On the regional impact of broadband on productivity: the case of Brazil

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Abstract

This paper analyses the incidence of broadband on regional productivity in Brazil, intending to find out if the economic impact is uniform across all territories of the country. The possibility of performing a regional approach to test the effect of broadband on productivity in an emerging country represents a novelty for the literature. Results suggest that the impact of broadband on productivity is positive although not uniform across regions. On the one hand, it seems to depend on connection quality and network effects. Faster download speed and critical-mass accounting for network externalities in the region enhance the economic impact of broadband. On the other hand, higher productivity gains are estimated for the less developed regions. The fact that the less productive regions in Brazil seem to be benefiting more from broadband may suggest that it can constitute a factor favoring regional convergence in the country.

JEL Classification: O33, O47, R11

Keywords: Broadband; ICT; Productivity

1. Introduction

Information and Communication Technologies (ICT) in general, and broadband in particular, have been extensively studied in the economic literature as a potential source for raising employment, income and economic activity. There are, however, some important gaps in the literature that remain unfilled and that motivate the present research.

In the first place, most of the evidence on the impact of broadband on output and productivity has been obtained so far from samples of countries. Although it is true that several studies have analyzed the effect of broadband availability and adoption on local or regional economies, these studies have focused on the impact on labor market outcomes (employment, wages), wealth (median income, poverty rates), and the business demography (number of new establishments, sales turnover). By contrast, evidence on the effect of broadband on productivity at a subnational level is rather scarce.

When exploring the effect of broadband at the subnational level, it is key to understand if broadband has a uniform impact on productivity across the regions of a country. If it is found that the impact of broadband on productivity differs territorially within a country, the question that must be answered is why some regions can extract more productivity spillovers from technology than others. The impact of broadband on productivity may depend on a variety of regional attributes, such as the quality of its infrastructures, the presence of network externalities, and the level of development, among others.

The possibility of working at a regional scale provides some advantages. Country-level analysis is usually affected by important heterogeneities across countries in terms of institutions, culture, regulations, etc. Even if some of these heterogeneities are time-invariant (and as a result can be tackled by country fixed effects), others may vary over time. In contrast to the country-level approach, a regional analysis provides a more homogeneous framework to get rid of those potential heterogeneities and, as a result, allows the impact of broadband on productivity to be measured more accurately.

To find out if there are differences in the regional productivity impact of broadband, additional factors should be considered as potential enablers, like connection quality and critical-mass externalities. The possibility of getting homogeneous data on download speeds provides the possibility of considering quality differentials in network infrastructures across regions. A question that motivates this approach is to find out if continuous improvements in speed levels of current connections should also be a priority for operators and policy-makers, along with universalization.

The studies carried out so far that analyze the impact of differences between or within countries on the availability and adoption of broadband share a common characteristic: they focus almost exclusively on the most developed economies, analyzing in detail the case of the United States. By contrast, the effect of the availability and adoption of advanced Internet technologies in emerging and developing countries is still rather scarce. This paper aims to contribute to fill this gap by considering the case of the Brazilian regional economies. Brazil is an emerging country which has reached important economic growth over the last decades, prior to the recent political turmoils. Since 2000, the country has been able to reduce significantly the levels of poverty, combining social policies with economic growth in most of those years. As a result of its potentiality, Brazil has been classified as one of the BRICs (the others being Russia, India and China). A key of this process was the openness of its economy for foreign investment. Since the nineties, when many state industries were privatized, the presence of Brazilian multinationals in the world has grown considerably as well. Its entrance onto the world stage has been reinforced by the high-profile international events hosted by the country: the football World Cup in 2014, and the Rio de Janeiro Olympic Games in 2016. However, despite recent advances, Brazil is still one of the most unequal countries in the world, exhibiting important disparities across its regions, including the deployment and adoption of broadband. As a result, public policies which may promote a reduction of those disparities should be at the top of the agenda.

A particularity of Brazil that makes it an appealing case study is its institutional design as a federal country. The Brazilian Federation is composed of 27 states (including the Federal District, Brasilia), each with its own executive, legislative and judiciary powers. As a result, they are empowered to promote region-specific public policies in order to stimulate the deployment of essential infrastructures such as broadband networks. While the Federal Government has promoted nation-wide plans such as the "Programa Nacional de Banda Larga”, there is still an important scope to design region-specific public policies with the aim to stimulate network deployment and promote the adoption and intensive use by enterprises and consumers. In that sense, the present paper intends to bring out some inputs about the economic impact of broadband across regions, as well as to infer policy recommendations according to each one. To be clear, the main hypothesis of this study is that broadband adoption has a positive impact on regional productivity, and that this impact may differ across regions. The possibility of performing the analysis in a big country such as Brazil, which exhibits important regional inequalities, may provide a better understanding of the regional dimension of the impact of broadband on productivity, and may contribute to evaluate its suitability as an instrument for regional cohesion in emerging economies.

Although the lack of data prevented us to include in the analysis indicators of the latest technologies (Internet of Things -IoT- or other advances related to industry 4.0), the evidence provided in this article allows anticipating some of the expected impacts of the adoption of the newest technologies in different territories of emerging economies. It also constitutes a guideline for future analyses of the spatial heterogeneity in the economic impact of these new technologies in such types of economies. As IoT and fiber optic penetration continues to increase in Brazil, and other advances such as 5G are still to come, this topic will remain at the top of policymakers agenda for the next decade.

The rest of the paper is structured as follows. The next section reviews the recent literature on the economic impact of broadband, paying special attention to the evidence from sub-national economies, while section 3 presents a theoretical framework that serves as the basis for the econometric analysis in the study. The dataset and variables are introduced in section 4. The results of the estimation of the effect of broadband on regional productivity are presented and discussed in section 5. Finally, section 6 briefly summarizes the main conclusions of the work, with some remarks and policy implications.

2. **Literature review**

The economic impact of infrastructures has been widely studied in the economic growth literature, following the initial contribution of Aschauer (1989), who included public capital as a productivity determinant. The impact of telecommunications infrastructure has also been studied, being Roller and Waverman (2001) an important contribution in the field. Attention has also been paid to the diversity of channels through which ICT can contribute to enhance productivity and promote economic growth (Cardona et al, 2013). In the last few years most of the ICT-derived contributions to productivity has come from the development of broadband high-speed internet connections, which has been classified as a General Purpose Technology (GPT) by some authors (Czernich et al, 2011; Mack and Faggian, 2013). Because of its attributes, they state that the new technologies influence productivity beyond the effect of regular capital goods. According to Jordan and De Leon (2011) and Mack and Faggian (2013), broadband now constitutes a key part of the necessary infrastructure for development, in the same way as oldest types of infrastructures such as railroads, roads and electricity.

Since the deployment of broadband in the late 1990s and early 2000s, there has been increasing interest in testing its impact on economic growth. Crandall et al (2007) is among the earliest studies providing evidence on this regard, concluding that the number of broadband lines per 100 persons stimulated employment and output growth in the period 2003-2005. However, the positive effect on output growth was only significant in the service industries. As the authors argued, the still early stages of the broadband's lifecycle during the period analyzed could have prevented accurate measurement of its overall impact on growth. In the following years a numerous group of studies contributed to the debate about the growth impact of broadband using data for sets of countries.[1] Koutroumpis (2009) studied a sample of 22 OECD countries for the period 2002-2007, finding that a 10% increase in broadband penetration contributed to 0.25% in GDP growth. Czernich et al (2011) extended the sample to 25 OECD countries and added some previous years 1996-2007, concluding that a 10% increase in broadband penetration raises annual growth in GDP per capita by 0.9-1.5 percentage points. Interestingly, and in contrast to the study by Crandall et al (2007), the last two addressed the endogeneity of the measure of broadband due to reverse causality and omitted variables. The solution adopted by Koutroumpis (2009) mimicked the structural approach in Roller and Waverman (2001), in which equations for the supply and demand of broadband are specified in addition to the one linking it with GDP. By contrast, Czernich et al (2011) used an IV approach based on the fact that broadband deployment took place over previous infrastructures. To be clear, they suggested a diffusion model of broadband that depends on pre-existing fixed-line telephony and cable TV. Similar strategies has been followed in the most recent studies, concluding in favor of a positive effect of broadband. For example, Gruber et al (2014) used the structural model approach to estimate, using simultaneous equations techniques, the growth impact of broadband access in 27 EU member states. Castaldo et al (2018), in turn, applied an IV strategy for a set of 23 OECD countries using the adoption of previous technologies (fixed and mobile telephony,

[1] See Bertschek et al (2015) for a survey of the studies analyzing the growth impact of broadband until 2014.

and cable) as instruments of broadband adoption.

