ULTRAHIGH-SPEED FIXED BROADBAND AND RURAL DEVELOPMENT

ANDRÉS ARRONTE LEDO* & ADELHEID HOLL**

* *Department of Economics, University Carlos III, Madrid, Spain.*
** *Institute of Public Goods and Policies, Spanish National Research Council (CSIC), Madrid, Spain*
E-mail: a.holl@csic.es (Corresponding author)

Received: November 2022; accepted October 2023

ABSTRACT

We study the relationship between ultrahigh-speed broadband coverage (≥100 Mbps) and population change in rural areas. Our goal is to determine whether improved telecommunications infrastructure can help to mitigate rural de-population. The study focuses on Spain during the years 2013–20, a period when most of the country's broadband network was deployed. We use instrumental variable estimation to test for a causal link between ultrahigh-speed broadband provision and rural population change. Although the data show a positive correlation between an increase in local ultrahigh-speed broadband coverage and local population growth, after accounting for potential confounding factors and endogeneity, we find no evidence of a causal effect.

Key words: Broadband; rural population growth; de-population

INTRODUCTION

In today's digital age, information and communications technology (ICT) has relevant social, economic and political implications. Yet, significant disparities exist in access and use of modern information and communications technology. This is commonly referred to as the digital divide and has drawn the attention of governments, organisations and academics alike. Closing the digital divide has become a top priority on the political agenda. For instance, the European Union's (EU) Digital Agenda Europe (DAE) set broadband coverage targets for 2020 (European Commission 2014). In 2016, the EU introduced new objectives in its Gigabit Society and Digital Decades strategy, aiming to provide universal connectivity with speeds of at least 100 Mbps by 2025 and gigabit connectivity by 2030 (European Commission 2016). The Next Generation EU (NGEU) funds, designed to aid European recovery from the COVID-19 crisis, prioritise digital transformation. The fact that broadband internet access constitutes a necessity for many activities of modern life has become very apparent during the lockdowns of the COVID-19 crisis, which has marked a turning point in our lifestyles and working conditions, including the rise of teleworking.

The digital divide in Europe is particularly pronounced between urban and rural areas, with the latter typically experiencing lower levels of internet access and digital connectivity. This divide persists due to significant disparities both in the quality and spatial coverage of broadband internet access. The EU has recognised that rural areas are particularly vulnerable to the digital divide, given the challenges of providing broadband infrastructure to sparsely populated regions. To address this issue, the EU has launched the Rural Development Programme, which aims to support the development of digital infrastructure and services in rural areas.

The urban–rural digital divide, which concerns both the availability and usage of the internet, has attracted interest in the academic literature (see e.g. Hindman 2000; Prieger 2003, 2013; Townsend *et al.* 2013; Reddick *et al.* 2020). Broadband access has been linked to migration patterns between urban and rural areas (Mahasuweerachai *et al.* 2010) and broadband access has been recognised as crucial for competitiveness and growth (for a review of this literature, see e.g. Bertschek *et al.* 2016; Abrardi and Cambini 2019), with important impacts on firm location (Mack and Grubesic 2009; McCoy *et al.* 2018) and employment (Kolko 2012; Atasoy 2013; Deller *et al.* 2022; Conroy and Low 2022).

The urban–rural divide is not only a problem of internet access per se, but importantly also about the quality and speed of access, as more advanced applications require higher capacity broadband networks. Rural areas are, however, particularly lagging behind in higher speed broadband availability (Prieger 2013; Briglauer *et al.* 2021), especially in terms of high-speed next-generation services (NGA) and very high-capacity networks (VHCN) (European Commission 2020). This lower coverage of higher speed internet can compromise rural areas' growth prospects at a time when fast access is crucial for emerging technologies, particularly for participating in the digitalization process. However, little is still known about the impacts of higher speed newer-generation broadband connectivity in rural areas.

Our study aims to investigate the impact of ultrahigh-speed broadband provision on local population change in rural municipalities. Specifically, we examine whether the availability of high-speed internet can help prevent de-population by retaining or attracting more people to these areas. Our study is based on Spanish data for 2013–20. Spain is an interesting country to study in this context because it has an extensive rural space suffering from continued de-population. About 70 per cent of Spanish municipalities are rural and over 60 per cent of municipalities have fewer than 1,000 inhabitants. More than half of the rural municipalities have population densities below 12.5 inhabitants per square kilometre, which is the EU criteria for sparsely populated areas. The 2021 annual report of the Bank of Spain estimated that 42 per cent of Spanish municipalities are at risk of de-population (Banco de España 2020).

Despite being one of the countries with the fastest development of its fibre network, the digital divide in Spain remains significant. While ultrahigh-speed broadband reached on average 88 per cent of the population in 2020, it was only available to 63 per cent of people in rural areas (Ministerio de Asuntos Económicos y Transformación Digital 2021). The Spanish Government, in the context of the Next Generation EU funds, has allocated an investment of more than 800 million euros exclusively for the provision of ultrahigh-speed broadband to rural areas (Gobierno de España 2021) in order to reduce the digital divide, increase cohesion among territories and combat rural de-population.

Our study contributes to the ongoing discussion on the local impacts of broadband provision. We focus specifically on rural areas. Most of the existing literature has shown that the positive impacts of broadband provision are correlated with urban traits (Mahasuweerachai *et al.* 2010; Forman *et al.* 2012; Atasoy 2013; Mack and Faggian 2013; Tranos and Mack 2016), but the evidence for rural areas is still largely inconclusive.

From a theoretical perspective, broadband provision has the potential to help rural areas mitigate the costs of remoteness and this way to retain population. It can weaken urban agglomeration forces and facilitate the dispersion of economic activities and people. Improved broadband connections together with the rising trend of teleworking, as more and more jobs can be done remotely, give people greater flexibility in choosing where to reside and work. The availability of high-speed internet in rural areas makes those locations more attractive to remote workers seeking affordable housing and to entrepreneurs seeking to start businesses in rural areas with lower factor costs. Moreover, high-speed internet connections can also help support existing businesses in rural areas by enabling them to compete more effectively in the global economy. Additionally, by improving access to online education and healthcare services, high-speed internet provision can also increase the attractiveness of rural locations. However, it is important to consider that the expansion of broadband infrastructure in rural areas might also lead to increased out-migration, as residents gain access to more information about job and educational opportunities elsewhere. Furthermore, if the internet is a complement rather than a substitute for face-to-face interactions (Glaeser 1998; Li and Mora 2022), broadband improvements may primarily benefit urban areas (Mack and Faggian 2013) and the impact of broadband in rural areas may then depend on their accessibility to cities.

We are specifically interested in exploring the impact of ultrahigh-speed broadband with a minimum download speed of 100 Mbps. This level of connectivity is considered essential for full teleworking functionality, including tasks such as streaming videos and video conferencing. It is also a key objective of the EU Digital Agenda, which aims to connect households through high-speed networks with download speeds of at least 100 Mbps by 2025.

RELATED LITERATURE

The urban–rural digital divide – Low population densities, remoteness and often challenging terrain conditions increase the average cost of deploying broadband in rural areas compared to urban areas. These higher costs, coupled with lower expected future profits, reduce private investment incentives in rural areas, leading to lower broadband coverage.

As the internet became more widespread, concerns about the unequal distribution of this new technology arose, giving rise to the term 'digital divide'. Introduced in the mid-1990s in the United States, the digital divide initially described the gap between individuals who had access to digital technologies and those who did not. Researchers soon recognised the importance of the territorial dimension of this divide (Hindman 2000; Prieger 2003, 2013; Townsend *et al.* 2013; European Commission 2020), emphasising the significance of geographical factors in determining access to broadband services.

Several studies have extensively investigated strategies aimed at bridging the digital infrastructure gap between urban and rural areas (Williams *et al.* 2016). These studies consistently indicate that government intervention and state aid are frequently necessary to address the issue (Parker 2000; Briglauer *et al.* 2019). Moreover, it has been observed that the digital divide persists not only in terms of access but also in internet usage among residents in urban and rural settings (Hindman 2000; Prieger 2003, 2013). Salemink *et al.* (2017) conducted a comprehensive review of the literature on the urban–rural divide, shedding further light on the topic.

