects do so when irrigation was implemented in 2011, as well as in other recently irrigated groups. In the south and south-east of the country, positive and significant effects for municipalities in the Guadiana and Jucar basins where irrigation began in 2001 are remarkable, and may result from intense irrigation developments (Albiac et al., 2021). However, this effect does not seem to persist. Furthermore, irrigated areas have also been markedly extended in recent times in the Guadalquivir basin (Tocados-Franco et al., 2023), for which we do not find any latter positive and significant effect.

5.4. An extended period: 1910-2011

Our final robustness check extends the time period to ascertain if the pattern of association between irrigation and population is also stable across time. A longer period covers early irrigation programs. These were less widespread than those carried out since the middle of the century, but implemented in an era in which the agricultural sector was by far the most predominant.[24] It could have been the case, then, that the first interventions occurred at the right time, and had a longer lasting effect, which cannot be seen when focusing on the 1950-2011 period. Notwithstanding, the impossibility of constructing and adding our control variable on employed population by sector is a limitation to be borne in mind when interpreting our evidence.

Figure A.4, Panel B, graphically shows the effect of irrigation on population assuming conditional parallel trends. According to unreported significance levels, pre-treatment effects are

[24] Sector shares (percentage of total employment) for Spain as a whole in 1910, 1950 and 2011 are: agriculture, forestry and fishing: 58.1, 47.7 and 4.1; manufacturing, extractive industries, and utilities 13.5, 17.4 and 13.6; construction: 4.4, 7.3 and 7.6; and service activities: 24.0, 27.7 and 74.8 (Prados de la Escosura, 2017: 318-320).

significant between 90 and 60 years before treatment, but not significant thereafter.[25] Keeping the above in mind, the pattern of post-treatment estimated coefficients points to a self-sustaining effect. In Table A.6, assuming conditional parallel trends, a positive effect, although relatively weak, is found for the group of municipalities where irrigation began in 1930, which is the closest census date prior to the Spanish Civil War. Event-study effects confirm a positive, significant and increasing impact, from 60 to 80 years after treatment. Admittedly, how reliable the size of the effect on population is (for Tp80, 100[exp(0.233)-1]= 26.2 percentage growth rate) is difficult to assure, given the lack of information to take into consideration long-term structural change.

6. Sensitivity analysis

Conditioning on pre-existing covariates adds plausibility to the parallel trends assumption, a crucial aspect of DiD approaches. However, there may remain unobserved time-varying confounding factors, which would cause outcomes for the treated and comparison groups not to move in parallel prior to treatment (Roth et al., 2023). Rambachan and Roth (2023) propose a sensitivity analysis that, instead of requiring that parallel trends holds exactly, it imposes restrictions on how different the post-treatment violations of parallel trends can be from the pre-treatment differences in trends. The approach builds on context-specific knowledge about possible confounding factors. We consider "smoothness restrictions" as the most suitable option put forward by the authors of the method for a long-term setting like ours, replete with substantial economic and social changes of different sorts. Thus, confounding is associated with secular trends that are assumed to evolve smoothly over time. And post-treatment violations of the parallel trends

[25] The results are again worse if we assume unconditional parallel trends (in Panel A), as all but one of effects for pre-treatment periods are significant.

should not deviate much for a linear extrapolation of the pre-treatment trend. The analysis bounds the extent of the change over time of the slope of the pre-tend.

Based on the significant event-study effects reported in Table 2, Figure A.5 depicts the sensitivity analysis for the effect of irrigation on population 10, 20 and 30 years after treatment. On the far left, the "Original" confidence interval refers to the specification in Table 2. For the rest of confidence intervals, M=0 allows only for linear violations of the parallel trends; and higher values of M allow larger deviations from linearity. The "breakdown values", or the highest deviation for which the effects are significant, are 0.01 (for Tp10), 0.03 (for Tp20) and 0.01 (for Tp30). In other words, effects remain significant within deviations from non-linearity of 0.01-0.03 percentage points. This makes the effect of irrigation particularly robust 20 years after its adoption. Unreported analyses showed that breakdown values were larger, between 0.04 and 0.08 percentage points, when focusing on rural municipalities (as in Table A.3).

7. Discussion and conclusion

The demographic decline of rural and urban areas has gained much attention in recent times in various countries. A number of place-based policies have been recommended and financed. One of these policies is the irrigation of lands, to boost productivity and adaptation to changes in the economy, and therefore improve the standard of living and maintain, or even increase, population. We concentrate on Spain, an apt setting for the comprehension of the relationship between irrigation and population. Spain is one of the European countries in which the phenomenon of the shrinking of regions is most pronounced. While irrigation has been widely implemented, both historically and currently. However, its effect on population has not been evaluated.

A major contribution of this article is the use of a long-term, highly spatially disaggregated, database. An historical approach contributes to a better understanding of the policy by assessing

the importance of not only immediate, but also self-sustaining effects. We exploit a staggered difference-in-differences design, making the most of a case in which irrigation started at different points in time. We rely on information at eleven census dates, for which we have been able to match population and irrigation data, as well as data for a series of covariates, at the municipality level. An aspect of the chosen estimator is the need to use a binary treatment variable, a limitation that is circumvented by setting different irrigation thresholds.

Three broad conclusions can be drawn from this study. Firstly, for the complete sample of municipalities, and adopting a bottom line, set-by-the-government, irrigation threshold, we found that only for those municipalities that started to be irrigated in 1970 has there been a positive and significant effect on population. This (census) date would reflect the solidification of the most ambitious irrigation programs until then. Complementarily, if we look at the dynamic effect, thirty years after the beginning of irrigation the population increase was around 6 percent. Afterwards, however, the effect disappears. These results are robust when we account for an alternative comparison group, anticipation of treatment, and potential bias resulting from different lengths of exposure to treatment.

Secondly, focusing on different sub-samples helps to delineate the period in which irrigation has left a clearer mark, and the type of municipality that has benefited the most. Starting with the latter, the population effect of irrigation has been stronger in the smallest municipalities (<2,000 inhabitants) and those less influenced by the agglomeration effects of cities. For example, forty years after the beginning of irrigation, the population increase in these two groups had been around 15 percent. However, it should also be noted that the effect stabilized over time. The most important demographic impact definitely occurred in municipalities that were part of the first peak in irrigation during the third quarter of the twentieth century. The results tend to hold when concentrating on smaller parts of the territory (i.e., river basins). Further robustness checks paint largely the same picture.

Finally, the effect of irrigation on population is noticeably higher and continues to rise over time when increasing the extent of the irrigated area (or intensity of irrigation). Another way of bypassing the limited effect of irrigation over time could have been achieved by starting much earlier, before the middle of the twentieth century, when the agricultural sector still held its role as a main driver of economic growth.

To summarize, our findings suggest that beyond a first upsurge in irrigation developments between the 1950s and the early 1970s, and perhaps the initial, pre-1950, developments, subsequent efforts have tended to prove inefficient in increasing or maintaining population. This would include a second upsurge in irrigation during the 1990s and the first decade or so of the present century, linked to the thorough modernization of irrigation infrastructures and technologies to adapt to a growing demand and a limited supply of water.