Except in the case of Crandall et al (2007), all the studies mentioned above compared the deployment/adoption of broadband and the evolution of GDP (in absolute or per capita terms) in sets of countries, which in addition are among the most developed economies. Conversely, the evidence on the effect of broadband on GDP from subnational economies is still scarce. The weak effect of broadband deployment in the output of 48 US states during the early 2000s reported by Crandall et al (2007) can be questioned on the basis of the lack of control of the endogeneity of the broadband indicator. From the estimation of a system of equations, in line with the structural model approach, Katz and Callorda (2013) concluded that broadband stimulated GDP growth of the administrative divisions in Ecuador over the 2008-2012 period. Similarly, Celbis and de Crombrugghe (2018) reported a positive effect of broadband availability on the per capita gross value added of the 26 NUTS 2 Turkish regions over the period 1999-2011. In addition, their results suggest that broadband increases the speed of convergence of each region to its steady state. However, this evidence can be discussed since the authors used the lagged values of the regressors as instruments to control endogeneity, rather than a proper set of external instruments.

The small number of studies that have analyzed the effect of broadband on the production of subnational spatial units contrasts with the numerous studies that have studied the effect of broadband on other local or regional economic indicators.[2] Lehr et al (2006) studied the impact of broadband on several economic variables in the US zip-code areas and states. Using regression analysis and matching estimators, they found out a positive effect of broadband on employment, number of businesses (overall and in IT-intensive sectors), and property values. Interestingly, they did not observe a significant effect on wages. Although Lehr et al (2006) combined results from regression analysis, for the state and zip-code data, with those obtained from matching estimators, for zip-code data, they recognized that endogeneity was one of the weaknesses of their study. In fact, they suggested that future improvements should developed instrumental variables that better control broadband availability. They even suggested using information about previous telecommunication infrastructures to build instruments of broadband. In contrast to their results for output, Crandall et al (2007) observed a positive effect of broadband on employment growth in the US states, although as mentioned above, their study has an endogeneity problem that prevents concluding

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[2] In most cases, this is explained by the lack of data at the subnational level on measures of "total economic activity", such as total output or GDP (see e.g. Lehr et al, 2006).

in favor of a causal effect. A similar conclusion was reached in other initial studies that did not take endogeneity into account (e.g. Shideler et al, 2007). In addition, these studies analyzed the effect of broadband deployment rather than broadband use, and make no distinction between broadband speeds.[3]

The number of studies that analyze the impact of broadband on local or regional economies has increased substantially since the early 2010s, probably due to the greater availability of data at the subnational level. Most of these studies have addressed in one way or another the problem of endogeneity. For example, Kandilov and Renkow (2010) used a difference-in-differences approach combined with a matching strategy to analyze the effect of a broadband deployment program in US rural areas, concluding that it had not a significant impact on their economic development (measured by employment, payroll, and the number of business establishments). The comparison of the economic performance of groups of spatial units with different degrees of deployment or use of broadband but otherwise similar characteristics, using matching techniques, has also been the strategy followed in order to estimate a causal link in the studies of Whitacre et al (2014) and Ford (2018). The former study used data for the US counties from 2001 to 2010, concluding that median household income, employment, and the number of firms increased faster in counties with higher broadband adoption, whereas they experienced lower unemployment. In addition, the results in Whitacre et al (2014) suggest that higher download speed is associated to less poverty and more creative class employment. Ford (2018) also focused on the local economic effects of increasing broadband speed, although his results are less optimistic. Using US county-level data for the 2013-2015 period and matching algorithms, his study shows that broadband services and upgrades are not randomly distributed in the territory, which could result in misleading conclusions about its economic impact. Once differences in observed characteristics between the counties are controlled, the study concludes that there is no significant effect of higher broadband speed on economic outcomes, including jobs, earnings, and total personal income.

Other recent studies at the subnational level have dealt with the endogeneity of the broadband indicator in a regression framework. They have included controls of the differences in observed and unobserved characteristics (fixed effects) of the spatial units under analysis to minimize the concern about the omitted variables bias. In addition, these studies used the IV approach to deal with the issue of reverse causality. For example, Forman et al (2012) used the cost of Internet deployment,

[3] See Holt and Jamison (2009) for more details.

local connections to ARPANET,[4] and a proxy of the demand for advance Internet investment outside the county, to identified a positive causal effect of investments in advanced Internet technologies on wages and employment in the US counties from 1995 to 2000. However, the positive effect was observed only for a reduced number of counties (6%) characterized by intensive usage of IT and high skills, income, and population density. Similarly, Kolko (2012) assessed the impact of broadband availability on county employment from an IV estimator that used the average slope of the terrain as an instrument of the broadband indicator. The results are suggestive of a positive causal effect of broadband on employment, although the author acknowledged that IV estimates might be upwardly biased. Meanwhile, Mack and Rey (2014) showed that broadband availability in 2004 stimulated the number of knowledge-intensive firms in the counties of 49 of the 54 US metropolitan areas analyzed in their study. In this case, the authors combined techniques to deal with spatial dependence with an IV estimator that used the lagged values of the broadband indicator and the county's household density.

Evidence about the impact of broadband on subnational economies in countries other than the US is scarce and very recent. The difference-in-differences analysis for the municipalities of the Italian province of Trento from 2008 to 2012 in Canzian et al (2015), and the spatial boundary discontinuity design for local areas in England for 2009 and 2010 in Ahlfeldt et al (2017), suggest a positive causal effect of broadband deployment on sales turnover and value added, and in property prices, respectively. A similar effect is observed by Ivus and Boland (2015) for the Canadian economic regions in 1997-2011. To be clear, they found that the deployment of broadband promoted employment and wages, but only in service industries of rural areas. They used variation in elevation as an instrument of broadband availability in the Canadian regions to obtain the estimate of the causal effect. Conversely, Czernich (2014) claimed that broadband availability did not reduce the unemployment rate of local German economies in 2006. She identified the effect of broadband by means of an IV strategy, using as instrument of availability the distance from every municipality to the location of the closest DSL main distribution frame. Finally, McCoy et al (2018) provided evidence on a significant positive effect of the availability of broadband on the location of new business establishments in Irish local areas from 2002 to 2011. However, causal implications cannot be derived from the results in this study, despite the fact that the broadband indicator and the other regressors are lagged one period and fixed effect are used to control for unobserved area characteristics.

[4] Concept that refers to a network that preceded Internet.

Overall, the review of the existing literature leads us to conclude that the evidence about the causal effect of broadband on the economic performance of subnational spatial units is inconclusive. Results vary with the set of spatial units, the period analyzed, and the specific economic indicator. Interestingly, conclusions also differ between studies using similar strategies of identification of the causal effect of broadband.

On the other hand, an ongoing debate in the literature is related to the link between the economic impact of the new technologies and the degree of development of the regions. It has been argued that ICTs can open possibilities for isolated regions to overcome traditional disadvantages associated to their remote location. As a result, new technologies and internet diffusion might reduce the role played by agglomerations. Some authors even talk about the "death of distance" as a result of an eventual widespread deployment of ICT services (Cairncross, 2001). According to this view, distance would be less important and peripheral regions would benefit from opportunities that were not available before (Bonaccorsi et al, 2005; Quah, 2000; Kelly, 1998; Negroponte, 1995). In some cases, the presence of broadband infrastructure facilitates the development of poor regions, enhancing some degree of territorial equilibrium (Suriñach et al, 2007). Isolated regions may present some advantages as lower wages and housing costs, which can be fully exploited if good broadband infrastructure is available. In that case, it can attract companies to locate in these regions, especially those which can suffer from congestion costs in more developed regions, increasing demand and activity in isolated areas. This might lead to a positive spiral of increased activity that may help even people who is not a user of broadband.[5]

Conversely, other authors argue that the economic impact should be bigger in high-income economies.[6] The reason for this statement may be linked to network externalities, as high-income economies usually exhibit larger broadband penetration. This critical-mass effect might lead to increasing returns to broadband penetration. On the other hand, regions may differ not only in ICT endowments, but also in the possibility to make a productive use of it, something that can lead to further disparities. Billón et al (2009) argued that agglomerations and internet may be complementaries rather than substitutes. According to Bonaccorsi et al

[5] Even if not related to regional analysis, Thompson and Garbacz (2011) find that broadband has a relatively more favorable economic impact in low-income countries than in high-income countries. Similarly, Fernández-Ardèvol and Vázquez Grenno (2011) suggested that the economic impact of mobile phones was larger in Latin America than in OECD countries.

[6] Although they do not perform regional-level analysis, there is evidence on this subject in Gruber and Koutroumpis (2011) and Katz (2012).