As broadband technology continues to evolve at a rapid pace, the rural digital divide in broadband speeds has become a topic of increasing interest in the literature. However, little is still known about the local development impacts of increasing the speed of broadband (see, Abrardi and Cambini 2019, for a review). Yet, speed is key nowadays since low-speed broadband is no longer sufficient for more advanced internet applications. With the latest advancements in internet technology, many broadband providers now offer higher capacity services with speeds of 100 Mbps and more, but not to all locations. Indeed, this type of connectivity shows an even larger divide between urban and rural areas (European Commission 2020), as well as among different rural areas. Therefore, ultrahigh-speed broadband coverage (≥100 Mbps) can constitute a distinctive advantage for firm and household location choices.

The economic impacts of the rural–urban digital divide – There is an extensive literature studying the effects of broadband provision on various economic outcomes, including firms' location decisions, start-up rates and income; factors which are typically related to population change. Crandall *et al.* (2007), for example examined the effect of broadband deployment on output and employment in US states between 2003 and 2005, finding a positive association between broadband and state employment and output. Mahasuweerachai *et al.* (2010)

investigated the impact of broadband access on in-migration in US urban and rural counties between 2000 and 2006, finding stronger effects for urban counties. In contrast, Atasoy (2013) studied the impact of broadband on employment change in US counties between 1999 and 2007 and found a positive effect that is more significant in rural and isolated counties. He concluded that broadband facilitated the integration of rural and isolated areas in national markets, opening up access to new business opportunities. Mack and Faggian (2013) examined the impact of broadband on US county earnings growth during the same period, finding that broadband alone does not raise earnings and that it is only in combination with high human capital that broadband generates economic gains. McCoy *et al.* (2018) studied the role of broadband for new firm location in Ireland, finding that the effects are strongly conditioned by the local human capital level.

Mack and Grubesic (2009) in their exploratory study of firm location in Ohio found that changes in broadband were not very strongly related to changes in firm location. Kim and Orazem (2017) analysed the role of broadband access for firms' location decisions in rural areas in the United States from 1990 to 2000, finding a significant positive effect of broadband on firms' location choice, with a greater effect in larger rural towns and those close to metropolitan areas. Kandilov and Renkow (2010) also focused specifically on rural areas, studying the impact of participation in the U.S. Department of Agriculture's Broadband Loan Program. They found evidence of positive effects for rural communities located within metro areas, but no effect or even a negative effect for rural areas outside metro counties.

In a similar vein, Duvivier *et al.* (2021) concluded in their study on broadband and firm birth in French municipalities, that broadband had positive effects in urban and peri-urban areas, but little impact in rural areas, except in locations with natural amenities and good quality of life that can attract creative and business services. De Vos *et al.* (2020) studied the relationship between labour mobility and broadband in Sweden, finding that broadband had positive effects on employment only in areas located between 20 and 50 km from urban cores. Conroy and Low (2022) investigated the effects of broadband and gender on entrepreneurship in rural municipalities in the United States from 2005 to 2007. They found that even though broadband access is positively correlated with start-ups in aggregated terms, the relationship is even stronger in remote rural counties. Deller and Whitacre (2019) found that broadband availability had a positive relationship with housing values, this way increasing the wealth of the rural population. Whitacre *et al.* (2014) focused on the differences between broadband availability and adoption in rural areas. Using data from 2008 to 2011 for non-metropolitan US counties, they found that broadband availability had a positive effect on job creation, but improvements in access did not show a significant impact on employment or income in rural areas.

A difficulty in the analysis of broadband effects is that the rollout of broadband networks is not random. Broadband providers respond to the demand for broadband services and install networks where they anticipate economic benefits. This is strongly related to local growth conditions. Hence, the relationship between broadband and local growth can suffer from reverse causality issues, where local growth attracts investment in broadband infrastructure.

Several studies have attempted to address this problem by adopting an instrumental variable (IV) approach. Kolko (2012), for example examined the effect of broadband on local economic growth in the United States using ZIP code data and the average slope of the terrain to instrument broadband availability. His results indicate that broadband has a positive impact on local growth, with stronger effects in areas with lower population density, which could result from decreasing returns in the most saturated areas. Czernich (2014) analysed the role of broadband in reducing unemployment rates in German municipalities. In OLS estimations, he found a negative relationship between broadband and unemployment rates, suggesting that broadband leads to lower unemployment. However, in IV estimations, based on the pre-existing voice–telephone network to control for reverse causality and omitted variables, he did not find a significant effect. On the contrary, Conroy and Low (2022) conducted an IV regression to test their hypothesis on whether broadband access promotes entrepreneurship in rural areas in the United States and found a positive effect of broadband on entrepreneurship. Tranos and Mack (2016) applied a Granger causality analysis to examine how broadband provision is related to the location of knowledge-intensive business services (KIBS) in US counties. They found significant heterogeneity across counties, but the causal effect of broadband provision tended to be stronger in counties with higher population densities and those that had earlier broadband access.

This is in line with the findings in Forman *et al.* (2012) regarding the relationship between internet investment and regional growth in US counties from 1995 to 2000. Their findings show positive effects on wage and employment growth, but only in a small number of counties with higher population, skills, income and ICT usage. They argue that the internet has actually intensified regional inequalities.

To conclude, the empirical evidence on the local impacts of broadband provision in rural areas is not yet fully conclusive. The literature suggests that it can benefit certain areas but not all, with some indications that the benefits might be mostly concentrated in urban areas and close to urban areas. This has led to a debate on whether broadband provision reinforces existing urban advantages or can effectively narrow the urban–rural divide (Wu *et al.* 2022). However, a better understanding of the impacts of rural broadband provision is crucial for the development of effective rural policies, as broadband access has become a key issue.

Effects of the broadband speed gap – As noted earlier, broadband speed has emerged a critical factor, beyond the mere availability of broadband. Recent research has emphasised the need to differentiate between basic broadband and newer-generation broadband services in economic impact studies (Briglauer and Gugler 2019). As low-speed broadband access becomes increasingly available in most parts of the territory, cutting-edge broadband speeds are gaining importance for the competitiveness, employment and economic growth prospects.

Briglauer *et al.* (2019) studied the impact of the Bavarian government aid for broadband speed upgrades between 2010 and 2011 on promoting cohesion among the municipalities and closing the technological and economic gap between the rural and the urban areas. They concluded that the government programme did indeed improve higher speed broadband availability in rural towns in Bavaria, and that the programme impacted positively the local employment rate. However, local job creation was not significantly affected by the improvement. Hence the speed upgrade of broadband coverage seemed to have reduced de-population in rural areas but with residents working at other locations.

A recent study by Deller *et al.* (2022) examined 2014 US rural county-level data and found a positive and significant correlation between broadband speed and business start-up rates across all industry analysed. In particular, the authors found that download speeds were generally more important than upload speeds. Additionally, their results showed that start-up rates increased with speeds up to 50 Mbps, with few sectors showing stronger correlations with 100 Mbps.

We focus on ultrahigh-speed broadband (≥100 Mbps) access in rural Spain, as this is the speed that the Government aims to provide broadband to all towns in the country. It is also the speed level targeted in the European Gigabit Society strategy to be provided at universal levels by 2025.[1] According to a recent study, it is the minimum speed required for teleworking, including video calls, VPN, cloud-based software licences or the sharing of large files, especially multiple devices need to be connected simultaneously (Miami-Dade Transportation Planning Organization 2021).

DATA

Population data – Yearly data on municipality population was collected from the Municipal

Register (Padrón) provided by the National Institute of Statistics (INE) of Spain. Municipalities in Spain constitute the lowest level of administrative division and the main tier of local government. There are about 8,000 municipalities with an average size of just 62 square kilometres.

Figure 1—Panel A shows the map of municipality population growth and decline over the period 2013–20. The total population in Spain remained almost stable over this period with just a small increase in slightly over 300,000 inhabitants, equivalent to a 0.7 per cent increase. Yet the pattern of growth and decline was very uneven, and growth was concentrated in few municipalities, mostly the urban ones.