Additional objectives of recent modernization programs indeed were the promotion of rural development and the creation of employment (Berbel et al., 2019: 1837). One expectation was that irrigated agriculture would connect to post-primary economic activities, principally the agro-industry. However, improvements in irrigation and the agro-industry may have in fact contributed to a reduction in labor demand (Lopez-Gunn et al., 2012: 88-89). A limited effect of the agro-industry that was also present in earlier times (Silvestre and Clar, 2010). Most recent accounts of immigration flows towards agricultural areas highlight the variety of experiences, but also note the importance of the seasonal or temporary, rather than permanent, character of jobs (Sampedro, 2022; Domingo et al., 2023).

Our analysis has policy implications. The ongoing Spanish irrigation scheme, as part of the Third Cycle Hydrological Plans for the 2022-2027 period, includes 6,500 measures with an investment of EUR 22,844 million to improve water management. EUR 5,071 million are to be specifically invested in irrigation infrastructure (Ministerio para la Transición Ecológica y el Reto

Demográfico, 2023). Several of these plans provide for the extension of the irrigated area.[26] A rearrangement of official figures features the importance of new irrigation developments in the Ebro basin, but also in other major basins such as Duero, Guadalquivir, Guadiana, Jucar and Segura (Observatorio de las Políticas del Agua, 2023). If dealing with depopulation continues to be a primary goal of irrigation policy, our findings do not seem to offer a hope for betterment.

At the very least, this article adds the recommendation of honing the target. Our analysis indicates that irrigation may be more effective in small and farther from urban conglomerations, municipalities. Small (<2,000 inhabitants) municipalities, for example, only represented six percent of the total of municipalities in 2011, which perhaps could make this group manageable. But even in this case the effect seems to lose its strength over time.

Our results certainly show that greatly increasing the intensity of irrigation may help to increase population. However, as recapitulated by Schoengold and Zilberman (2007), irrigation entails not only benefits, such as food supply expansion, but also environmental and economic costs. Negative impacts have been brought to light in Spain. For example, in a recent country report the OECD (2019, esp. p. 4) points to over-exploitation of water resources, extensive development of infrastructure (especially damns), water salinization, and deterioration of ecosystems. In fact, the agricultural sector in Spain, primarily its irrigated cropland, accounts for around 75-85 percent of water use.[27] Moreover, Spain has one of the highest, present and projected, hydric stress levels in Europe (Kuzma et al., 2023). Hence, the complex need to adapt to availability of less water in climate change scenarios (e.g. Iglesias et al., 2018).

[26] The 26 plans are enacted at the national and/or regional levels. See a detailed list at https://www.miteco.gob.es/es/agua/temas/planificacion-hidrologica/planificacion-hidrologica/planes-cuenca.html.

[27] Estimates vary (e.g., Montoya et al., 2016; Ministerio para la Transición Ecológica y el Reto Demográfico, 2022; Albiac et al., 2023).

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Figures

Figure 1. Population and irrigation at census dates

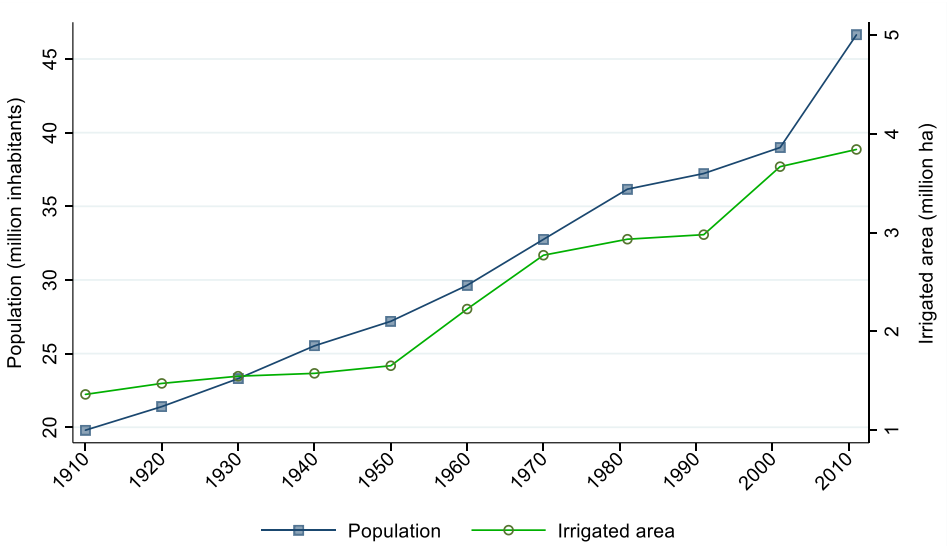
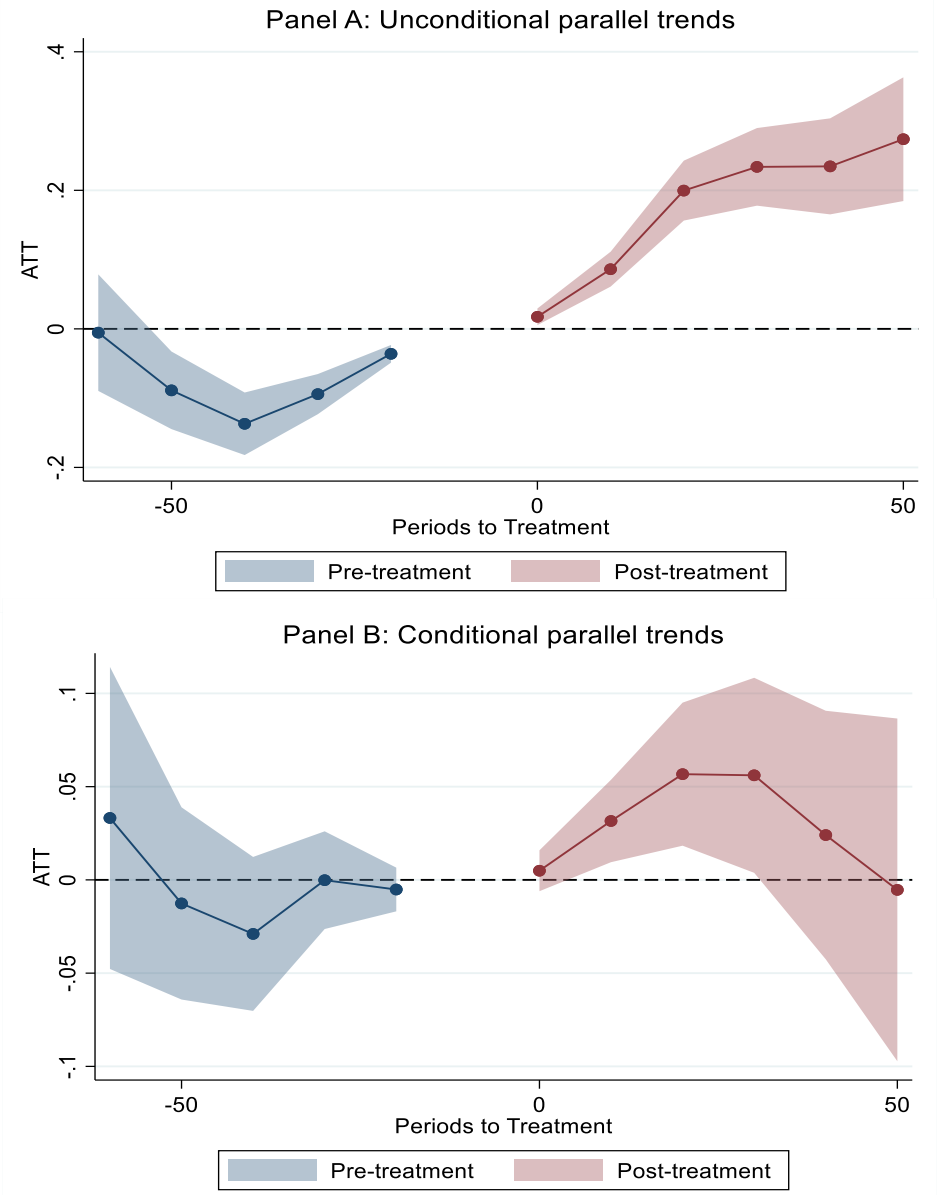


Figure 2. Parallel trends, 1950-2011



Notes: Irrigation threshold: 20 percent of total cultivated land. Comparison group: never-treated municipalities. No anticipation effects are allowed. ATT= Average treatment effect for the treated subpopulation. Periods to treatment expressed in years. Event-study coefficients. Panel B considers that parallel trends only hold conditional on the set of climatic and geographic, and economic and political variables presented in Table 1.