(2005), disparities and inequalities seemed to be reinforced, rather than reduced, by ICT diffusion. Similarly, Forman et al (2012) found that internet exacerbated regional wage inequality across US counties. Along with that, the importance of complementarities (i.e., ICT and human capital), sectoral composition and institutional framework may contribute to a higher economic impact in more developed economies (e.g. Katz et al, 2010; Mack and Faggian, 2013). At the same time, the decrease of the role of distance as a result of the new technologies may be over-optimistic, referred to earlier, as only codified knowledge can be transmitted through ICTs, meaning that for tacit knowledge diffusion distance will remain to be relevant. Other authors, as Bauer (2018), argue that the net impact of connectivity on income distribution needs to be assessed carefully on a case-by-case basis, given the conjunction of both positive and potentially negative effects.

Finally, it is worth mentioning that a relatively unstudied aspect of the economic impact of broadband is that related to differences in the quality of the infrastructure (proxied by the download speed). Rohman and Bohlin (2012) concluded that broadband speed exerted a significant positive effect in the growth prospects of a sample of 34 OECD countries during the period 2008-2010. To avoid the problem of endogeneity, this study used as instruments of speed the penetration and price of broadband and telecom revenue. Similarly, Ahlfeldt et al (2017) and Stocker and Whalley (2018) have also argued about the relevance of internet speed, providing evidence on the positive economic effect of increasing the speed of broadband connections. From the results in these studies it can be deduced that the quality of the internet connections, in terms of speed, can cause regional differences in the economic impact of broadband.

3. Theoretical framework and empirical specification

In this section we derive an empirical model to estimate the impact of broadband on regional productivity. It is based on the augmented Solow (1956) framework, where economies are supposed to produce according to a Cobb-Douglas production function with various input factors:

$$Y_{it} = A_{it} K_{it}^{\alpha} L_{it}^{\beta} H_{it}^{\gamma} \qquad (1)$$

where Y represents output, K is physical capital stock, L is labor and H denotes human capital, approximated as $H = e^{h}$, where h reflects the efficiency of a unit of labor, in a similar fashion as Hall and Jones (1999). Subscripts *i* and *t* denote respectively regions and time periods. The term *A* represents Total Factor Productivity (TFP), which reflects differences in production efficiency across regions over time. TFP is expressed as:

$$A_{it} = \Omega_{it}(X)\ BB_{it}^{\Phi} \tag{2}$$

Therefore TFP is assumed to depend on some region-specific characteristics, represented by Ω*(X)*, a term which is influenced by a vector of control variables *X*, varying across regions and over time, and time invariant idiosyncratic productivity effects, which may make some regions more productive *per se* because of unobserved characteristics. As it is supposed that broadband use contributes to increase productivity, among other channels by facilitating the development of new products and processes and the adoption of new technologies devised by others, *A* is assumed to depend positively on the level broadband deployment, denoted by *BB*. The stock of broadband infrastructure is used, instead of investment, because users demand infrastructure and not investment *per se* (Koutroumpis, 2009). It is expected a positive value for Φ, indicating the productivity gains derived from broadband.

The empirical specification is derived omitting the subscripts for region and time period for the sake of simplicity. The lack of available data for state-level physical capital stocks in Brazil require of some assumptions and rearrangements to derive a workable empirical specification. Adopting the assumption that markets are competitive, capital earns its marginal product (Romer, 2006), and thus firms in this economy will acquire physical capital until its marginal productivity equals its price, usually approximated by the real interest rate *r*:

$$\frac{\partial Y}{\partial K} = A\alpha K^{\alpha-1} L^{\beta} H^{\gamma} = r$$

From this expression, the demand for physical capital can be derived as:

$$K = [\frac{\alpha A L^{\beta} H^{\gamma}}{r}]^{\frac{1}{1-\alpha}}$$

Inserting the derived demand for physical capital in (1), yields an expression for output which do not depends on physical capital on the right-hand side:

$$Y = A[\frac{\alpha A L^{\beta} H^{\gamma}}{r}]^{\frac{\alpha}{1-\alpha}} L^{\beta} H^{\gamma}$$

Under the assumption of constant returns to scale for physical capital and labor[7], $\alpha+\beta=1$, the previous expression can be easily manipulated to obtain a measure of labor productivity which does not depend on the stock of physical capital:

$$\frac{Y}{L} = \frac{\alpha^{[\frac{\alpha}{1-\alpha}]} A^{[\frac{1}{1-\alpha}]} \; H^{\gamma[\frac{1}{1-\alpha}]}}{r^{[\frac{\alpha}{1-\alpha}]}}$$

Inserting the expression for TFP in (2) and log-linearising results in:

$$log\,[\frac{Y}{L}] = [\frac{1}{1-\alpha}] log\,\alpha + [\frac{1}{1-\alpha}] log\,\Omega(X) + [\frac{1}{1-\alpha}] \Phi log\,BB + [\frac{1}{1-\alpha}] \gamma h - [\frac{\alpha}{1-\alpha}] log\,r$$

The interest rate is easily assumed to be the same across the regions because financial markets are integrated inside the country.[8] Similarly, it is assumed as constant as the long-term rate is supposed to vary little over the time period analyzed. Renaming the constant factor $\Gamma_0 = [\frac{1}{1-\alpha}] log\,\alpha - [\frac{\alpha}{1-\alpha}] log\,r$, and the following parameters successively as Γ_i, the empirical specification can be written as:

$$log\,[\frac{Y}{L}] = \Gamma_0 + \Gamma_1 log\,\Omega(X) + \Gamma_2 log\,BB + \Gamma_3 h \qquad (3)$$

As a result, labor productivity is assumed to depend on broadband, human capital, and some regional controls. The parameter α cannot be identified from the empirical specification, so the figure for the physical capital share in income from the Brazilian national accounts will be used to recover the structural parameters associated to broadband: $\Phi = \Gamma_2\,(1-\alpha)$.[9]

The previous specification is a sort of baseline empirical model that is useful to obtain a common-regional measure of the impact of broadband on productivity, but is inappropriate to explore the existence of differences across regions in the impact. As a result, the empirical exercise in this paper will consider further strategies which will require slight modifications of the TFP term expressed in (2).

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[7] This assumption has been made before in empirical research for the Brazilian case (see for instance Da Silva Filho, 2002)

[8] In any case, any difference will be absorbed by the region fixed effects.

[9] It is important to note that this implies a return to physical capital which is common to all regions. Lack of constraints in the inter-regional mobility of capital in Brazil favors such assumption, although severe differences in the industrial mix could lead to cast some doubts under imperfect inter-sectoral mobility. This issue will be further discussed in section 6.

On the one hand, it is worth mentioning that service adoption does not automatically means that individuals and enterprises will make a productive use of it. However, the lack of region-specific data regarding the intensity of productive-use of broadband makes it difficult to derive cross-region differences in usage patterns, although we can expect those to be strongly correlated with adoption and other features. In this regard, the economic impact of broadband may vary depending on some characteristics of the infrastructure, such as the quality of the connection, and the presence of network externalities. Similarly, as stated in the literature review, broadband may have a different impact depending on the degree of economic development of the region. To explore these matters, we will consider a more general expression for (2) to account for heterogeneities in the effect of broadband on productivity:

$$A = \Omega(X)\ BB^{(\delta_0 + \delta_1 Z)} \qquad (2a)$$

where Z refers to the set of factors which may have an incidence on the economic impact of broadband, to be defined on course, and the vector of parameters $\delta_1$reflects the incidence of the other factors in interaction with broadband. The procedure to derive the empirical specification and the strategy for recovering structural parameters is similar to that indicated in the baseline model.

As in previous studies of the impact of ICT in general, and broadband in particular, endogeneity is a concern due to the omitted variable bias (OVB) and reverse causality. To minimize the OVB, in addition to the production inputs we include in the specification a set of time-varying regional controls (R&D intensity, imports, industrial mix, unemployment) that could be associated to each region's productivity and, at the same time, correlate with broadband use. Besides, the panel structure of the data set for the Brazilian states allows us to control for time-invariant unobserved region characteristics, by the inclusion of state fixed effects. As a result, the pernicious influence of confounding factors omitted in the specification (e.g. the effect of geography and differences across regions in managerial talent that evolves smoothly over time) is less a concern in our empirical exercise. Still, a common critique of the estimation of the effect of broadband is that the results could determine correlation rather than a causal effect, because investments in broadband may be considered as a driver, but also a result of productivity and economic growth (e.g. Cardona et al, 2013). This likely reverse causality may arise because individuals and firms in high-income economies may also have higher resources to pay for broadband, because policy interventions aiming to stimulate deployment and use of broadband might depend on the level of development of each economy, and because adoption of broadband can run in parallel to other technological advances (Czenich, 2011). As mentioned in the previous section, some studies using country-level data address endogeneity by estimating the effect of interest from structural multi-equation models (Koutroumpis, 2009; Gruber et al, 2014; Katz and Callorda, 2013). Others applied the single-equation IV estimator using lagged values of the broadband indicator as instruments (Mack and Rey, 2014; Celbis and de Crombrugghe, 2018; Haftu, 2018), or other variables that are expected to determine broadband but not the outcome variable in a direct way (Czernich et al, 2011; Rohman and Bohlin, 2012; Forman et al, 2012; Kolko, 2012, Czernich, 2014; Mack and Rey, 2014; Ivus and Boland, 2015; Castaldo et al, 2018).