For the identification of rural municipalities, we use the definition of functional urban areas (FUAs) developed by the Organization for Economic Cooperation and Development (OECD) and Eurostat (Dijkstra *et al.* 2019). FUAs are defined as an economic unit of a densely populated urban core area and its hinterland based on the labour market and commuting relations. Urban areas are defined on the basis of continuous 1 square kilometre grid cells with a minimum density of 1,500 inhabitants and a population of at least 50,000 people. Commuting areas include all those municipalities for which at least 15 per cent commute to the city. Municipalities that neither belong to urban core areas nor to urban hinterlands are classified as rural areas. Hence, the definition of rural areas applied here does not include small municipalities in spatial continuity or within the commuting zones of larger cities. This leaves us with an estimation sample of 6,763 rural municipalities.[2] Panel B of Figure 1 blends out urban core areas and their hinterlands and shows the population change of our sample of rural municipalities. This reflects very clearly that most population growth was concentrated in and around the major urban agglomerations and along the Mediterranean coast, while most interior and rural areas suffered population decline.

Broadband data – Fixed broadband provision started to grow rapidly in Spain in the early and mid-2000s. According to the Spanish National Markets and Competition Commission (CNMC in Spanish), the number of users was less than 70,000 in 2000. However, this number grew exponentially over the following years, overpassing one million users in just 2 years and reaching 10 million users in 2010. Despite this rapid growth, over 98 per cent of internet connections still had speeds below 20 Mbps.

Several investment programmes allowed Spain to become the fastest country in Europe in developing a Fibre to the Home (FTTH) technology network, leading to a rapid increase of high-speed broadband across the territory. This fast development was in part possible thanks to the usage of already installed

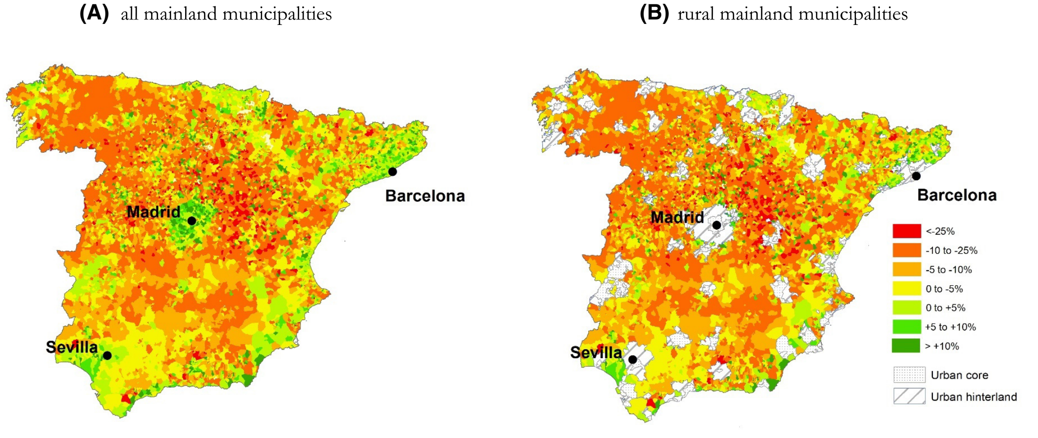

Figure 1. *Municipality population growth and decline between 2013 and 2020. (A) All mainland municipalities. (B) Rural mainland municipalities.*

civil infrastructure to expand new networks. The number of high-speed broadband lines (100 Mbps or more) increased from 1.3 million in 2014, representing 11 per cent of total lines, to 11.9 million in five years, representing more than three quarters of all lines.

According to the European Commission Digital Scoreboard (European Commission 2023), as of 2021, Spain had the highest share of 100 Mbps broadband lines (86.6 per cent) of all European countries, which is significantly above the European average of 52.2 per cent. Yet, the digital divide in Spain remains very marked. As expected, the spatial pattern of the deployment of broadband technology in Spain over the years has been significantly affected by the country's territorial distribution of population.

Our key variable of interest is the ultrahigh-speed broadband coverage of rural municipalities, where coverage is understood as the proportion of homes in the municipality that are able of having a speed above 100 Mbps (i.e. are passed by a fixed broadband technology offering this speed). This differs from the proportion of homes that have actually implemented those lines (for which we do not have available data). Broadband coverage data have been obtained for the years from 2013 to 2020 from the Ministry of Economic Matters and Technological Transition (Ministerio de Asuntos Economics y Transformación Digital). This data set specifies the coverage at 4 different speeds: ≥2 Mbps, ≥10 Mbps, ≥30 Mbps and ≥100 Mbps for all Spanish municipalities.

In 2013, only 56 per cent of population had access to broadband speeds above 100 Mbps. This increased to 88 per cent of the population in 2020 (Figure 2). In terms of spatial coverage, broadband speeds above 100 Mbps were available in less than 6 per cent of municipalities in 2013 and this increased to about 37 per cent of municipalities by 2020. Figure 3 shows the map of coverage of ultrahigh-speed broadband in 2013 and in 2020. A salient feature is that in 2013, broadband access was still mainly limited to major cities. By the 2020, the situation had improved significantly, but a lack of a narrowing of the urban–rural divide is still noticeable, especially in the northern interior regions. While there has been a very fast and strong increase in coverage during the period under analysis, there is still an important number of rural municipalities that is not covered by high-speed broadband.

Figure 4 shows the increase in ultrahigh-speed broadband coverage from 2013 to 2020 for rural and urban areas. Ultrahigh-speed broadband coverage increased strongly in both types of municipalities, but the gap between urban and rural municipalities has not closed. While at the beginning of our period, the mean coverage in rural municipalities was approximately 3 per cent compared to 22

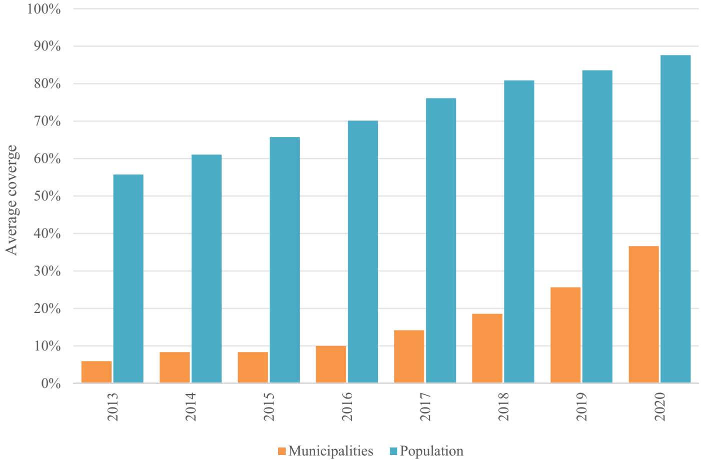

Figure 2. *Increase in broadband ≥100 Mbps coverage from 2013 to 2020.*

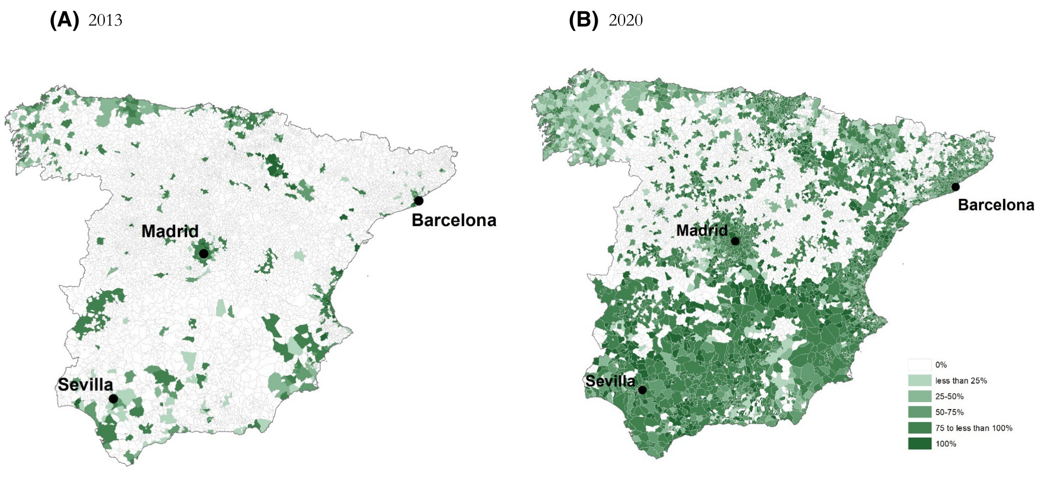

Figure 3. *Ultrahigh-speed broadband coverage ≥100 Mbps: 2013 and 2020. (A) 2013. (B) 2020.*