Tables

Table 1. Summary statistics

	1950-2011			1910-2011		
	Obs.	Mean	Std. Dev.	Obs.	Mean	Std. Dev.
Outcome variable:						
Total population (log)	27,991	6.44	1.50	47,557	6.65	1.38
Treatment variable:						
Irrigation, 20% threshold (yes/no)	28,182	0.33	0.47	47,872	0.25	0.43
Control variables:						
Climate and geographic variables						
SPEI	28,182	-0.07	0.20	47,872	-0.01	0.20
Ruggedness (mt.)	28,140	100.16	90.99	47,806	101.46	91.19
Distance to nearest river (km.)	28,182	35.74	116.11	47,872	37.84	114.09
Economic and political variables						
Employed population by sector						
Agrarian pop. (% of employed pop.)	27,537	0.49	0.29	n.a.	n.a.	n.a.
Manufacturing pop. (% of employed pop.)	27,537	0.12	0.12	n.a.	n.a.	n.a.
Mining and quarrying pop. (% of employed pop.)	27,537	0.01	0.04	n.a.	n.a.	n.a.
Energy supply pop. (% of employed pop.)	27,537	0.01	0.02	n.a.	n.a.	n.a.
Construction pop. (% of employed pop.)	27,537	0.09	0.08	n.a.	n.a.	n.a.
Trade, accom. and food serv. pop. (% of employed pop.)	27,537	0.09	0.09	n.a.	n.a.	n.a.
Other services activities (% of employed pop.)	27,537	0.19	0.15	n.a.	n.a.	n.a.
Rural/urban nature (yes/no)						
Rural<2,000 inhabitants	28,182	0.78	0.42	47,872	0.76	0.43
Intermediate, 2,000-10,000 inhabitants	28,182	0.18	0.38	47,872	0.20	0.40
Urban>10,000	28,182	0.04	0.20	47,872	0.04	0.19
Distance to coast (km.)	28,140	130.58	88.03	47,806	128.65	88.83
Distance to provincial capital (km.)	28,140	46.87	24.01	47,806	46.92	24.04

Table 2. The effect of irrigation on population, 1950-2011

TWFE		Simple weighted average		Group-specific effects		Event-study effects	
Treated	0.106***	ATT	0.0271	Group average	0.0159	Pre-treatment average	-0.0027
	(0.0106)		(0.0160)		(0.0115)		(0.0182)
				G1960	0.0255	Post-treatment average	0.0280
					(0.0268)		(0.0217)
				G1970	0.0634*	Tp0	0.00492
					(0.0297)		(0.00560)
				G1981	0.0338	Tp10	0.0316**
					(0.0353)		(0.0113)
				G1991	0.0149	Tp20	0.0567**
					(0.0175)		(0.0196)
				G2001	0.0160	Tp30	0.0561*
					(0.0142)		(0.0267)
				G2011	-0.0365**	Tp40	0.0241
					(0.0138)		(0.0340)
						Tp50	-0.00535
							(0.0469)

Notes: N= 27,362. Irrigation threshold: 20 percent of total cultivated land. Comparison group: never-treated municipalities. No anticipation effects are allowed. Parallel trends conditional on the set of climatic and geographic, and economic and political variables presented in Table 1 (Mining and quarrying is the omitted variable). *Treated* is the estimated coefficient of a post-treatment dummy variable from a TWFE specification. *ATT* is the simple weighted average (by group size) of all group-time average treatment effects obtained from Callaway and Sant'Anna's (2021) estimator. *Group-specific effects* refer to the average treatment effects by the timing of treatment (For example, G1960 corresponds to the group of municipalities that started to be irrigated in 1960). *Event-study effects* refer to the average treatment effects by length of exposure to treatment (For example, Tp10 corresponds to a treatment of 10 years, for all groups of municipalities combined). Cluster-robust standard errors at municipality level (in parentheses). * $p<0.05$; ** $p<0.01$; *** $p<0.001$.

Table 3. The effect of irrigation on population, 1950-2011. Increasing irrigation intensity

Panel A. Group-specific effects

	Irrigation threshold (%)								
	10	20	30	40	50	60	70	80	90
Group average	0.0227	0.0159	0.0346***	0.0505***	0.0626***	0.0697***	0.0671***	0.0830***	0.0875***
	(0.0127)	(0.0115)	(0.0103)	(0.00948)	(0.00950)	(0.0102)	(0.0104)	(0.0105)	(0.0112)
G1960	0.0153	0.0255	0.0524*	0.114***	0.150***	0.170***	0.138***	0.219***	0.276***
	(0.0277)	(0.0268)	(0.0258)	(0.0251)	(0.0283)	(0.0293)	(0.0334)	(0.0382)	(0.0470)
G1970	0.0761**	0.0634*	0.0963**	0.104**	0.181***	0.191***	0.224***	0.171***	0.207***
	(0.0290)	(0.0297)	(0.0293)	(0.0330)	(0.0371)	(0.0360)	(0.0343)	(0.0319)	(0.0380)
G1981	0.0236	0.0338	0.0360	0.0513	0.0802*	0.0657	0.0666	0.106**	0.149***
	(0.0382)	(0.0353)	(0.0333)	(0.0329)	(0.0407)	(0.0371)	(0.0475)	(0.0366)	(0.0314)
G1991	0.0190	0.0149	0.0445*	0.0469**	0.0703***	0.0549**	0.0483**	0.0308	0.0533*
	(0.0186)	(0.0175)	(0.0185)	(0.0174)	(0.0185)	(0.0184)	(0.0174)	(0.0218)	(0.0233)
G2001	0.0254	0.0160	0.0196	0.0186	0.00663	0.00561	0.0328*	0.0531***	0.0368
	(0.0151)	(0.0142)	(0.0130)	(0.0120)	(0.0120)	(0.0130)	(0.0141)	(0.0148)	(0.0268)
G2011	-0.0156	-0.0365**	-0.00388	0.00375	0.00225	0.0140	0.00148	0.0148	0.00888
	(0.0161)	(0.0138)	(0.0111)	(0.00975)	(0.00922)	(0.0114)	(0.00988)	(0.0107)	(0.0122)