Given the characteristics of the case under analysis and the available data, we tackle endogeneity of the indicator of broadband by means of the IV approach. Following Czernich et al (2011) and Bertschek et al (2013), in the empirical exercise we build on the idea that most common broadband roll-out (i.e. DSL or Cable Modem) rely on the copper wire of pre-existing voice-telephony networks. The required access to an existing infrastructure built for other purposes, such as that of fixed telephony, makes it a suitable instrument for this estimation strategy. In our study, the instrument is the number of voice-telephony fixed access lines per 100 inhabitants in each Brazilian state with a five-year lag. Our assumption is that infrastructures of previous telecommunication technologies determine the spatial diffusion of current technologies, because networks of traditional technologies made the deployment of broadband less costly. That is to say, although it was not deployed with this aim, the network of traditional voice fixed access lines in the Brazilian states in the past conditions their current broadband connections. With this instrument we thus aim to account for the supply side of broadband penetration, discarding the mechanisms linked to the level of development (demand side), and the influence of other new technologies that do not depend on pre-existing networks. The assumption is that conditioned to the included set of time-variant and time-invariant state characteristics, the extension of the traditional technology in the state does not affect current productivity in a direct way, but only through its influence on the deployment of the new technology.

In addition to the instrument based on the traditional technology, we use another one based on deeply lagged population density in the Brazilian states. The assumption is that broadband deployment depends on demographic factors, in particular on the potential number of subscribers in each territory. Providers are thus willing to serve areas with high population density. However, it can be argued that current density might also correlate with productivity. Therefore, rather that current values we use the figures of population density in each state in the first part of the last century (census performed between years 1920 and 1950). The instruments are lagged considerably to break any possibility of being affected by contemporary shocks that also impacted on productivity, while they correlate with current density due to persistence in the geographical distribution of population. That is to say, we assume that deeply lagged density satisfies the exclusion restriction, which implies that it does not affect in a direct way the region's productivity but only indirectly through its effect on broadband. In this regard, it is worth noting that we expect that any impact of contemporary density on productivity to be captured by the time-variant controls and the state fixed effects.[10]

4. Dataset and variables

To test the effect of broadband connections on regional productivity, this study estimates the key parameters of the empirical model sketched in the previous section using data from the 27 Brazilian states in the period from 2007 to 2011. Table 1 provides the precise definition and source of the key variables used in the empirical analysis.[11] As for the dependent variable, labor productivity is computed as the ratio of gross value added (GVA) to employment in each state and year. GVA, that subtracts intermediate inputs from the gross output, is usually considered a more accurate measure of the actual surplus created by the regional economy (Cardona et al, 2013). The data, extracted from the Instituto Brasileiro de Geografia e Estatística (IBGE) database, is deflated to 2000 constant Reais prices. Data for the workforce, total number of workers in each state, comes from the Instituto de Pesquisa Econômica Aplicada (IPEA) database. For cases of missing 2010 employment information, interpolation using data for 2009 and 2011 was used to fill gaps.

[10] Other studies (e.g. Kolko, 2012 and Ivus and Boland, 2015) use geographical characteristics of the spatial units as instruments of the broadband indicator. The argument is that the cost of broadband deployment varies depending on the characteristics of the local terrain. In our view, this type of instrument is not appropriate when dealing with large spatial units as in the case of this study.

[11] A descriptive analysis of the variables used in the empirical analysis is reported in the Supplemental Material.

Table 1. Variables used in the empirical analysis

Variable	Definition	Source	Mean
Labor productivity	Gross Value Added per worker in Reais at 2000 constant prices	Computed using data from IBGE and IPEA	14490.230 [7371.610]
Broadband	Number of subscriptions (>512 Kbps) per 100 inhabitants	Telebrasil	2.972 [3.210]
Literacy rate	Literacy rate of population over 15 years old	IPEA	88.249 [6.291]
Public R&D intensity	R&D expenditures of state governments in relation to their GVA	Ministério da Ciência, Tecnologia e Inovação	0.001 [0.001]
Imports	Imports in relation with GVA	Ministério da Indústria, Comércio Exterior e Serviços	0.082 [0.090]
Agriculture	Relation of sectoral GVA	IBGE	0.091 [0.067]
Services	Relation of sectoral GVA	IBGE	0.313 [0.055]
Unemployment	Unemployment rate (in %)	IBGE	8.500 [2.400]

Note: standard deviation in brackets

Regarding the key variable in the study, broadband, some preliminary comments are in order. Considering the importance of ICT to increase the competitiveness of territories, inequalities detected in its diffusion can have implications for economic growth, human development and the creation of wealth (Vicente and López, 2011; Billón et al, 2009; ITU, 2006). One of the consequences of the lack of broadband connections is that it generates a new divide between those who have access to a large number of applications, for which broadband is needed, and those who do not have access (Billón et al, 2009).

A wide definition of digital-divide includes a large number of technology-related variables. Nevertheless, given the scope of the paper the empirical analysis focus on fixed broadband only. In this regard, it is worth noting that despite the evidence on the current importance of mobile broadband for SMEs, figures compiled by the Centro Regional de Estudos para o Desenvolvimento da Sociedade da Informação (CETIC) suggest that over the period analyzed, 65% of firms in Brazil used fixed connections to internet while only 23% did it by mobile connections. Unfortunately, there is no publicly available data at the state level on firms' broadband adoption in Brazil. But, as stated by Vicente and López (2011), firm adoption is expected to be highly correlated with the overall spread of broadband across the entire population. As a result, like other contributions to the extant literature (e.g. Koutroumpis, 2009; Czernich et al, 2011), our empirical analysis uses penetration among the inhabitants as a broadband indicator.[12]

Broadband is defined as internet access provided at a certain high level of speed capacity (considering the standards for the period under analysis). In Brazil, most internet available at the end of the 90s and beginning of the 2000s were based on slow dial-up connections, which imposed restrictions for its usability and ability to make full use and take full advantage of internet applications. The introduction of broadband allowed the possibility of exploiting internet full potential. The OECD[13] in 2006, and the International Telecommunications Union (ITU)[14] in 2007 defined broadband as those internet connections with speeds above 256 Kbps. In this case, Telebrasil (the Brazilian Association of Telecommunications) classified internet connections by speed considering a threshold of 512 Kbps. Therefore, for the purpose of this research, only broadband connections that reach at least 512 Kbps or more were considered for the study. In our opinion this constitutes a much more realistic approximation for broadband than that based on a threshold of 256 Kbps, which hardly served for the most advanced applications during the period under analysis. As a result, *Broadband* is defined as the number of connections above the 512 Kbps threshold per 100 inhabitants in the region.

Regarding human capital, it is proxied by the literacy rate, which despite being a measure of the basic skills of the population, is appropriate in our study as they are far from being universal in the case of the Brazilian regions.[15]

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[12] Data on the percentage of enterprises with fixed broadband connection is available only for the five macro-region in which Bazil can be divided, from the CETIC database "TIC Empresas". Clearly, the number of spatial units available from this source is not large enough for the purpose of the empirical analysis carried out in this study. In any case, the correlation between these figures for the period 2007 to 2011 and the corresponding ones for the penetration in the population is close to 0.5 and highly statistically significant. A higher correlation is even observed between the penetration of broadband in the population of these five spatial units and the share of firms using an own website. On the other hand, the correlation between fixed broadband per inhabitant and per firm in the set of the European Union member states is as high as 0.8, which confirms the association between the two indicators of broadband penetration. This evidence (details are available from the authors upon request) supports the decision of using penetration in the state's population as a proxy of broadband in the study of the Brazilian case.

[13] http://www.oecd.org/sti/broadband/oecdbroadbandstatisticstodecember2006.htm

[14] https://www.itu.int/ITU-D/ict/material/IndDef_e_v2007.pdf

[15] As stated by Caselli (2005), more conventional measures of human capital as data on years of schooling for population over 25 years old may seem appropriate for developed countries with a large share of college graduates, but it is not appropriate for most developing countries. In order to proxy for more advanced skill levels than literacy rate, we also considered to add school enrollment from the population aged between 15 and 17 years old (lagged 5-years), but its coefficient was always insignificant while the main results remained unchanged.