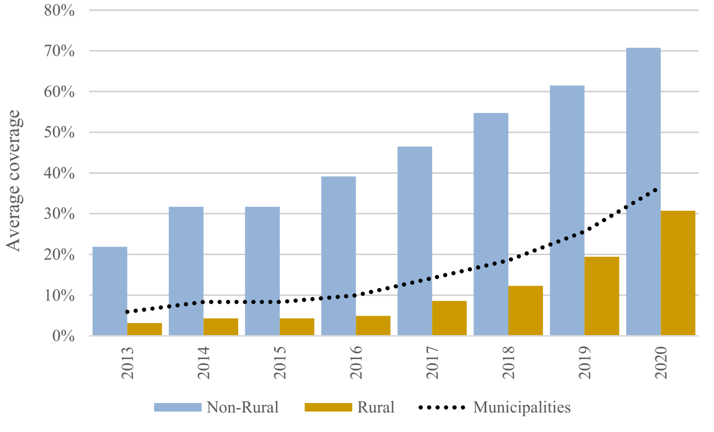

Figure 4. *Ultrahigh-speed broadband coverage from 2013 to 2020: rural areas compared with urban areas.*

per cent in urban municipalities, in 2020 the mean coverage reached 30 per cent in rural municipalities compared with 70% in urban municipalities.

Control variables – Rural municipalities with coverage of broadband speed above 100 Mbps show different traits compared to those rural municipalities without ultrahigh-speed broadband. Thus, we include a wide set of variables to control for potential confounding factors.

Socio-economic and demographic controls – The size of the local population is a crucial factor that affects the deployment of broadband, as it determines the level of demand for broadband services and also the average deployment costs. At the same time, the size of the local population can have an impact on the local population growth due to agglomeration economies. Furthermore, municipalities suffering from population ageing grow less due to falling birth rates. But controlling for population age is also important because older people use the internet to a lesser degree and lower growth translates into less future demand for broadband. However, attracting middle-age and retirement people has also been linked to higher local business start-up rates in rural areas (Deller *et al.* 2019), which could have a positive effect on the local demand for broadband. We include the municipality population and the average population age of the local population in the base year. Moreover, rural areas in Spain that have attracted foreign-born immigrants have suffered less from de-population (Collantes *et al.* 2014). Hence, we also include the share of foreign-born residents in 2011.

Education is another relevant factor, as evidence shows that a more educated population leads to higher local population growth (Faggian *et al.* 2017, among others). In the context of broadband deployment, several studies have emphasized the role of human capital for demand for broadband services but also as an important mediator for growth (Atasoy 2013; Mack and Faggian 2013; McCoy *et al.* 2018). Better-educated people potentially derive a higher utility from new broadband services, as they tend to be more intensive users (Briglauer *et al.* 2021). Moreover, education is closely linked to digital skills and the ability to take advantage of the benefits of new technologies (Mack and Faggian 2013). Hence, broadband provision could have stronger effects in retaining rural population where educational levels are higher. We include as a control variable the proportion of population with tertiary education.[3]

Employment opportunities are critical for attracting and retaining population in rural areas (Biagi *et al.* 2011; Veneri and Ruiz 2016). Municipalities with fewer job opportunities are more likely to experience out-migration to urban areas. To control for this effect, we include the number of employed people at the municipality level. We also include the share of employment in manufacturing and services, as these sectors may have different impacts on population growth and broadband demand.

Infrastructure, natural geography and history controls – Rural areas' accessibility to urban areas has been found as an important determinant of their growth potential (Partridge *et al.* 2007; Veneri and Ruiz 2016; Holl 2018). Furthermore, broadband lines tend to follow existing infrastructure, including transportation infrastructure, as this also reduces the costs of the rollout (Czernich *et al.* 2011; Kolko 2012). To account for these factors, we include the distance of the rural municipality to the nearest province capital and the length of highways that cross each municipality. We also include the percentage of homes that had already internet access in 2011 and the share of residential homes in the municipality in 2011. In addition, we include altitude, land area and distance to the coast as natural geography control variables. Finally, we control for historic population growth during the second half of the 20th century. This covers the periods of strongest rural–urban migration in Spain and is included to account for long-term population growth patterns.

Appendix Table A1 shows the definition and data sources for the explanatory variables. Table 1 shows the means of the socio-economic, demographic, geographical and historical characteristics of (a) rural municipalities that already had ultrahigh-speed broadband at the beginning of our study period, (b) rural municipalities that gained ultrahigh-speed broadband access during our study period and (c) rural municipalities that remained without access to ultrahigh-speed broadband by the end of our study period. The three groups of rural municipalities differ significantly in all characteristics and the statistics indicate that ultrahigh-speed broadband in rural areas has been concentrated in larger municipalities with a younger, more educated population and greater accessibility and those that experienced less population decline. This strongly suggest the non-random allocation of broadband infrastructure.

In addition to observable differences that influence the probability that a municipality had seen its broadband coverage improved, there could also be unobservable factors. Hence, all estimations furthermore include

Table 1. *Rural municipalities summary descriptive statistics: Mean differences.*

Variable	With UH-broadband in 2013	Gained UH-broadband between 2013 and 2020	With no UH-broadband in 2020	***F*-stat** (difference in means) & significance
% Population change 2013–20	–2.04	–5.80	–10.96	224.31***
Population in 2013 (thousands)	14.81	2.98	0.36	1692.20***
Average population age in 2013	42.48	45.29	52.57	1552.07***
Share of foreign-born residents 2011 (%)	9.25	9.37	5.46	198.05***
Percentage of working age population with tertiary education 2011	13.41	10.62	7.01	323.28***
Percentage of homes with internet access in 2011	47.88	39.48	26.18	875.94***
Share of secondary residential homes in 2011 (%)	30.23	40.15	55.30	895.17***
Local employment in 2011 (thousands)	4.68	0.87	0.09	1597.69***
Share of employed in manufacturing 2011 (%)	23.28	14.83	7.36	337.93***
Share of employed in service sector 2011 (%)	9.86	7.41	5.01	115.07***
Average annual historic population growth: 1950–2001 (%)	1.12	–0.37	–1.16	108.62***
Distance to nearest province capital	40.58	45.76	48.30	25.32***
Length of highways in 2010 (km)	19.36	10.50	6.33	280.88***
Distance to the coast (km)	47.57	97.15	162.91	649.98***
Altitude (metre)	235.7	512.0	784.09	1037.83***
Land area (square kilometre)	120.38	81.46	46.07	224.03***

Note: *** statistically significant at the 1% level.

province-fixed effects to control for regional unobserved factors.

EMPIRICAL STRATEGY

We analyse the role of broadband provision on rural population change by relating population change in municipality i over period t to our key independent variable of interest which is the percentage point change in ultrahigh-speed broadband coverage ≥100 Mbps in municipality i over period t, lagged by 1 year.

$$\Delta \log(\text{pop})_{it} = \alpha_o + \alpha_1 * \Delta(\text{UH}-\text{broadband})_{i,t-1} + a_2 X_{i,t_0} + \gamma_r + \varepsilon_i \quad (1)$$

Here, $\Delta\log(\text{pop})_{it} = \log(\text{pop}_{i2020}) - \log(\text{pop}_{i2014})$ is the change in the logarithm of population in period t (between 2014 and 2020) for municipality i. $\Delta(\text{UH-broadband})_{i,t\text{-}1}$ is the 1 year lagged dependent variable defined as the change in the percentage of ultrahigh-speed broadband coverage between 2013 and 2019 for municipality i. $X_{i,t0}$ is a vector of base year municipality i characteristics measuring fixed and persistent local factors, and γ_r are regional fixed effects at the level of provinces. εi is the usual standard error. Identification comes from variation across municipalities within provinces.

This specification may, however, suffer from various sources of endogeneity. Reverse causality issues could arise from the non-random allocation of broadband infrastructure. Providers tend to develop broadband where they expect to receive economic benefits, which depend on the local demand and the cost of rollout, and hence, the size of the local population. In addition, endogeneity may also arise due to government subsidy programmes aimed at bringing broadband to rural, sparsely populated areas.[4] However, within the framework of such programmes, private providers will still pick the most desirable locations from the list of targeted areas. Moreover, omitted variable bias could also cause endogeneity as rural areas experiencing population growth may have received other services and infrastructures besides broadband connections. Therefore, to isolate the causal effect of the improvements in ultrahigh-speed broadband coverage on population change from other confounding factors, we employ an instrumental variables (IV) estimation approach.