Panel B. Event-study effects

	Irrigation threshold (%)								
	10	20	30	40	50	60	70	80	90
Post-treatment average	0.0228	0.0280	0.0580**	0.104***	0.145***	0.162***	0.154***	0.185***	0.225***
	(0.0230)	(0.0217)	(0.0206)	(0.0198)	(0.0215)	(0.0219)	(0.0239)	(0.0251)	(0.0282)
Tp0	0.0142*	0.00492	0.0150**	0.0187***	0.0209***	0.0237***	0.0211***	0.0324***	0.0328***
	(0.00622)	(0.00560)	(0.00515)	(0.00491)	(0.00500)	(0.00549)	(0.00564)	(0.00582)	(0.00717)
Tp10	0.0400***	0.0316**	0.0473***	0.0570***	0.0703***	0.0659***	0.0784***	0.0950***	0.112***
	(0.0121)	(0.0113)	(0.0108)	(0.0105)	(0.0111)	(0.0115)	(0.0122)	(0.0122)	(0.0153)
Tp20	0.0553**	0.0567**	0.0797***	0.106***	0.151***	0.141***	0.136***	0.150***	0.178***
	(0.0209)	(0.0196)	(0.0186)	(0.0183)	(0.0196)	(0.0198)	(0.0209)	(0.0202)	(0.0218)
Tp30	0.0457	0.0561*	0.0856***	0.134***	0.198***	0.191***	0.202***	0.225***	0.276***
	(0.0280)	(0.0267)	(0.0257)	(0.0253)	(0.0279)	(0.0278)	(0.0309)	(0.0306)	(0.0326)
Tp40	0.0105	0.0241	0.0625	0.136***	0.213***	0.248***	0.255***	0.278***	0.336***
	(0.0359)	(0.0340)	(0.0323)	(0.0316)	(0.0351)	(0.0356)	(0.0394)	(0.0406)	(0.0487)
Tp50	-0.0291	-0.00535	0.0579	0.171***	0.218***	0.302***	0.235***	0.331***	0.417***
	(0.0495)	(0.0469)	(0.0447)	(0.0430)	(0.0478)	(0.0492)	(0.0557)	(0.0657)	(0.0803)

Notes: The irrigation threshold is gradually increased by a 10 percent until reaching 90 percent of total cultivated land (No municipalities are 100 percent irrigated). Cluster-robust standard errors at municipality level (in parentheses). * p<0.05; ** p<0.01; *** p<0.001. See also the Notes to Table 2.

Appendix: figures and tables

Figure A.1. Density plot for the population variable

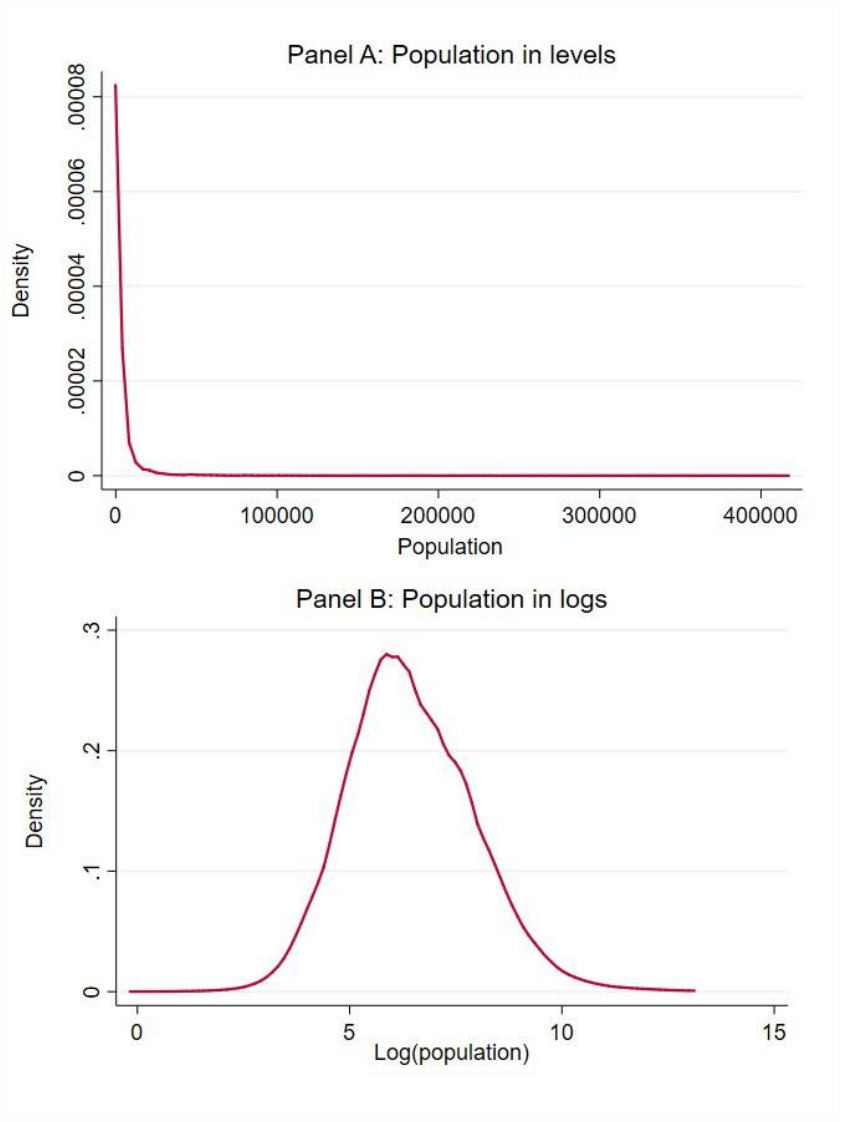
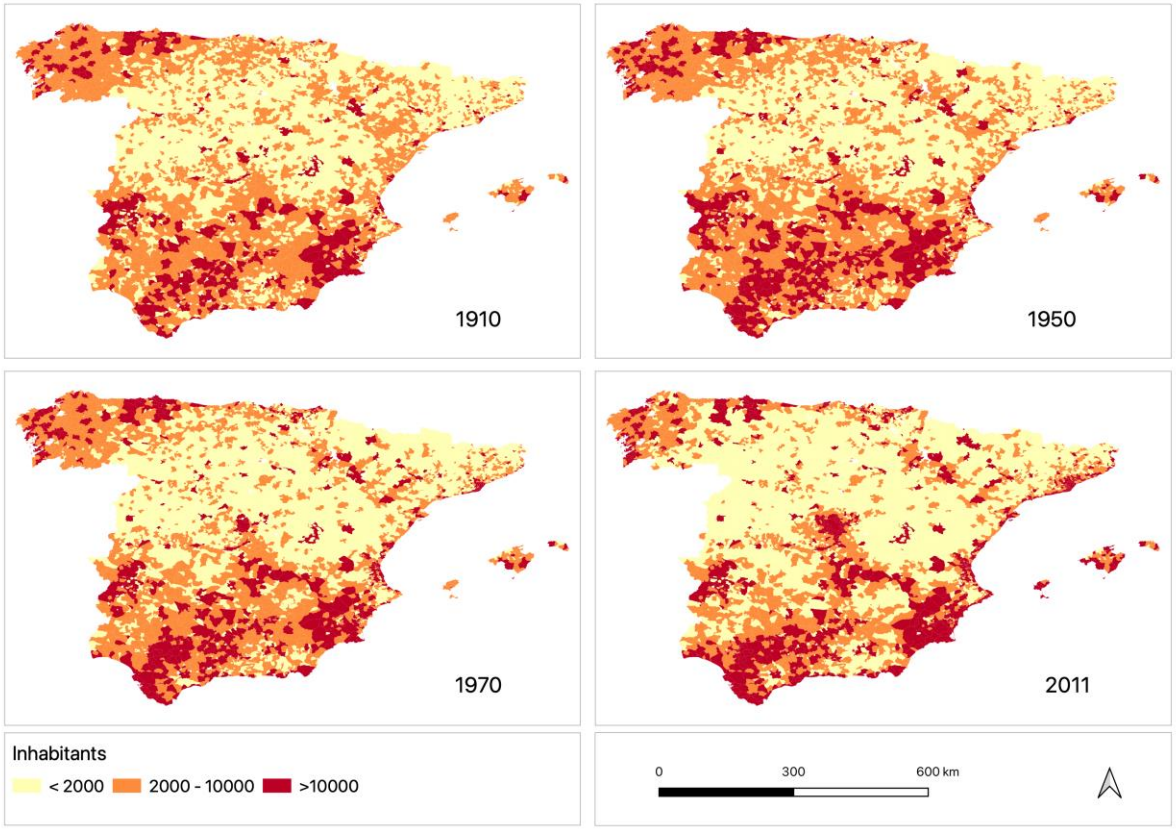