Finally, as stated above, TFP is assumed to depend on some region-specific characteristics. Most of them may surely constitute time invariant regional features, such as idiosyncrasy, culture, geographic location, climate, natural resources, etc. Therefore, region fixed effects are expected to capture all those components of unobserved heterogeneity which may make some regions more productive than others and, at the same time, correlate with the penetration of broadband. Beyond that, to control for further productivity differences across regions, a number of variables were considered. In the first place, R&D activities have been identified in the literature as relevant to foster productivity (Romer, 1990). To account for it, we include the percentage of R&D expenditures of the regional governments in relation to its GVA, which can also be interpreted as a proxy for absorptive capacity and as a measure of innovation-prone environment. Besides, as Coe and Helpman (1995) pointed out, TFP may depend not only on domestic R&D but also on foreign R&D, through the exposure to foreign trade. We control for this effect by the ratio of imports to regional GVA.

To take into account additional sources of heterogeneity, we also check the robustness of the results to the inclusion of measures of the sectoral composition of the economy, represented by the percentage of agriculture and services in regional GVA, and the unemployment rate, in order to capture any cyclical component which may affect productivity.

5. **Results**

5.1. ***Baseline specification***

This section presents and discusses the results of the estimation of the effect of broadband on productivity in the Brazilian regions, using the specifications described in section 3. As mentioned in that section, it is not possible to identify α directly from the estimated coefficients. To do so, additional information on the capital share in income from the Brazilian economy is used. In that sense, Feenstra et al (2015), using the Penn World Table data (PWT), find that the labor share in the income of Brazil averaged 0.55 in the period 2007-2011. Under the assumption of constant returns to scale, this implies α=0.45, value that will be used to recover the structural parameter of interest.

Table 2 reports estimates of the baseline model that assumes no interaction between broadband penetration and regional attributes. Column (i) reports the Ordinary Least Squares (OLS) estimate of the effect of broadband on productivity in a simple specification that does not include controls and state fixed effects. The estimated coefficient is very large in magnitude and highly significant. The implied effect of broadband,Φ, indicate that a 10% increase in broadband penetration raises an average state's productivity by about 0.9%. However, this estimate might be capturing the effect of some omitted regional characteristics that affect productivity and correlate with broadband penetration. To account for the likely omitted variable bias, the estimate reported in column (ii) includes the first group of regional controls described in the previous section and the state fixed effects. The coefficient of *Broadband* is still found to be highly significant and sizeable in magnitude in this extended specification. The implied estimated effect,Φ, suggests that a 10% increase in broadband penetration improved regional productivity by 0.2%. To assess the magnitude of this effect is worthwhile taking into consideration that the overall average of *Broadband* in the sample is 3 connections per 100 inhabitants. Therefore, a 10% increase represents moving that value up to 3.3 connections per 100 inhabitants. As for the estimate of the coefficients of the other regressors, it is obtained a positive and significant (at 5%) effect of the literacy rate on productivity. This suggests that differences in the endowment of basic skills in the population contribute to explaining productivity disparities among brazilian regions. On the other hand, conditional to the other observable and unobservable regional characteristics, public spending in R&D as a percentage of the region's GVA do not exert a significant effect on productivity. In contrast, the effect of the relative amount of regional imports is positive and significant, which suggests that more open regions benefit from foreign R&D embodied in traded goods and, as a result, tend to be more productive.

Although the magnitude of this estimate of the effect of broadband penetration is similar to that in other empirical studies in the literature, additional estimations have been performed to evaluate its robustness. In the first place, column (iii) in Table 2 includes additional regressors, with the aim of controlling for the existence of further regional specific differences in Ω. Particularly, three additional variables are included: the percentages of agricultural and services activities in local GVA (as controls of differences in the sectoral composition) and the unemployment rate, as a proxy for any cyclical component which may affect productivity. Results in column (iii) reveal that only the coefficient of the share of services in total GVA is statistically significant and, most importantly, that the inclusion of these controls does not alter the results for the estimated effect of *Broadband*. In other words, the estimate of its impact is robust to the addition of further controls in the regional production function.

Table 2. Estimation of the baseline model

Estimation	(i)	(ii)	(iii)	(iv)	(v)
Iog(Broadband)	0.157***	0.037***	0.036***	0.030**	0.030**
	[0.024]	[0.013]	[0.012]	[0.015]	[0.013]
Literacy rate		0.022**	0.022**	0.024***	0.024***
		[0.008]	[0.008]	[0.008]	[0.008]
Imports		0.599**	0.545**	0.608**	0.545**
		[0.242]	[0.246]	[0.239]	[0.231]
Public R&D intensity		-0.327	-0.262	-0.334	-0.261
		[0.258]	[0.274]	[0.225]	[0.228]
Agriculture			-0.189		-0.213
			[0.444]		[0.420]
Services			-1.024**		-1.021***
			[0.470]		[0.367]
Unemployment			-0.000		-0.001
			[0.005]		[0.004]
State Fixed Effects	NO	YES	YES	YES	YES
Implied Φ	0.086	0.020	0.020	0.017	0.017
Observations	135	135	135	132	132
R-squared	0.243	0.643	0.670	0.537	0.572
Method	OLS	OLS	OLS	IV	IV
Weak identification test				62.183	60.239
Over-id test statistic				1.731	2.598

*Note: *p<10%, **p<5%, ***p<1%. Robust standard errors in brackets. Instruments for Broadband in IV: telephone fixed voice lines per 100 inhabitants (lagged 5 years), and population density in the first part of the XX century (census 1920-1950). First-step estimates for columns (iii) and (iv) are reported in Table S.3 of the Supplemental Material. Stock-Yogo weak identification test critical values: 8.68 (10% maximal LIML size).*

As discussed in section 3, the OLS estimator will provide biased estimates of the effect of *Broadband* if there is reverse causality. To account for this possibility, columns (iv) and (v) in Table 2 report the results based on an IV estimator that uses the instruments discussed in section 3.[16] In both cases, the statistic of the

[16] The IV-LIML estimator is used as it has been proved to be more robust in the presence of weak instruments.

overidentifying restrictions test fails to reject the null hypothesis of exogeneity of the instruments, while the weak instruments test rejects that they are weakly correlated with *Broadband*. Therefore, from an econometric point of view, the results of the tests support our arguments in favor of the validity of the instruments used. The IV estimated coefficient of *Broadband* in column (iv) is only marginally smaller than that reported by OLS. To be clear, it remains positive although decreases somewhat its significance (significant at a 5% level) as a result of a slight decrease in the size of the coefficient and also a small increase in the standard error. In any case, the implied effect of broadband derived from the IV estimation points to a substantial effect of broadband on the region's productivity (a 10% increase in fast broadband penetration raises regional productivity by 0.17%). As with the OLS, the estimated effect of *Broadband* remains unchanged when further control variables are included (column v).[17] Overall, these results provide support to the hypothesis that broadband intensification caused a positive impact on the level of productivity of the Brazilian regional economies.[18]

5.2. ***Regional heterogeneity in the effect of broadband***

Once the impact of broadband on the productivity of the Brazilian regional economies has been verified, it seems interesting to assess whether the impact is uniform across states or if, on the contrary, it varies with some characteristics of the infrastructure and with the level of development of the territorial units. With this aim, the empirical model is modified to accommodate the TFP function in equation (2a). In the first place, it is assumed that there is a certain critical-mass

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[17] In addition to the inclusion of the state controls and fixed effects, and the instrumentalization of broadband, we carried out a falsification test similar to that in Forman et al (2012). In brief, we run a regression with the five-years lag of productivity as dependent variable and the current values of broadband and the state controls. A significant coefficient for broadband in this specification would cast doubts on the causal interpretation of the estimated coefficient of broadband in this paper. By contrast, we get an estimate of the broadband coefficient that is not statistically significant, meaning that there is no correlation between current broadband penetration and past productivity in the sample of Brazilian states. These results are reported in the Supplemental Material (Table S.4).