Instrumental variables – Difficult topography can challenge the rollout of broadband infrastructure, as it increases the rollout costs (Kolko 2012). For instance, more rugged terrain requires more infrastructure for broadband deployment via cables buried in the ground, or via waves which then requires more transmission masts. However, topographic variables such as slope and terrain ruggedness have also been shown to be related directly to local population growth (see e.g. Burchfield *et al.* 2006, or Holl 2019, for the case of Spain) and local business creation (Stephens *et al.* 2022) and hence may not necessarily meet the exogeneity condition. To ensure that our instruments are relevant to the increase in ultrahigh-speed broadband provision but do not have a direct effect on local population growth, we focus on the topographical features surrounding the population entities of rural municipalities. By bringing broadband to the population entities of a given municipality, the infrastructure has to traverse nearby areas and the topographical features of these areas can affect the cost of broadband installation. Based on the Spanish national digital terrain model (MDT200), we calculate the Riley *et al.* (1999) index of terrain ruggedness for 750 m grid cells. We exclude from our measure all grid cells falling within a radius of 3 kilometres distance from rural population entities. This makes our terrain ruggedness instrument less likely to fail the exclusion restriction. Nevertheless, all our estimations do include a wide number of additional controls that account for potential effects of ruggedness beyond its direct effect on broadband provision and hence we are confident that the instrument is uncorrelated with the error term.

In robustness checks, we test the sensitivity of our results to alternative instrument specifications. Installations are especially costly in remote areas far from urban centres but can be facilitated where those areas are crossed by existing infrastructure such as transport corridors. Such corridors show path dependency and here we exploit the layout of ancient Roman roads. Garcia-López *et al.* (2015) and Holl (2016) have shown how Roman roads still relate to modern transport corridors in Spain. There are two features of Roman road construction that imply that they can still relate to the present day's costs of broadband installation in rural areas. First, Romans aimed to take whenever possible the straightest path between two locations. Thus, rural municipalities located within or close to Roman road corridors imply less length of infrastructure installation. Second, Roman engineers were very knowledgeable about diverse landscape conditions. Beyond slope gradients, they took into account soil conditions to avoid difficult terrains whenever possible. Such soil conditions can also make the installation of telecommunication network infrastructure more costly and hence influence the layout of broadband infrastructure. Finally, within transport corridors rights of way can be shared.[5] This allows broadband providers to expand their networks more efficiently and cost-effectively. As an alternative instrument, we hence use the distance of each municipality to the nearest Roman road based on the digital vector maps developed in Holl (2016) and based on Carreras and de Soto (2010).

The rollout of broadband is furthermore affected by the existing copper telephone network. On the one hand, the cost of installing fibre optics cables is much lower when existing conduits of copper cabling can be used without the need to open new trenches or install new posts. This is a relevant issue in the case of Spain, where fibre cables could be installed in many areas using the existing civil infrastructure. On the other hand, the rollout of fibre cables is also influenced by operators' incentives to retire the copper network. Copper networks are expensive to maintain and by covering entire zones (even if some villages within those areas may not meet demand criteria for provision), operators do not have to keep the old technologies running. This allows them to the switch off the copper network in those areas, saving costs and selling old copper cables. As a third instrument, we test the interaction between the distance to the Roman road network and the percentage of households covered in the municipalities by traditional copper telephone lines in 1991.

RESULTS

Table 2 reports OLS results when we regress the population change between 2014 and

Table 2. *OLS results: Ultrahigh-speed broadband effects on rural population change.*

	2014–20 Δ log(population)		
	(1)	(2)	(3)
Δ *Ultrahigh-speed broadband (2013–19)*	0.020***	0.010**	0.007**
	(0.004)	(0.004)	(0.003)
2013 log(population)	Y	Y	Y
Socio-economic & demographic controls			Y
Geographic & historic controls		Y	Y
Regional fixed effects	Y	Y	Y
Observations	6713	6713	6457
R-squared	0.183	0.220	0.307

Note: (1) Robust standard errors in parenthesis; *p*-values in brackets; ***, ** and * = statistically significant at the 1, 5 and 10% levels. (2) Controls include: (a) Socio-economic & demographic controls: *2011 average population age, 2011 share of foreign-born residents, 2011 % tertiary education, 2011 % homes with internet access, 2011 share of secondary residential homes, 2011 local employment*; *2011 share of employed in manufacturing, 2011 share of employed in services* (b) Geography & historic controls: *historic population growth (1950–2001), distance to province capital, Length of highways in 2010, distance to the coast, altitude, land area.*

2020 on the percentage increase in ultrahigh-speed broadband coverage. In column 1, estimations include only our main variable of interest, base year population and unreported province-fixed effects. The results suggest a positive relationship between the increase in ultrahigh-speed broadband coverage and rural population growth. In Column 2, we add geographical and historical controls. The coefficient of our broadband variable remains significant but is halved in size. In Column 3, we further add socio-economic controls, which again significantly weakens the estimated coefficient of ultrahigh-speed broadband. This suggests a spurious relationship between ultrahigh-speed broadband and local population growth, underscoring the importance of controlling for a broad set of potentially confounding factors related to geography, history, as well as socio-economic and demographic factors.

Full OLS estimation results can be found in Appendix Table A2. These results show that nearly all control variables included are statistically significant, with the exception of sectoral employment shares, distance to the coast and land area. The factors most strongly related to rural population decline are population ageing, lack of employment opportunities and poor access to highways. The literature suggests that broadband can matter more in areas with higher levels of human capital. To explore this possibility, we included the interaction between our human capital variable and the broadband term. The interaction term is not significant, and both the human capital variable and the broadband variable lose significance. Alternatively, we tested an interaction between our population age variable and the broadband variable. In this case, the interaction term is significant at the 5 per cent level and does indicate that municipalities with an older population tend to show a weaker impact of broadband improvements on local population growth.[6]

However, the relationship between ultrahigh-speed broadband and local population growth could suffer from endogeneity issues. To address this, we turn to instrumental variable estimations. Appendix Table Table B1 contains our first-stage regression results that show that our instruments are not weak. Table 3 presents our main TSLS results. In line with our OLS benchmark estimation, column 1 only includes base year population and unreported province-fixed effects as controls, along with our main variable of interest. The coefficient for the increase in ultrahigh-speed broadband coverage is positive and significant. However, the estimated coefficient is suspiciously high, suggesting a strong upward bias stemming from omitted variables. In column 2, we add our geographic and historical controls. The coefficient of the increase in ultrahigh-speed broadband turns insignificant. In column 3, we add all socio-economic and demographic control variables. Again, we find that ultrahigh-speed broadband coverage has no significant causal effect on rural population growth. In columns 4 to 6, we use the alternative instrument specifications. In none of these regressions is the increase in ultrahigh-speed broadband coverage statistically significant. Again, we have also tested for the possibility that broadband effects are moderated by local human capital, but the interaction term is not significant and neither is the broadband term in the IV estimations. With the population age variable, we also obtain an interaction term that is not significant and a broadband term that continues to be insignificant.[7]

CONCLUSIONS

Rural de-population has become a top priority on the Spanish policy agenda. The government has taken steps to combat the loss of rural population by implementing aid packages, including a commitment to provide ultrahigh-speed broadband of over 100 megabits per second to the entire country by 2025.

While the provision of ultrahigh-speed broadband can enhance the quality of life in rural areas, it is crucial to study the causal relationship between broadband coverage and population growth or decline. Despite a significant increase in ultrahigh-speed broadband coverage in rural areas over the last decade, rural areas still lag behind urban areas. However, assessing the relationship between ultrahigh-speed broadband and rural population growth and decline is challenged by the strong endogeneity of broadband provision.