Table A.1. Area equipped for irrigation and actual irrigated surface for Spain

	1910	1920	1930	1940	1950	1960	1970	1981	1991	2001	2011
AEI estimate (this article)	1,361,853	1,473,020	1,546,360	1,574,981	1,651,980	2,225,700	2,770,324	2,932,235	2,978,394	3,666,530	3,840,734
Actual irrigated surface (IS) estimate	1,350,171	1,400,854	1,453,440	1,508,000	1,519,448	1,952,214	2,280,256	2,849,770	2,876,836	3,235,510	3,417,406
(AEI /IS)*100	101%	105%	106%	104%	109%	114%	121%	103%	104%	113%	112%

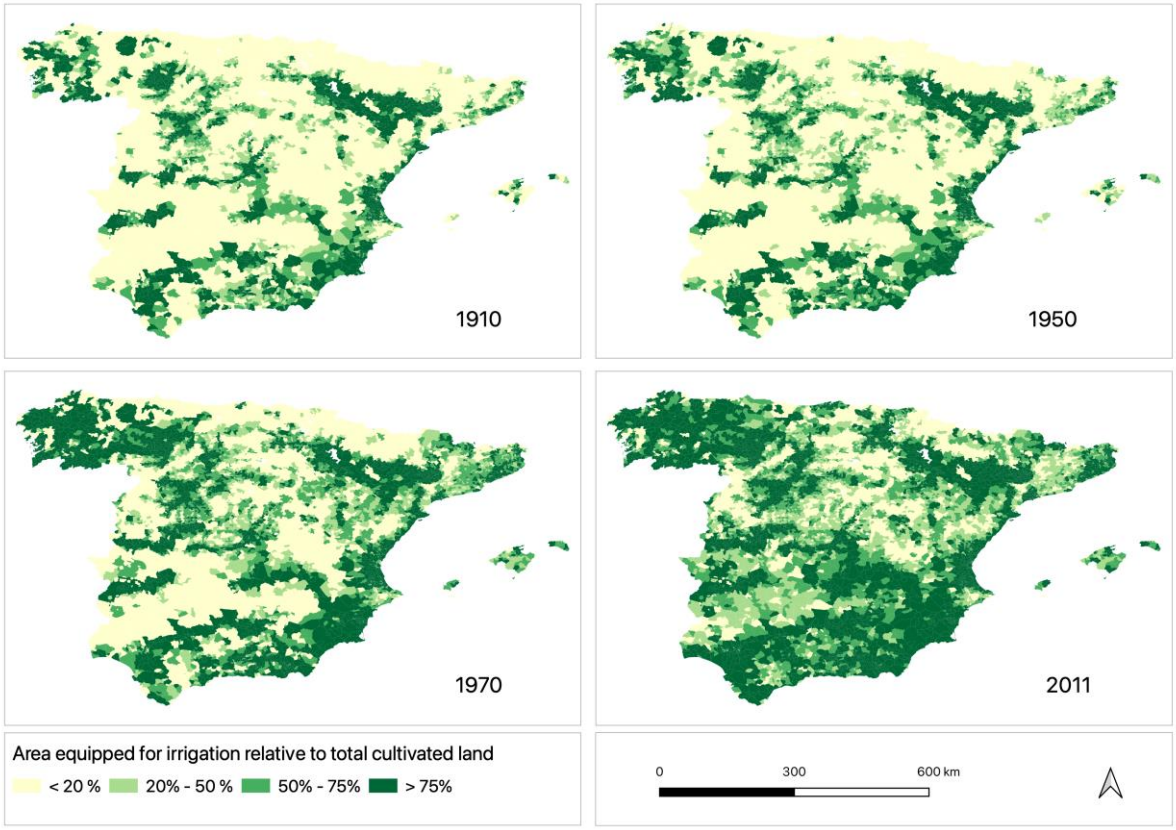
Notes: This table compares our area equipped for irrigation (AEI) estimate, as explained in Section 3.1, with the actual irrigated surface (IS) estimate, which has been constructed using two main sources: the 2004 Water Plan (Ministerio de Medio Ambiente, 2004: 81), for the 1910-1991 period; and the Encuesta sobre Superficies y Rendimientos de Cultivos [Survey on Crop Surfaces and Yields] (Ministerio de Agricultura, Pesca y Alimentación, 2024), for the 2001-2011 period.

Figure A.2. Population (inhabitants) at selected dates



Notes: Municipalities.

Figure A.3. Extent of irrigation relative to total cultivated land (percentage) at selected dates



Notes: Municipalities. Selected irrigation thresholds as reported in Table A.2.

Table A.2. Distribution of municipalities according to their irrigation status at selected thresholds

A. 1950–2011

	Irrigated (yes/no)		20% of total cultivated land		50% of total cultivated land		75% of total cultivated land	
	N	%	N	%	N	%	N	%
Irrigation always	4,739	58%	3,312	41%	1,814	22%	776	10%
Irrigation, never	516	6%	1,339	16%	2,844	35%	4,783	59%
Irrigation 1960	818	10%	726	9%	363	4%	186	2%
Irrigation 1970	383	5%	312	4%	201	2%	126	2%
Irrigation 1981	144	2%	171	2%	127	2%	107	1%
Irrigation 1991	192	2%	206	3%	163	2%	130	2%
Irrigation 2001	1,169	14%	771	9%	436	5%	225	3%
Irrigation 2011	123	2%	501	6%	595	7%	384	5%
Irrigation on/off	38	0%	784	10%	1,579	19%	1,405	17%
Total	8,122	100%	8,122	100%	8,122	100%	8,122	100%