[18] As mentioned at the beginning of this section, the effect of *Broadband* on productivity is estimated using the value of the share of capital in income deduced from the data in the PWT for the entire Brazilian economy (0.45). Alternatively, it is possible to compute the share of capital in income for each Brazilian state for 2010 and 2011 from the Brazilian Regional Accounts. The results obtained in that case are shown in Table S.5 in the Supplemental Material. It is observed that the estimated effect for the entire country is somewhat smaller in this case due to the highest share of capital in this alternative source. In any case, these results reveal some important differences across regions, with the estimated effect ranging from 0.010 in Espirito Santo to 0.018 in Amapá.

required to get benefits from network externalities. To be clear, the TFP function in (2a) is specified as:

$$A = \Omega(X)\, BB^{(\delta_0^M + \delta_1^M Mass)}$$

where *Mass* is a binary variable defined as a function of a given threshold of broadband penetration: it equals 1 for regions with level of penetration above the threshold, and 0 otherwise. To define the threshold, it should be taken into account that even the lowest thresholds considered in previous studies for OECD countries were found to be far above from the Brazilian standards during the period under analysis.[19] Therefore, after analyzing the distribution of the values of the variable, a minimum threshold of 6% penetration is adopted, a level which means approximately 20% of households with broadband connection.[20] Under this specification, regions in which penetration was below this threshold are supposed to get no productivity gains of increases in *Broadband.* It is when reaching the threshold that improvements in *Broadband* start leading to higher productivity in the region. Therefore, we expect δ_1^M>0.[21]

Another important aspect that could shape the impact of broadband on regional productivity is the existence of differentials in the quality of connections. To approximate quality, following Rohman and Bohlin (2013), the measure used is the average speed of connections in the region. Available data from Telebrasil allows to consider differences in average bandwidths across regions. Broadband download average speed is constructed with data which classifies subscriptions to different groups depending on its speed. More precisely, average speed for each interval were weighted by the corresponding penetration levels (see the Supplemental Material for the description of this variable).[22]

In this case, the specification of equation (2a) is as follows:

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[19] For instance, Koutroumpis (2009) considers as critical the threshold of 20% penetration per inhabitant, while Czernich et al (2011) measure network externalities from a 10% level.

[20] The average size of Brazilian households is 3.2 persons.

[21] 16% of the observations in the sample are above the threshold (*Mass*=1). The percentage increased over the analyzed period from 0% in 2007 to 37% in 2011.

[22] Telebrasil offers data on fixed broadband connections across the following speed intervals: (1) 512 Kbps - 2 Mbps; (2) 2 Mbps - 34 Mbps; and (3) higher than 34 Mbps. The formula for computing average download speed for region *i* at time *t* is: $Quality_{it}=1.25*[BB(1)_{it}]+18*[BB(2)_{it}]+50*[BB(3)_{it}]$, where *BB(i)* refer to share of connections in speed interval *i* (=1, 2, 3). Assigned speed values for intervals (1) and (2) correspond to the mean of the corresponding interval. Speed for the interval (3) is right-censored, and the election of 50 mbps is somewhat arbitrary, although results are not sensible to different approximations. The equivalence formula is 1 Mbps = 1024 Kbps.

$$A = \Omega(X)\, BB^{(\delta_0^Q + \delta_1^Q Quality)}$$

The moderating effect of the average quality of connections in the region is hypothesised to be positive, i.e. $\delta_1^Q > 0$. In other words, for two regions with the same relative amount of broadband connections, we expect to observe a higher impact on productivity for the region with the higher average speed.

The results of the IV estimation of the parameters of the specifications allowing for these types of heterogeneities in the effect of *Broadband* are reported in the first block of columns in Table 3.[23] In both cases, two groups of instruments have been used to account for the interaction between the corresponding variable (*Mass* or *Quality*) and (the log of) *Broadband*. In the first place –columns (i) and (iii)–, the interaction between the variable and the two instruments used before are added to the list of instruments. This assumes that *Mass* and *Quality* are exogenous regressors. Since the instruments based on the interactions would not be appropriate if *Mass* and *Quality* are endogenous, we also report results that exclude the interactions from the list of instruments –columns (ii) and (iv).

As expected, the estimate of the coefficient for the interaction between *Mass* and *Broadband*, δ_1^M, is positive, although it is only statistically significant at 10% when just the two original instruments are used. This result confirms that there is a threshold above which further penetration of broadband leads to improvements in regional productivity, whereas this is far from guaranteed below the threshold (the estimated effect for regions below the threshold, i.e. *Mass*=0, is not statistically significant).

As for the moderating effect of quality, results confirm the hypothesis that the impact of *Broadband* is increasing with the average speed in the region. At the overall average speed in the sample, the implied $\Phi$is estimated at 0.022, whereas it takes a value of 0.013 and 0.050 at the minimum and maximum values of speed, respectively. That is two say, the impact of broadband on productivity is fourfold in the region with the highest average speed with respect to that in the region in which the average speed was the lowest. This confirms that quality of the connection matters for the impact of broadband on productivity.[24] As in the case

[23] Only the specification that does not include the sector and unemployment controls is considered in this subsection given that their addition to the list of regressors does not modify the estimate of the key parameters. The corresponding results are available upon request.

[24] Consistent with the specification, the estimate of the coefficient of *log(Broadband)* in columns (iii) and (iv) is not statistically different from zero. This is the expected effect when the average

of the interaction involving *Mass*, there is a decrease in the significance of the coefficient of the interaction when only the original instruments are used. This seems to be caused by the higher standard error as the magnitude of the coefficient remains the same in the two estimations.

Table 3. Estimation allowing for regionally heterogeneous effects

Estimation	(i)	(ii)	(iii)	(iv)	(v)
log(Broadband)	0.025 [0.016]	0.015 [0.018]	0.009 [0.017]	0.008 [0.021]	0.034*** [0.013]
*Mass*log(Broadband)*	0.015** [0.008]	0.027* [0.015]			
*Quality*log(Broadband)*			0.003*** [0.001]	0.003* [0.002]	
*LP*log(Broadband)*					0.044*** [0.016]
*MP*log(Broadband)*					-0.007 [0.019]
Implied Φ[min, max]	[0.014, 0.022]	[0.008, 0.023]	[0.013, 0.050]	[0.012, 0.050]	
Implied Φ HP					0.019
Implied Φ LP					0.043
Implied Φ MP					0.015
Observations	132	132	132	132	132
Weak identification test	27.117	8.782	12.969	11.157	7.083
Over-id test statistic	2.298	–	0.004	–	3.377

*Note: Estimations corresponding to the IV method. Instruments as in Table 2, with the addition of their interaction with the Mass or the Quality variables in (i) and (iii). First stage estimates available upon request. *p<10%, **p<5%, ***p<1%. Robust standard errors in brackets. LP and MP denote dummy variables for low- and medium-productive regions, respectively. The omitted category is the group of high-productive regions. All specifications include region fixed effects and as control variables the Literacy rate, Imports, and Public R&D intensity. The "–" denotes that the Over-id test statistic is not available for the corresponding estimates due to the lack of overidentifying restrictions.*

Finally, we explore the relationship between the size of the effect of *Broadband* and the level of development in the region. The hypothesis is that more peripheral regions, with lower density of economic activity and, thus, less developed, may

speed in the region is zero.

obtain higher productivity gains from broadband connections as this technology will allow economic agents in these regions to offset some of the costs of peripherality, making location in the region more attractive for production. To test this hypothesis, regions are classified in three groups according to the level of development, measured through the average GVA per worker in the period under analysis.[25] Based on this classification, binary variables were created to identify the regions belonging to each group (*LP*, *MP* and *HP* for low-, medium-, and high-productivity, respectively).

Using this information, the specification of equation (2a) is defined as:

$$A = \Omega(X)\ BB^{(\delta_{HP}+\delta_{MP}MP+\delta_{LP}LP)}$$

where δ_{HP} measures the effect of *Broadband* for the group of most developed regions, and that for the other two groups is obtained by adding the corresponding parameter, δ_{MP} or δ_{LP}. A conspicuous way of checking the hypothesis under analysis is testing that $\delta_{MP} = \delta_{MP} = 0$.

The last column in Table 3 summarizes the results of the IV estimation of this specification. They confirm that important differences among regions do in fact exist, and that they are linked to the level of development. All regions benefit from broadband, but the less developed appear to obtain much larger productivity gains than medium and highly developed regions. To be clear, the increase in regional productivity induced by increasing broadband penetration by 10% is estimated to be 0.19% and 0.15%, respectively, in the groups of regions with high and medium levels of development, while it raises up to 0.43% in the group of the less developed Brazilian regions. Therefore, on average, these results suggests that the impact of broadband on productivity is particularly high for regional economies with low levels of productivity and, therefore, of development, and falls to about half as the regions develop further. Overall, these results support the hypothesis in this paper about the regionally differentiated impact of broadband on productivity.

[25] Low-Productive regions: Piauí, Maranhão, Ceará, Paraíba, Alagoas, Rio Grande do Norte, Bahia, Pernambuco, Sergipe. Medium-Productive regions: Tocantins, Goiás, Pará, Mato Grosso do Sul, Minas Gerais, Acre, Amapá, Paraná, Roraima. High-Productive regions: Mato Grosso, Rondônia, Santa Catarina, Espírito Santo, Rio Grande do Sul, Amazonas, Rio de Janeiro, São Paulo, Distrito Federal.