Table 3. *TSLS results: Ultrahigh-speed broadband effects on rural population change.*

	2014–20 Δ log(population)					
	(1)	(2)	(3)	(4)	(5)	(6)
Δ *Ultrahigh-speed broadband (2013–19)*	0.245***	−0.083	−0.022	−0.084	−0.040	0.003
	(0.053)	(0.063)	(0.071)	(0.106)	(0.063)	(0.60)
Instruments						
Ruggedness	Y	Y	Y		Y	Y
Distance Roman roads (Rom)				Y	Y	
Rom#1991 telephone lines						Y
Controls						
2013 log(population)	Y	Y	Y	Y	Y	Y
Socio-economic & demographic controls			Y	Y	Y	Y
Geographic & historic controls		Y	Y	Y	Y	Y
Regional fixed effects	Y	Y	Y	Y	Y	Y
Observations	6713	6713	6457	6457	6457	6449
First-stage stat.	67.9	38.6	23.9	12.7	15.8	18.2
Overid. *p*-value					0.60	0.59

Note: (1) Robust standard errors in parenthesis; *p*-values in brackets; ***, ** and * = statistically significant at the 1, 5 and 10% levels. (2) Controls include: (a) Socio-economic & demographic controls: *2011 average population age, 2011 share of foreign-born residents, 2011% tertiary education, 2011% homes with internet access, 2011 share of secondary residential homes, 2011 local employment; 2011 share of employed in manufacturing, 2011 share of employed in services* (b) Geography & historic controls: *historic population growth (1950–2001), distance to province capital, Length of highways in 2010, distance to the coast, altitude, land area.*

Our research indicates that, after accounting for endogeneity, ultrahigh-speed broadband improvements do not causally affect rural population change. These findings have important implications for policy. Policy-makers in rural areas often consider better connections as a key measure to address de-population. While universal broadband provision can be a policy justified to reduce inequalities in access to basic services between rural and urban areas, its effectiveness as a policy tool to combat rural de-population requires careful examination.

Broadband availability alone is unable to change the fate of rural areas. Studies have emphasised that adoption is more important as a driver of economic growth (Whitacre *et al.* 2014; Abrardi and Cambini 2019). However, increasing availability does not necessarily lead to higher adoption rates, especially in rural areas where take-up rates tend to be lower. Achieving widespread adoption requires a skilled and educated population and a dynamic economic environment that is able to take advantage of broadband. These are all key factors that contribute to the resilience and adaptability of peripheral areas (De Renzis *et al.* 2022). Therefore, rural policies should prioritise initiatives that promote digital literacy and skills development. Furthermore, supporting the digitalization of small and medium-sized enterprises in rural areas can help create a more dynamic economic environment capable of leveraging the potential of broadband infrastructure in transitioning to Industry 4.0 (Norris 2020; Holl and Rama 2023).

Our research is not without limitations. Although we have analysed the relationship between ultrahigh-speed broadband coverage and population change in rural areas from 2013 to 2020, it is important to note that some of the impacts of improved broadband may take longer to materialise due to the slow mobility of households. There is, therefore, a need for further research to examine the long-term impacts of ultrahigh-speed broadband coverage on rural population change. This may require the use of alternative estimation methods to capture the potential delayed effects. Additionally, given the transformative effects of the COVID-19 pandemic on teleworking and digital reliance, further research should specifically focus on how lockdowns and teleworking during the pandemic have influenced the importance of broadband for rural population growth and development. COVID-19 and the rise of teleworking could well have heightened the importance of broadband for rural population growth since the pandemic.

Our empirical analysis has controlled for a diverse set of socio-economic, demographic, geographical and historical characteristics of rural municipalities. However, the list is not exhaustive and other potential local factors should be studied in future research. While we are also confident that terrain ruggedness in the surroundings of the municipality is a valid and strong instrument, further research should also be conducted to test the robustness of our findings to alternative instrumental variable specifications. For example, it would be worth exploring subsidies for broadband provision.

There are several important additional directions for future work. First, local differences in retail broadband prices might also matter and this should be considered in future research, as affordability remains a significant barrier to digital inclusion. Understanding the impact of varying prices on broadband adoption and usage patterns can help inform policy interventions aimed at improving access to affordable high-speed internet services in rural areas.

Second, there is also a need to gain a better understanding of how access to high-speed internet affects various social and economic outcomes, such as education, health care, employment and community development. Such insights can inform targeted interventions to address the specific needs of rural communities.

Third, future research should also examine the role of local and regional governance and community-based organisations in promoting digital inclusion. Better knowledge about the challenges faced by marginalised communities, such as low-income individuals, elderly populations or people with disabilities, in accessing and utilising high-speed internet services is necessary to explore strategies for promoting digital inclusion and bridging the digital divide for vulnerable groups in rural areas.

Fourth, more research is needed on the role of broadband infrastructure in enabling smart agriculture practices, precision farming and rural industries' digital transformation. High-speed internet connectivity could enhance agricultural productivity, supply chain efficiency and economic diversification and can therefore have important implication for rural development. Similarly, it will be important to analyse the potential for innovation and entrepreneurship driven by broadband-enabled technologies in agricultural and rural sectors.

Fifth, another important topic for future research is to study the interactions and synergies between broadband infrastructure and transportation infrastructure in local development. This can inform comprehensive strategies to overcome the challenges associated with geographic isolation.

Finally, it will require research from different disciplines to gain a comprehensive and nuanced knowledge that can inform policy-makers and other stakeholders on the most effective ways to promote sustainable rural development in the digital age. It will also be important to assess the outcomes and impacts of broadband policies across different countries or regions to identify best practices, lessons learned and policy transferability for sustainable rural development.

ACKNOWLEDGEMENT

Adelheid Holl gratefully acknowledges project PLEC2021-007750 – MCIN/AEI /10.13039/501100011033 and European Union NextGenerationEU/PRTR, project H2019/HUM-5859-MIMA-CM financed by the Autonomous Community of Madrid and the PTI Mobility 2030 (https://pti-mobility2030.csic.es/).

Endnotes

1 The Broadband Coverage in Europe study specifically monitors progress towards the universal broadband coverage objective of providing internet with speeds at least 100 Mbps by 2025. https://digital-strategy.ec.europa.eu/en/library/broadband-coverage-europe-2021.

2 In robustness checks, we have used the Spanish Government's definition of rural municipalities: that is those municipalities whose density of population is lower than 100 inhabitants per square kilometre and which have a total population of fewer than 30,000 inhabitants. Results are qualitatively highly similar and available upon request.

3 Tertiary education in Spain refers to higher education and includes bachelor's degrees, master's degrees and doctoral degrees.

4 Spain has developed important subsidy programmes to bridge the digital divide and extend the coverage of telecommunication services to rural areas. In 2008, the government launched the Avanza Infraestructuras programme, which targeted the so-called 'white' spots (areas with no broadband provider and with no private investors being expected to cover those areas in the next 3 years). This programme was extended in 2019 with a budget of €400 million to run from 2020 to 2022. Furthermore, the current Next Generation EU funds will allocate an important share to the funding of the digitalization of rural areas.

5 Rights of way refers to the legal right to pass through land/property in order to construct, maintain or upgrade infrastructure.

6 These unreported results are available upon request.

7 These unreported results are available upon request.

REFERENCES

Abrardi, L. & C. Cambini (2019), Ultra-Fast Broadband Investment and Adoption: A survey. *Telecommunications Policy* 43(3), pp. 183–198.

Atasoy, H. (2013), The Effects of Broadband Internet Expansion on Labor Market Outcomes. *Industrial and Labor Relations Review* 66(2), pp. 315–345.

Banco de España (2020), Informe Anual. Capitulo 4: La distribución espacial de la población en España y sus implicaciones económicas.

Bertschek, I., W. Briglauer, K. Hüschelrath, B. Kauf & T. Niebel (2016), The Economic Impacts of Telecommunications Networks and Broadband Internet: A Survey. *Review of Network Economics* 14, pp. 201–227.

Biagi, B., A. Faggian & P. McCann (2011), Long and Short Distance Migration in Italy: The Role of Economic, Social and Environmental Characteristics. *Spatial Economic Analysis* 6(1), pp. 111–131.

Briglauer, W., N.S. Dürr, O. Falck & K. Hüschelrath (2019), Does State Aid for Broadband Deployment in Rural Areas Close the Digital and Economic Divide? *Information Economics and Policy* 46, pp. 68–85.

Briglauer, W., N. Dürr & K. Gugler (2021), A Retrospective Study on the Regional Benefits and Spillover Effects of High-Speed Broadband Networks: Evidence from German Counties. *International Journal of Industrial Organization* 74, 102677.