B. 1910–2011

	Irrigated (yes/no)		20% of total cultivated land		50% of total cultivated land		75% of total cultivated land	
	N	%	N	%	N	%	N	%
Irrigation, always	4,207	52%	2,971	37%	1,635	20%	699	9%
Irrigation, never	516	6%	1,338	16%	2,844	35%	4,772	59%
Irrigation 1920	208	3%	136	2%	68	1%	23	0%
Irrigation 1930	119	1%	71	1%	41	1%	21	0%
Irrigation 1940	46	1%	14	0%	17	0%	7	0%
Irrigation 1950	159	2%	109	1%	42	1%	16	0%
Irrigation 1960	818	10%	723	9%	343	4%	167	2%
Irrigation 1970	383	5%	312	4%	199	2%	124	2%
Irrigation 1981	144	2%	171	2%	126	2%	106	1%
Irrigation 1991	192	2%	206	3%	163	2%	130	2%
Irrigation 2001	1,169	14%	771	9%	436	5%	224	3%
Irrigation 2011	123	2%	501	6%	595	7%	384	5%
Irrigation, on/off	38	0%	799	10%	1,613	20%	1,449	18%
Total	8,122	100%	8,122	100%	8,122	100%	8,122	100%

Table A.3. The effect of irrigation on population, 1950-2011. Area and type of municipality

Panel A. Group-specific effects

	Baseline specification	Area added	Type of municipality		
			Rural	Intermediate	Urban
Group average	0.0159	0.0348**	0.0594***	-0.0169	0.974***
	(0.0115)	(0.0114)	(0.0132)	(0.0260)	(0.116)
G1960	0.0255	0.0527*	0.105***	-0.141	-1.777***
	(0.0268)	(0.0259)	(0.0270)	(0.0799)	(0.389)
G1970	0.0634*	0.101***	0.144***	0.0638	-0.00494
	(0.0297)	(0.0295)	(0.0330)	(0.0722)	(0.0558)
G1981	0.0338	0.0717	0.0263	0.0636	-0.375**
	(0.0353)	(0.0370)	(0.0455)	(0.0657)	(0.115)
G1991	0.0149	0.0166	0.0474	0.0154	1.439***
	(0.0175)	(0.0178)	(0.0268)	(0.0251)	(0.427)
G2001	0.0160	0.0308*	0.0374*	0.0309	1.254***
	(0.0142)	(0.0141)	(0.0171)	(0.0211)	(0.145)
G2011	-0.0365**	-0.0357**	-0.0261	-0.0436*	-0.0661*
	(0.0138)	(0.0138)	(0.0182)	(0.0179)	(0.0327)

Panel B. Event-specific effects

	Baseline specification	Area added	Type of municipality		
			Rural	Intermediate	Urban
Post-treatment average	0.0280	0.0580**	0.105***	-0.0845	-0.226
	(0.0217)	(0.0212)	(0.0226)	(0.0598)	(0.326)
Tp0	0.00492	0.0134*	0.0184**	0.00812	0.669***
	(0.00560)	(0.00562)	(0.00685)	(0.0110)	(0.0962)
Tp10	0.0316**	0.0516***	0.0745***	0.0187	1.321***
	(0.0113)	(0.0112)	(0.0138)	(0.0225)	(0.207)
Tp20	0.0567**	0.0853***	0.121***	-0.0122	0.531
	(0.0196)	(0.0192)	(0.0224)	(0.0517)	(0.715)
Tp30	0.0561*	0.0946***	0.143***	-0.0909	-1.180*
	(0.0267)	(0.0264)	(0.0286)	(0.0751)	(0.477)
Tp40	0.0241	0.0671*	0.141***	-0.155	-1.067*
	(0.0340)	(0.0330)	(0.0352)	(0.0965)	(0.508)
Tp50	-0.00535	0.0362	0.133**	-0.276*	-1.628***
	(0.0469)	(0.0456)	(0.0466)	(0.121)	(0.369)

Notes: N= 27,362. Baseline specification, as in Table 2, versus specifications adding area of municipality as covariate ("Area added"); and specifications for three sub-samples of types of municipalities, "Rural" (<2,000 inhabitants), "Intermediate" (2,000-10,000) and "Urban" (>10,000). Cluster-robust standard errors at municipality level (in parentheses). * p<0.05; ** p<0.01; *** p<0.001. See also the Notes to Table 2.

Table A.4. Spillovers

Panel A. Adjacent-municipalities-based criteria to consider a municipality as irrigated

		Adjacent municipalities								
		always	**never**	**G1960**	**G1970**	**G1981**	**G1991**	**G2001**	**G2011**	**on/off**
Municipality itself	**always**	always	always	always	always	always	always	always	always	always
	never	always	never	G1960	G1970	G1981	G1991	G2001	G2011	never
	G1960	always	G1960	G1960	G1960	G1960	G1960	G1960	G1960	G1960
	G1970	always	G1970	G1960	G1970	G1970	G1970	G1970	G1970	G1970
	G1981	always	G1981	G1960	G1970	G1981	G1981	G1981	G1981	G1981
	G1991	always	G1991	G1960	G1970	G1981	G1991	G1991	G1991	G1991
	G2001	always	G2001	G1960	G1970	G1981	G1991	G2001	G2001	G2001
	G2011	always	G2011	G1960	G1970	G1981	G1991	G2001	G2011	G2011
	on/off	always	on/off	G1960	G1970	G1981	G1991	G2001	G2011	on/off

Notes to Panel A: The treatment refers to the irrigation threshold of 20 percent of total cultivated land. A municipality is considered to be a) *always treated* if the municipality itself or the adjacent municipalities have been treated since the beginning of the period under study; b) *never treated* if both the municipality itself and the adjacent municipalities have never been treated, or if the municipality itself has never been treated and the treatment of the adjacent municipalities is not staggered, that is to say, they are on/off municipalities; c) *not-yet-treated*, i.e., G1960, G1970, etc., on the basis of the beginning of treatment for the municipality itself or the adjacent municipalities; and d) *on/off* if the treatment for both the municipality itself and the adjacent municipalities is not staggered, or if the treatment for the municipality itself is not staggered and the adjacent municipalities have never been treated.

Panel B. The effect of irrigation on population, 1950-2011. Adjacent municipalities

Group-specific effects			Event-study effects		
	Baseline specification	Adjacent		Baseline specification	Adjacent
Group average	0.0159	0.0247	Post-treatment average	0.0280	0.0665*
	(0.0115)	(0.0202)		(0.0217)	(0.0300)
G1960	0.0255	0.0620	Tp0	0.00492	0.00190
	(0.0268)	(0.0333)		(0.00560)	(0.0103)
G1970	0.0634*	0.109*	Tp10	0.0316**	0.00693
	(0.0297)	(0.0488)		(0.0113)	(0.0235)
G1981	0.0338	0.0986*	Tp20	0.0567**	0.0866**
	(0.0353)	(0.0473)		(0.0196)	(0.0270)
G1991	0.0149	0.0585**	Tp30	0.0561*	0.115**
	(0.0175)	(0.0224)		(0.0267)	(0.0357)
G2001	0.0160	-0.0722	Tp40	0.0241	0.0995*
	(0.0142)	(0.0466)		(0.0340)	(0.0444)
G2011	-0.0365**	-0.00606	Tp50	-0.00535	0.0896
	(0.0138)	(0.0210)		(0.0469)	(0.0672)

Panel C. The effect of irrigation on population, 1950-2011. Distance to an urban municipality