6. **Conclusions**

This paper has aimed to provide evidence on the impact of broadband on productivity in an emerging country such as Brazil and, particularly, on the fact that these effects are not uniform across the territory. In fact, broadband seems to be yielding higher productivity gains for regions which exhibit a minimum threshold of penetration levels (providing evidence of network effects), as well as regions with higher quality in its internet infrastructures, denoted by the broadband speed. Moreover, further analysis provided evidence of a higher effect of broadband on productivity for the less developed regions. With due caution and acknowledging the limitation of the study, this results suggest that isolated regions have been able to overcome some of the disadvantages associated to their remote location, and to benefit from opportunities that were not available before. Another possible explanation may be related to disadvantaged regions benefiting from lower costs, as broadband surely reduced the relevance of distance to the core. Finally, diminishing returns might be contributing to reduce the economic impact in most advantaged regions, although this would be in conflict with the evidence reported as to the importance of a critical mass in broadband adoption.

Even if a convergence analysis remained out of the scope of this paper, our results suggest that broadband connectivity might constitute a factor favoring regional cohesion in an emerging economy such as the Brazilian. Barrios et al (2008) found that ICT investments contributed significantly to regional convergence in Spain. They also stated that the development of ICT activities constitute a potentially good candidate for promoting regional development. In the same line, Ding et al (2008) suggested that telecommunication infrastructure contributed significantly to regional convergence in China, supporting investment policies in telecom in lagged regions of developing countries. They pointed out that facilitating telecommunication infrastructures is important for assisting economic growth in the least developed regions of developing countries with poorly developed telecom infrastructure. To confirm that assertion for the case of Brazil, further research will be required, especially when long enough time series data is available to perform a long-term growth-regression analysis.

In any case, broadband connectivity appears to be a source of productivity gains in Brazil, something that would provide empirical support to the recently deployed public program of connectivity "Programa Nacional de Banda Larga”, although data availability from more recent periods and a robust analysis of the causal effect will be needed for a proper assessment of the impact of this policy intervention.

To conclude, some policy implications can be derived from the analysis. The importance of broadband for regional development makes that all levels of government should implement policies that encourage broadband deployment. Although referring to the case of Europe, Barrios and Navajas (2008) stated the importance to adopt, together with country-level initiatives, regional policies, because the nature of technological change and innovation have a strong regional component that make that public policies must be designed taking the regional dimension into account. In Brazil, its federal configuration makes possible for some states to promote active policies for the deployment of broadband networks, designed according to the particularities of each region. Some states have already started to follow this strategy, as for instance Paraná and Amapá, which have launched state-based public broadband plans with the aim of complementing the national plan. In the same vein, Barrios and Navajas (2008) highlighted the importance that regional cohesion policies consider the relevance of ICT infrastructure, aiming to favor the attractiveness of less developed regions. They even call for differentiated intervention, even among regions within a country. Regional policies should also promote ICT skills and the use of ICT by small and medium size enterprises (Barrios et al, 2008).

In this context, investment from service providers in broadband infrastructure is critical, both in terms of coverage and speed. As stated by Crandall et al (2007), it is essential that regulatory policies do not reduce investment incentives for carriers. In particular, policymakers should adopt measures that promote, or at least do not inhibit, the growth of broadband. In density-populated areas, private competition will surely provide the required incentives which will lead to higher investments and better connectivity. In those markets, it will be necessary from federal and state governments to reduce barriers and promote investment by service providers. Beyond promoting a competitive market, public authorities can contribute to reduce investment costs by, for instance, allowing operators the use of public infrastructures, giving facilities for network sharing, and reducing bureaucracy and other red-tape associated costs. On the other hand, in distant areas, with low levels of population and economic density, or affected by adverse geographical conditions, public intervention will definitely become vital for infrastructure deployment. In those cases, universalization policies might become crucial. As stated by Frieden (2005), broadband investment requires important levels of public and private cooperation. The results in this paper prove that the return of these policies is likely to be quite high.

Beyond broadband, most recent advances related to Industry 4.0, such as IoT, Big Data and Artificial Intelligence, will surely provide further productivity gains, and as a result, public authorities should design specific programs in order to massify those deployments. Most advanced countries such as Germany, Sweden, Italy or Spain have launched specific Industry 4.0 programs in recent years. Emerging economies, such as Brazil, should not afford missing the opportunity of being part of this so-called fourth industrial revolution. However, results in this paper suggest that there may be winner and loser territories in this process, as deployment of these sophisticated technologies and their impact on productivity may widely vary across regions within the same country.

Policy will also need to promote connectivity from the demand-side. Lower prices are necessary to increase penetration, because, as stated by Galperin and Ruzzier (2013), broadband demand is elastic. Promoting flexibility in commercial offers, as well as tax reductions for low-income segments, and small-low productive firms, may constitute feasible alternatives to tackle affordability barriers. Additionally, to maximize demand and social returns to broadband deployment, policymakers should address eventual ICT-related skills among the workforce.

Our results confirm that downloading speed is relevant to enhance the economic impact of broadband, and it will probably become more important in the future, as data traffic through the networks is increasing and will start to strain current infrastructures. For that reason, policymakers should provide a framework which can stimulate the deployment of high-speed networks, such as fiber optic and 5G, particularly in the less dynamic areas of the country.

Although not addressed in this study, mobile broadband may also constitute an opportunity to close the digital-divide, especially through its potential to connect isolated distant areas (Katz, 2012). In that sense, spectrum allocations will be required to provide necessary resources for deployment of new generation services as 5G.

The results reported and the implications derived from them might be affected by the assumptions and limitations of the study. In the first place, lack of data prevented us to contrast other possible sources of regional heterogeneity in the impact of broadband on productivity, which may explain why less developed regions are extracting more benefits from this technology. Secondly, while we have proxied firm-level broadband diffusion with population penetration, more accurate results will surely be found if the former data were available. Similarly, we used a measure of fixed broadband, which was the most common in Brazilian enterprises during the period analyzed, although a more complete analysis should have also considered other technologies for internet access. Thirdly, even when our state-level analysis in Brazil marks a clear advance over previous studies about the impact of broadband on aggregate productivity, data unavailability prevented us from carrying out the study with more disaggregated geographical units. In this regard, it can be argued that smaller geographical units will increase the sample size with which the effect of interest will be estimated and, at the same time, will decrease heterogeneity within the spatial units analyzed. However, working with smaller units usually involves, at best, imperfect information about the determinants of aggregate productivity, and even lack of data to compute such outcome variable. In addition, different sources of externalities that are likely to cross the borders of smaller spatial units (such as counties and municipalities) might lead to over- or under-estimate the impact of broadband on productivity. Such type of spillovers are likely to be captured in estimates using wider geographical units such as the Brazilian states. Last, but not least, we should acknowledge that the quality of the results and the corresponding implications lie on the quality of the indicator of broadband and the instruments used to implement the IV estimator. Further studies should confirm or refute the results in this study for Brazilian states and/or for other emerging and developing countries.

References

Ahlfeldt, G., Koutroumpis, P., & Valletti, T. (2017). Speed 2.0: Evaluating access to universal digital highways. *Journal of the European Economic Association*, 15(3), 586-625.

Aschauer, D. A. (1989). Is Public Expenditure Productive? *Journal of Monetary Economics,* 23, 177-200.

Barrios, S. & Navajas, E. (2008). The location of ICT activities in EU regions. Implications for Regional Policies. *Investigaciones Regionales*, 13, 179-210.

Barrios, S., Mas, M., Navajas, E., & Quesada, J. (2008). Mapping the ICT in EU regions: location, employment, factors of attractiveness and economic impact. IPTS, Joint Research Centre, European Commission (DOI 10.2791/88700)

Bauer, J. M. (2018). The Internet and income inequality: Socio-economic challenges in a hyperconnected society. *Telecommunications Policy*, 42, 333-343.

Bertschek, I., Briglauer, W., Hüschelrath, K., Kauf, B., & Niebel, T. (2015). The economic impacts of broadband internet: A survey. *Review of Network Economics*, 14(4), 201-227.

Bertschek, I., Cerquera, D., & Klein, G. (2013). More Bits – More Bucks? Measuring the Impact of Broadband Internet on Firm Performance. *Information Economics and Policy*, 25, 190-203.

Billón, M., Ezcurra, R., & Lera-López, F. (2009). Spatial effects in website adoption by firms in European Regions. *Growth and Change*, 40, 54-84.