Briglauer, W. & K. Gugler (2019), Go for Gigabit? First Evidence on Economic Benefits of High-Speed Broadband Technologies in Europe. *Journal of Common Market Studies* 57(5), pp. 1071–1090.

Burchfield, M., H.G. Overman, D. Puga & M. Turner (2006), Causes of Sprawl: A Portrait from Space. *Quarterly Journal of Economics* 121, pp. 587–633.

Carreras, C. & P. de Soto (2010), *Historia de la movilidad en la península ibérica: Redes de transporte en SIG*, Barcelona, Spain: Editorial UOC.

Collantes, F., V. Pinilla, L.A. Sáez & J. Silvestre (2014), Reducing Depopulation in Rural Spain: The Impact of Immigration. *Population, Space and Place* 20(7), pp. 606–621.

Conroy, T. & S.A. Low (2022), Entrepreneurship, Broadband, and Gender: Evidence from Establishment Births in Rural America. *International Regional Science Review* 45(1), pp. 3–35.

Crandall, R., Lehr, W. & Litan, R. (2007), *The Effects of Broadband Deployment on Output and Employment: A Cross-Sectional Analysis of US Data, Issues in Economic Policy, No. 6*, Washington, DC: The Brookings Institution.

Czernich, N. (2014), Does Broadband Internet Reduce the Unemployment Rate? Evidence for Germany. *Information Economics and Policy* 29, pp. 32–45.

Czernich, N., O. Falck, T. Kretschmer & L. Woessmann (2011), Broadband Infrastructure and Economic Growth. *Economic Journal* 121(552), pp. 505–532.

De Renzis, A., A. Faggian & G. Urso (2022), Distant but Vibrant Places. Local Determinants of Adaptability to Peripherality. *Tijdschrift voor economische en sociale geografie* 113(5), pp. 483–501.

Deller, S., M. Kures & T. Conroy (2019), Rural Entrepreneurship and Migration. *Journal of Rural Studies* 66, pp. 30–42.

Deller, S. & B. Whitacre (2019), Broadband's Relationship to Rural Housing Values. *Papers in Regional Science* 98(5), pp. 2135–2156.

Deller, S., B. Whitacre & T. Conroy (2022), Rural Broadband Speeds and Business Startup Rates. *American Journal of Agricultural Economics* 104(3), pp. 999–1025.

Dijkstra, L., H. Poelman & P. Veneri (2019), *The EU-OECD Definition of a Functional Urban Area*, OECD Regional Development Working Papers, No. 2019/11, Paris: OECD Publishing.

Duvivier, C., E. Cazou, S. Truchet-Aznar, C. Brunelle & J. Dubé (2021), When, Where, and for What Industries does Broadband Foster Establishment Births? *Papers in Regional Science* 100(6), pp. 1377–1401.

European Commission (2014), *Digital Agenda for Europe: Rebooting Europe's economy*, Brussels: Publications Office of the EU.

European Commission (2016), *Connectivity for a Competitive Digital Single Market – Towards a European Gigabit Society, COM(2016) 587 final*, Brussels. 14 September 2016, https://digital-strategy.ec.europa.eu/en/library/communication-connectivity-competitive-digital-single-market-towards-european-gigabit-society.

European Commission (2020), *Broadband Coverage in Europe 2019'*, Luxemburg: Publications Office of the EU. Available at <https://wayback.archive-it.org/12090/20210827215258/https://digital-strategy.ec.europa.eu/en/related-content?topic=132>.

European Commission (2023), Digital Scoreboard: Share of Fixed Broadband Subscriptions. Available at <https://digital-agenda-data.eu/>.

Faggian, A., M. Partridge & E.J. Malecki (2017), Creating an Environment for Economic Growth: Creativity, Entrepreneurship or Human Capital? *International Journal of Urban and Regional Research* 41(6), pp. 997–1009.

Forman, C., A. Goldfarb & S. Greenstein (2012), The Internet and Local Wages: A Puzzle. *American Economic Review* 102(1), pp. 556–575.

Fundación BBVA and Ivie (2015), Series homogéneas de población 1900–2011 (noviembre 2015). Available at <https://www.fbbva.es/bd/cambios-la-estructura-localizacion-la-poblacion-series-homogeneas-1900-2011/>.

Garcia-López, M.À., A. Holl & E. Viladecans-Marsal (2015), Suburbanization and Highways in Spain when the Romans and the Bourbons Still Shape its Cities. *Journal of Urban Economics* 85, pp. 52–67.

Glaeser, E.L. (1998), Are Cities Dying? *Journal of Economic Perspectives* 12(2), pp. 139–160.

Gobierno de España (2021), Recovery, Transformation and Resilience Plan.

Hindman, D.B. (2000), The Rural-Urban Digital Divide. *Journalism & Mass Communication Quarterly* 77(3), pp. 549–560.

Holl, A. (2016), Highways and Productivity in Manufacturing Firms. *Journal of Urban Economics* 93, pp. 131–151.

Holl, A. (2018), Local Employment Growth Patterns and the Great Recession: The Case of Spain. *Journal of Regional Science* 58(4), pp. 837–863.

Holl, A. (2019), Natural Geography and Patterns of Local Population Growth and Decline in Spain: 1960–2011. *Sustainability* 11(18), 4979.

Holl, A. & R. Rama (2023), Spatial patterns and drivers of SME digitalization. *Journal of the Knowledge Economy*. https://link.springer.com/article/10.1007/s13132-023-01257-1

Kandilov, I.T. & M. Renkow (2010), Infrastructure Investment and Rural Economic Development: An Evaluation of USDA's Broadband Loan Program. *Growth and Change* 41(2), pp. 165–191.

Kim, Y. & P.F. Orazem (2017), Broadband Internet and New Firm Location Decisions in Rural Areas. *American Journal of Agricultural Economics* 99(1), pp. 1–18.

Kolko, J. (2012), Broadband and Local Growth. *Journal of Urban Economics* 71(1), pp. 100–113.

Li, Y. & R. Mora (2022), On the Use of Social Networking Services and the Ability to Socialize: Evidence from Chinese Children Aged 10 to 15. *Applied Economics* 54(49), pp. 5639–5654.

Mack, E. & A. Faggian (2013), Productivity and Broadband: The Human Factor. *International Regional Science Review* 36(3), pp. 392–423.

Mack, E.A. & T.H. Grubesic (2009), Broadband Provision and Firm Location in Ohio: An Exploratory Spatial Analysis. *Tijdschrift voor economische en sociale geografie* 100(3), pp. 298–315.

Mahasuweerachai, P., B.E. Whitacre & D.W. Shideler (2010), Does Broadband Access Impact Migration in America? Examining Differences between Rural and Urban Areas. *Review of Regional Studies* 40(1), pp. 5–26.

McCoy, D., S. Lyons, E. Morgenroth, D. Palcic & L. Allen (2018), The Impact of Broadband and Other Infrastructure on the Location of New Business Establishments. *Journal of Regional Science* 58(3), pp. 509–534.

Miami-Dade Transportation Planning Organization (2021), Miami-Dade TPO Teleccomute Study.

Ministerio de Asuntos Económicos y Transformación Digital (2021), Informe cobertura banda ancha a 30 de junio de 2020.

Norris, L. (2020), The Spatial Implications of Rural Business Digitalization: Case Studies from Wales. *Regional Studies, Regional Science* 7(1), pp. 499–510.

Parker, E.B. (2000), Closing the Digital Divide in Rural America. *Telecommunications Policy* 24(4), pp. 281–290.

Partridge, M.R., D. Bollman, M. Rose Olfert & A. Alasia (2007), Riding the Wave of Urban Growth in the Countryside: Spread, Backwash, or Stagnation? *Land Economics* 83(2), pp. 128–152.

Prieger, J.E. (2003), The Supply Side of the Digital Divide: Is there Equal Availability in the Broadband Internet Access Market? *Economic Inquiry* 41(2), pp. 346–363.

Prieger, J.E. (2013), The Broadband Digital Divide and the Economic Benefits of Mobile Broadband for Rural Areas. *Telecommunications Policy* 37(6–7), pp. 483–502.

Reddick, C.G., R. Enriquez, R.J. Harris & B. Sharma (2020), Determinants of Broadband Access and Affordability: An Analysis of a Community Survey on the Digital Divide. *Cities* 106, 102904.