Group-specific effects				Event-study effects			
	Baseline specification	>25 km.	<25 km.		Baseline specification	>25 km.	<25 km.
Group average	0.0159	0.0535***	-0.0300	Post-treatment average	0.0280	0.107***	-0.0453
	(0.0115)	(0.0124)	(0.0174)		(0.0217)	(0.0237)	(0.0341)
G1960	0.0255	0.105***	-0.0477	Tp0	0.00492	0.0208**	-0.0182*
	(0.0268)	(0.0294)	(0.0447)		(0.00560)	(0.00743)	(0.00835)
G1970	0.0634*	0.178***	-0.0468	Tp10	0.0316**	0.0756***	-0.0215
	(0.0297)	(0.0335)	(0.0465)		(0.0113)	(0.0155)	(0.0166)
G1981	0.0338	0.0593	0.0404	Tp20	0.0567**	0.134***	-0.00830
	(0.0353)	(0.0475)	(0.0504)		(0.0196)	(0.0270)	(0.0290)
G1991	0.0149	-0.00682	-0.00914	Tp30	0.0561*	0.181***	-0.0359
	(0.0175)	(0.0376)	(0.0205)		(0.0267)	(0.0319)	(0.0417)
G2001	0.0160	0.0322	-0.0248	Tp40	0.0241	0.145***	-0.0846
	(0.0142)	(0.0166)	(0.0208)		(0.0340)	(0.0366)	(0.0543)
G2011	-0.0365**	-0.0297*	-0.0429	Tp50	-0.00535	0.0853	-0.103
	(0.0138)	(0.0142)	(0.0238)		(0.0469)	(0.0458)	(0.0761)

Notes: *Panel B*: baseline specification, as in Table 2, versus a specification using the alternative adjacent-municipalities-based outcome variable, as explained in the notes to Panel A. *Panel C*: baseline specification versus specifications for two sub-samples of municipalities within or outside 25 km distance of an urban municipality (>10,000 inhabitants). Cluster-robust standard errors at municipality level (in parentheses). * p<0.05; ** p<0.01; *** p<0.001. See also the Notes to Table 2.

Table A.5. The effect of irrigation on population, 1950-2011. River basins

Panel A. Group-specific effects

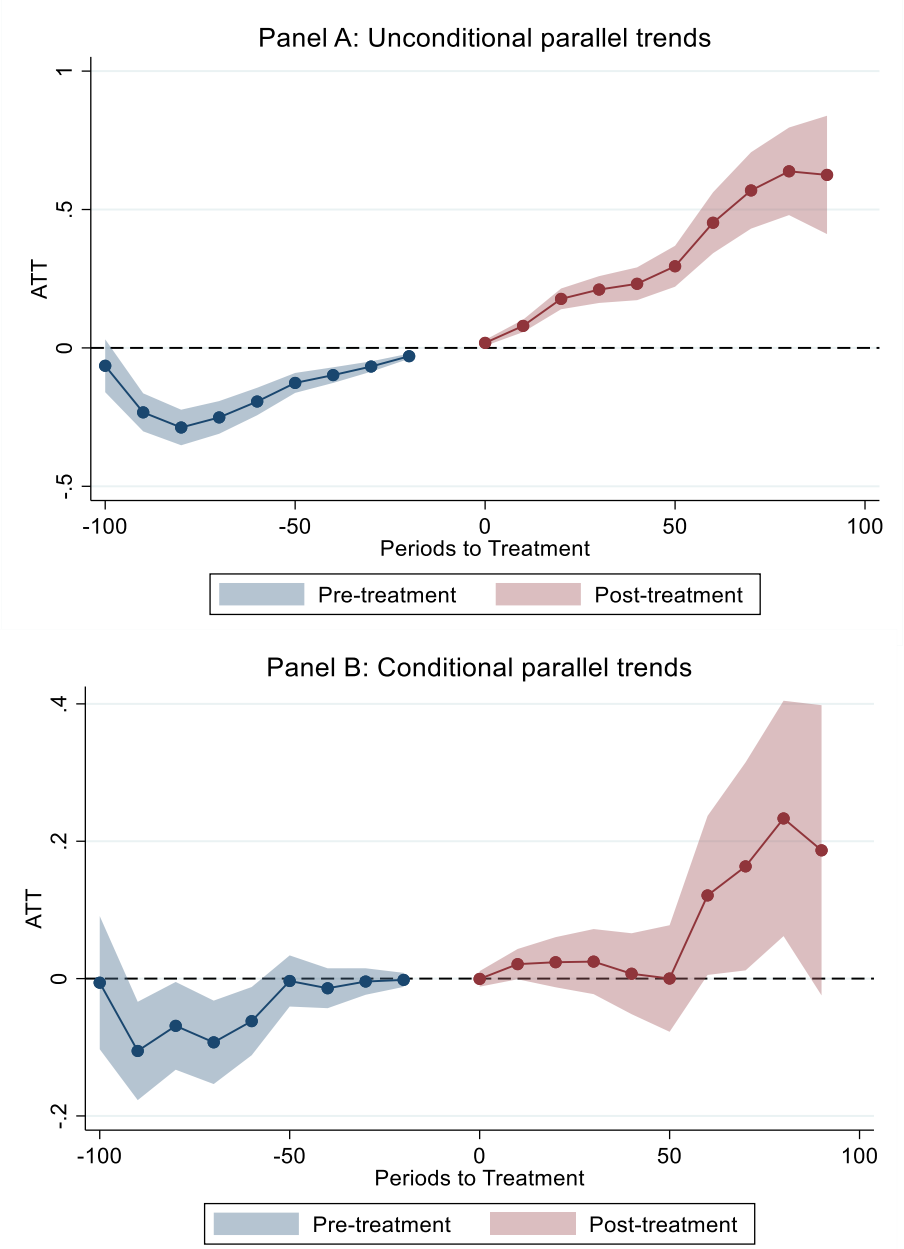
	Baseline specification	Duero	Ebro	Guadalquivir	Guadiana	Júcar	Tajo
G. average	0.0159	0.0387*	0.101	-0.700*	1.144	0.429***	0
	(0.0115)	(0.0172)	(0.0565)	(0.357)	(0.610)	(0.109)	(.)
G1960	0.0255	0.0948**	0.214***	-6.144	1.501*	-0.326*	0.281
	(0.0268)	(0.0309)	(0.0466)	(3.661)	(0.691)	(0.141)	(0.144)
G1970	0.0634*	0.0879*	0.109	0.344***	0.352***	2.581**	-0.0613
	(0.0297)	(0.0352)	(0.0707)	(0.0661)	(0.0996)	(0.788)	(0.171)
G1981	0.0338	0.0654	-0.139	0.155	8.278	-0.494	0
	(0.0353)	(0.0736)	(0.658)	(0.0961)	(5.810)	(0.516)	(.)
G1991	0.0149	0	-0.0775	-1.422***	0.0985	-1.623**	0
	(0.0175)	(.)	(0.0686)	(0.270)	(0.198)	(0.542)	(.)
G2001	0.0160	0.0444	0.0606	-0.118***	0.154***	2.806***	-0.0424
	(0.0142)	(0.0379)	(0.0346)	(0.0270)	(0.0345)	(0.304)	(0.0457)
G2011	-0.0365**	-0.0482	-0.0769*	0.00407	-0.0621***	0.0612	-0.0526
	(0.0138)	(0.0278)	(0.0344)	(0.0210)	(0.0161)	(0.0480)	(0.0506)

Panel B. Event-study effects

	Baseline specification	Duero	Ebro	Guadalquivir	Guadiana	Júcar	Tajo
Post-treatment average	0.0280	0.0835**	0.167**	-3.542	1.900*	-0.0527	0.314*
	(0.0217)	(0.0254)	(0.0597)	(2.177)	(0.910)	(0.142)	(0.126)
Tp0	0.00492	0.0114	0.0344	0.0514	1.234	0.694***	-0.0383
	(0.00560)	(0.0118)	(0.0192)	(0.119)	(0.654)	(0.162)	(0.0254)
Tp10	0.0316**	0.0791***	0.0490	-0.764	0.722	0.209	-0.0267
	(0.0113)	(0.0200)	(0.0586)	(0.435)	(0.626)	(0.273)	(0.0517)
Tp20	0.0567**	0.123***	-0.0539	-2.336	4.903*	-0.935	0.0693
	(0.0196)	(0.0277)	(0.123)	(1.364)	(2.323)	(0.575)	(0.127)
Tp30	0.0561*	0.133***	0.504**	-3.413	3.069	0.103	0.127
	(0.0267)	(0.0336)	(0.182)	(2.363)	(1.817)	(0.145)	(0.138)
Tp40	0.0241	0.0952*	0.275***	-4.154	0.850***	-0.168	0.138
	(0.0340)	(0.0388)	(0.0601)	(2.852)	(0.258)	(0.0894)	(0.144)
Tp50	-0.00535	0.0599	0.196**	-10.64	0.620	-0.220	1.616**
	(0.0469)	(0.0553)	(0.0720)	(6.401)	(0.346)	(0.120)	(0.493)

Notes: Baseline specification, as in Table 2. Principal six river basins according to the available number of observations and the extent of irrigation. In Panel A, four group-specific effects cannot be estimated due to the lack of observations.

Figure A.4. Parallel trends, 1910-2011



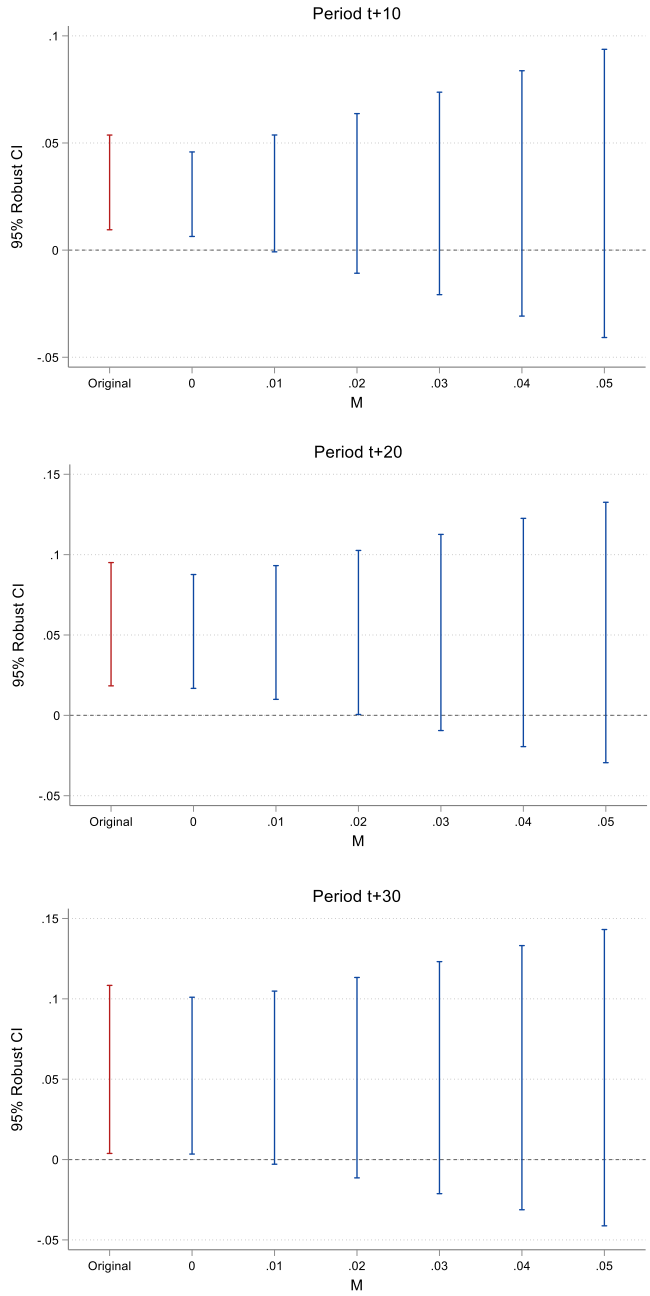
Notes: Irrigation threshold: 20 percent of total cultivated land. Comparison group: never-treated municipalities. No anticipation effects are allowed. ATT= Average treatment effect for the treated subpopulation. Periods to treatment expressed in years. Event-study coefficients. Panel B considers that parallel trends only hold conditional on the set of climatic and geographic, and economic and political variables presented in Table 1, except for employed population by sector.

Table A.6. The effect of irrigation on population, 1910-2011

TWFE		Simple weighted average		Group-specific effects		Event-study effects	
Treated	0.139***	ATT	0.0241	Group average	0.0133	Pre-treatment average	-0.0398
	(0.0130)		(0.0183)		(0.0129)		(0.0217)
				G1920	0.0578	Post-treatment average	0.0781*
					(0.0528)		(0.0383)
				G1930	0.163*	Tp0	-0.000447
					(0.0794)		(0.00580)
				G1940	-0.0374	Tp10	0.0211
					(0.158)		(0.0113)
				G1950	0.0334	Tp20	0.0238
					(0.0450)		(0.0186)
				G1960	-0.00915	Tp30	0.0247
					(0.0285)		(0.0242)
				G1970	0.0367	Tp40	0.00709
					(0.0304)		(0.0301)
				G1981	0.0870*	Tp50	0.0000962
					(0.0346)		(0.0396)
				G1991	-0.00627	Tp60	0.121*
					(0.0195)		(0.0591)
				G2001	0.0244	Tp70	0.163*
					(0.0156)		(0.0773)
				G2011	-0.0365**	Tp80	0.233**
					(0.0140)		(0.0874)
						Tp90	0.187
							(0.108)

Notes: N=47,519. Irrigation threshold: 20 percent of total cultivated land. Comparison group: never-treated municipalities. No anticipation effects are allowed. Parallel trends conditional on the set of climatic and geographic, and economic and political variables presented in Table 1, except for employed population by sector. *Treated* is the estimated coefficient of a post-treatment dummy variable from a TWFE specification. *ATT* is the simple weighted average (by group size) of all group-time average treatment effects obtained from Callaway and Sant'Anna's (2021) estimator. *Group-specific effects* refer to the average treatment effects by the timing of treatment. *Event-study effects* refer to the average treatment effects by length of exposure to treatment. Cluster-robust standard errors at municipality level (in parentheses). * $p<0.05$; ** $p<0.01$; *** $p<0.001$.

Figure A.5. Sensitivity analysis, 1950-2011



Notes: Rambachan and Roth's (2023) sensitivity analysis. Option: smoothness restrictions. Irrigation threshold: 20% of total cultivated land. Comparison group: never-treated municipalities. No anticipation effects are allowed. Parallel trends conditional on the set of climatic and geographic, and economic and political variables presented in Table 1. Based on the significance of event-study coefficients in Table 2, effect of irrigation on population 10, 20 and 30 years after treatment. Pre-treatment effects obtained using a universal base period (see Roth, 2024). Robust confidence intervals. M= breakdown values for the significance of effects. See also Section 6 for further details.

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