Riley, S.J., S.D. De Gloria & R. Elliot (1999), A Terrain Ruggedness Index that Quantifies Topographic Heterogeneity. *Intermountain Journal of Science* 5(4), pp. 23–27.

Salemink, K., D. Strijker & G. Bosworth (2017), Rural Development in the Digital Age: A Systematic Literature Review on Unequal ICT Availability, Adoption, and Use in Rural Areas. *Journal of Rural Studies* 54, pp. 360–371.

Stephens, H.M., Mack, E.A. & Mann, J. (2022). Broadband and entrepreneurship: An empirical assessment of the connection between broadband availability and new business activity across the United States. *Telematics and Informatics* 74, pp. 101873.

Townsend, L., A. Sathiaseelan, G. Fairhurst & C. Wallace (2013), Enhanced Broadband Access as a Solution to the Social and Economic Problems of the Rural Digital Divide. *Local Economy* 28(6), pp. 580–595.

Tranos, E. & E.A. Mack (2016), Broadband Provision and Knowledge-Intensive Firms: A

Causal Relationship? *Regional Studies* 50(7), pp. 1113–1126.

Veneri, P. & V. Ruiz (2016), Urban-to-Rural Population Growth Linkages: Evidence from OECD TL3 Regions. *Journal of Regional Science* 56(1), pp. 3–24.

de Vos, D., U. Lindgren, M. van Ham & E. Meijers (2020), Does Broadband Internet Allow Cities to 'Borrow Size'? Evidence from the Swedish Labour Market. *Regional Studies* 54(9), pp. 1175–1186.

Whitacre, B., R. Gallardo & S. Strover (2014), Does Rural Broadband Impact Jobs and Income? Evidence from Spatial and First-Differenced Regressions. *The Annals of Regional Science* 53(3), pp. 649–670.

Williams, F., L. Philip, J. Farrington & G. Fairhurst (2016), 'Digital by Default' and the 'Hard to Reach': Exploring Solutions to Digital Exclusion in Remote Rural Areas. *Local Economy* 31(7), pp. 757–777.

Wu, S., P. Wang & B. Sun (2022), Can the Internet Narrow Regional Economic Disparities? *Regional Studies* 56(2), pp. 324–337.

APPENDIX A

Table A1. *Variable definitions and data sources.*

Variables	Definitions and data sources
Δlog (population)	log(population 2020)-log(population 2014); INE; Padrón Municipal
log (population 2013)	INE; Padrón Municipal
Δ *Ultra-high-speed broadband*	% of coverage 2019 - % of coverage 2013; where coverage =% of homes passed by fixed broadband lines offering 100 Mbps or more; Ministry of Economic Affairs and Digital Transformation
Controls	
Socioeconomic & demographic controls	
Average population age	Average age of residents; Census 2011
Share of foreign-born residents	% of foreign population in total municipality population; Padron 2011
Share of tertiary education	% of population with a higher education degree in total municipality population; Census 2011
Local employment (log)	2011 Social Security Data
Share employed in manufacturing	2011 Social Security Data
Share employed in services	2011 Social Security Data
% homes with internet access	Census 2011
% secondary residential homes	Census 2011
Geographic & historic controls	
Distance to province capital (km)	GIS, own calculation
Length of highways (km)	Own calculation for the year 2010 based on Holl (2011)
Altitude (in 100 m units)	National Geographic Institute
Land area (square km)	National Geographic Institute
Distance to the coast (km)	GIS, own calculation
Historic population growth (1950–2001)	Log(population 2001)-log(population 1950)/51; Fundación BBVA and IVIE (2015); decennial population data from 1950 to 2001
Instruments	
Terrain ruggedness	Terrain ruggedness index: see Riley *et al.* (1999). GIS's calculation is based on National Geographic Institute data; 750 m grid cell size
Distance Roman roads (Rom)	GIS, own calculation, based on Carreras and de Soto (2010) and Holl (2016)

Table A2. *Full OLS results: Ultrahigh-speed broadband effects on rural population change.*

	2014–2020 Δ log(population)		
Variables	(1)	(2)	(3)
Δ ultrahigh broadband 2013–2019	0.020***	0.010***	0.007**
	(0.004)	(0.004)	(0.003)
log (population 2013)	0.014***	0.001	–0.026***
	(0.001)	(0.002)	(0.004)
Average population age 2011			–0.006***
			(0.001)
% foreign born residents 2011			–0.002***
			(0.000)
% tertiary education 2011			0.050*
			(0.031)
% homes with internet access 2011			0.081***
			(0.017)
%f secondary residential homes 2011			0.0005***
			(0.000)
(log) local employment 2011			0.020***
			(0.004)
% employed in manufacturing 2011			–0.000
			(0.000)
% employed in services 2011			0.000
			(0.000)
Historic population growth (1950–2001)		1.494***	0.526**
		(0.220)	(0.212)
Distance to province capital (km)		–0.001***	–0.0003***
		(0.000)	(0.000)
Length of highways in 2010 (km)		0.001***	0.001***
		(0.000)	(0.000)
Distance to the coast (km)		–0.000	0.0001
		(0.000)	(0.000)
Altitude		0.000	–0.00001**
		(0.000)	(0.000)
Land area		0.000	0.000
		(0.000)	(0.000)
Observations	6,713	6,713	6,457
R-squared	0.183	0.220	0.307

Note: Robust standard errors in parentheses.
$^{***}p < 0.01$,
$^{**}p < 0.05$,
$^{*}p < 0.1$.

Appendix B

Table B1 show the first-stage regression results. In column 1 to 3 we use our terrain ruggedness instrument. The terrain ruggedness measure is negatively and statistically significantly related to the increase in ultrahigh-speed broadband coverage. Conditional on our controls that account for differences in demand for broadband, the results confirm that coverage increased less in more difficult terrains as this increases the cost to roll-out the necessary infrastructure. Overall, the first stage regressions show a high R^2 and a high F-statistic even when we include the full set of control variables. In column 4 we use the distance to Roman roads as instrument. Distance to Roman roads is also negatively and significantly related to higher growth in ultrahigh-speed broadband coverage. First-stage results, hence, indicate that Roman roads do predict increases in ultrahigh-speed broadband with a first-stage F-statistic above the commonly suggested thresholds. In column 5 we include the terrain ruggedness instrument together with the Roman roads instrument. Both instruments show a negative and statistically significant relationship with ultrahigh-speed broadband coverage increases and pass the overidentification test. In column 6 we include the terrain ruggedness instrument together with the interaction of Roman road distance and the share of households with telephone lines in 1991. Again, both instruments are negative and statistically significant and pass the overidentification test.

Table B1. *First stage regressions.*

	2013–2019 Δ log(Ultrahigh-speed broad band)					
	(1)	(2)	(3)	(4)	(5)	(6)
Ruggedness	−0.007***	−0.006***	−0.005***		−0.005***	−0.005***
	(0.001)	(0.001)	(0.001)		(0.001)	(0.001)
Distance Roman roads (Rom)				−0.077***	−0.060***	
				(0.001)	(0.021)	
Rom#1991 telephone lines						−0.001***
						(0.0003)
2013 log(population)	0.077***	0.056***	0.061***	0.057***	0.060***	0.060***
	(0.003)	(0.005)	(0.009)	(0.009)	(0.009)	(0.010)
Socioeconomic & demographic controls			Y	Y	Y	Y
Geographic & historic controls		Y	Y	Y	Y	Y
Regional fixed effects	Y	Y	Y	Y	Y	Y
Observations	6,713	6,713	6,457	6,457	6,457	6,449
Centered R-squared	0.351	0.356	0.367	0.366	0.368	0.367
First-stage stat.	67.9	38.6	23.9	12.7	15.8	18.2
Overid. *p*-value					0.60	0.59

Notes: (1) Robust standard errors in parenthesis; p-values in brackets; ***, ** & * = statistically significant at the 1, 5 and 10% levels. (2) Controls include: (a) Socioeconomic & demographic controls: *2011 average population age, 2011 share of foreign-born residents, 2011 % tertiary education, 2011 % homes with internet access, 2011share of secondary residential homes, 2011 local employment*; *2011 share of employed in manufacturing, 2011 share of employed in services* (b) Geography & historic controls*: historic population growth (1950-2001)*, *distance to province capital, Length of highways in 2010, distance to the coast, altitude, land area.*