Billón, M., Marco, R., & Lera-López, F. (2009). Disparities in ICT adoption: A multidimensional approach to study the cross-country digital-divide. *Telecommunications Policy*, 33, 596-610.

Bonaccorsi, A., Piscitello, L., & Rossi Lamastra, C. (2005). The ICT Diffusion: A Spatial Econometric Approach. ERSA conference papers ersa05p92, European Regional Science Association.

Cairncross, F. (2001). *The Death of Distance: how the communications revolution will change our lives*. Harvard Business School Press, Cambridge, MA, USA.

Canzian, G., Poy, S., & Schüller, S. (2015). Broadband Diffusion and Firm Performance in Rural Areas: Quasi-Experimental Evidence. IZA Discussion Paper No. 9429

Cardona, M., Kretschmer, T., & Strobel, T. (2013). ICT and Productivity: conclusions from the empirical literature. *Information Economics and Policy*, 25, 109-125.

Caselli, F. (2005). Accounting for cross-country income differences. *Handbook of Economic Growth*, 1, 679-741.

Castaldo, A., Fiorini, A., & Maggi, B. (2018). Measuring (in a time of crisis) the impact of broadband connections on economic growth: an OECD panel analysis. *Applied Economics,* 50(8), 838-854.

Celbis, M. G., & de Crombrugghe, D. (2018). Internet infrastructure and regional convergence: Evidence from Turkey. *Papers in Regional Science*, 97(2), 387-409.

Coe, D. T. & Helpman, E. (1995). International R&D spillovers. *European Economic Review*, 39, 859-887.

Crandall, R. W., Lehr, W., & Litan, R. E. (2007). The effects of Broadband deployment on Output and Employment: a cross-sectional analysis of US data. The

Brookings Institution, Issues in Economic Policy, June. http://www.brookings.edu/research/papers/2007/06/labor-crandall.

Czernich, N., Falck, O., Kretschmer, T., & Woessman, L. (2011). Broadband infrastructure and Economic Growth. *The Economic Journal,* 121, 505-532.

Czernich, N. (2014). Does broadband internet reduce the unemployment rate? Evidence for Germany. *Information Economics and Policy*, 29, 32-45.

Da Silva Filho, T. N. T. (2002). Estimating Brazilian potential output: A production function approach. Working Papers Series 17, Central Bank of Brazil, Research Department.

Ding, L., Haynes, K. E., & Liu, Y. (2008). Telecommunications infrastructure and regional income convergence in China: panel data approaches. *The Annals of Regional Science*, 42, 843-861.

Feenstra, R. C., Inklaar, R., & Timmer, M. P. (2015). The Next Generation of the Penn World Table. *American Economic Review,* 105, 3150-3182.

Fernández-Ardèvol, M. & Vázquez Grenno J. (2011). Estimación de la contribución de la telefonía móvil al crecimiento y reducción de la pobreza. In Fernández-Ardèvol, M., Galperin, H., & Castells, M. (eds), *Comunicación móvil y desarrollo económico y social en América Latina*, Barcelona, Spain: Ariel, Fundación Telefónica, 81-131.

Frieden, R. (2005). Lessons from Broadband development in Canada, Japan, Korea and the United States. *Telecommunications Policy*, 29, 595-613.

Ford, G. S. (2018). Is faster better? Quantifying the relationship between broadband speed and economic growth. *Telecommunications Policy*, 42(9), 766-777.

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

Galperin, H. & Ruzzier, C. A. (2013). Price elasticity of demand for Broadband: evidence from Latin America and the Caribbean, *Telecommunications Policy*. 37, 429-438.

Gruber, H., Hätönen, J., & Koutroumpis, P. (2014). Broadband access in the EU: An assessment of future economic benefits. *Telecommunications Policy*, 38(11), 1046-1058.

Gruber, H., & Koutroumpis, P. (2011). Mobile telecommunications and the impact on economic development. *Economic Policy*, 26(67), 387-426.

Haftu, G. G. (2018). Information Communications Technology and economic growth in Sub-Saharan Africa: A panel data approach. *Telecommunications Policy,* in press: https://doi.org/10.1016/j.telpol.2018.03.010

Hall, R. E. & Jones, C. I. (1999). Why Do Some Countries Produce so much more Output per Worker than Others. *Quarterly Journal of Economics*, 114: 83–116.

Holt, L., & Jamison, M. (2009). Broadband and contributions to economic growth: Lessons from the US experience. *Telecommunications Policy*, 33(10-11), 575-581.

International Telecommunication Union (2006). *World telecommunication/ICT development report 2006. Measuring ICT for social and economic development*. Geneva: ITU.

Ivus, O., & Boland, M. (2015). The employment and wage impact of broadband deployment in Canada. *Canadian Journal of Economics/Revue canadienne d'économique,* 48(5), 1803-1830.

Jordán, V. & De León, O. (2011). Broadband and the digital revolution. In Jordán, V. & Galperín, H. (eds), *Fast-tracking the digital revolution: Broadband for Latin America and the Caribbean*, 13-48. Santiago, Chile: United Nations.

Kandilov, I. T., & Renkow, M. (2010). Infrastructure investment and rural economic development: an evaluation of USDA's broadband loan program. *Growth and Change*, 41(2), 165-191.

Katz, R. (2012). *Impact of Broadband on the Economy. Broadband series. Telecommunication Development Sector*. International Telecommunications Union. Geneva, Switzerland.

Katz, R., & Callorda, F. (2013). Economic impact of Broadband deployment in Ecuador. IDRC Digital Library. https://idl-bnc-idrc.dspacedirect.org/handle/10625/53797

Katz, R., Vaterlaus, S., Zenhäusern, P., & Suter, S. (2010). The impact of Broadband on jobs and the German economy. *Intereconomics*, 45, 26-34.

Kelly, K. (1998). *New rules for the new economy. Ten ways the network economy is changing everything*. Fourth Estate, London, UK.

Kolko, J. (2012). Broadband and Local Growth. *Journal of Urban Economics,* 7, 100-113.

Koutroumpis, P. (2009). The economic impact of Broadband on growth: a simultaneous approach. *Telecommunications Policy*, 33, 471-485.

Lehr, W. H., Osorio, C. A., Gillett, S. E., & Sirbu, M. A. (2006). Measuring Broadband's Economic Impact, MIT Engineering Systems Division WP Series ESD-WP-2006-02.

Negroponte, N. (1995). *Being Digital*. Knopf, New York, NJ, USA.

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

Mack, E. A., & Rey, S. J. (2014). An Econometric Approach for evaluating the linkages between Broadband and Knowledge Intensive Firms. *Telecommunications Policy*, 38, 105-118.

McCoy, D., Lyons, S., Morgenroth, E., Palcic, D., & Allen, L. (2018). The impact of broadband and other infrastructure on the location of new business establishments. *Journal of Regional Science*, 58(3), 509-534.

Quah, D. (2000). Internet cluster emergence. *European Economic Review*, 44, 1032-1044.

Rohman, I. K. & Bohlin, E. (2012). Does Broadband speed really matter as a driver of economic growth? Investigating OECD countries. *International Journal of Management and Network Economics*, 2, 336-356.

Röller, L. H. & Waverman, L. (2001). Telecommunications infrastructure and economic development: a simultaneous approach. *American Economic Review*, 91, 909-923.

Romer, D. (2006). *Advanced Macroeconomics*, McGraw Hill, New York.

Romer, P. M. (1990). Endogenous technological change. *Journal of Political Economy*, 98, S71-S102.

Shideler, D., Badasyan, N., & Taylor, L. (2007). The economic impact of broadband deployment in Kentucky. *Regional Economic Development*, (Nov), 88-118.

Solow, R. (1956). A contribution to the theory of economic growth. *Quarterly Journal of Economics*, 70, 65-94.

Stocker, V. & Whalley, J. (2018). Speed isn't everything: A multi-criteria analysis of the Broadband consumer experience in the UK. *Telecommunications Policy* 42, 1-14.

Suriñach, J., Romaní, J., & Termes, M. (2007). ¿Afecta la banda ancha al crecimiento económico? Evidencia sobre agentes y territorio. *Investigaciones Regionales*, 10, 207-235.

Thompson, H. G. & Garbacz, C. (2011). Economic impacts of mobile versus fixed Broadband. *Telecommunications Policy*, 35, 999-1009.

Vicente, M. R. & López, A. J. (2011). Assessing the regional digital-divide across the European Union-27. *Telecommunications Policy*, 35, 220-237.

Whitacre, B., Gallardo, R., & Strover, S. (2014). Broadband′ s contribution to economic growth in rural areas: Moving towards a causal relationship. *Telecommunications Policy*, 38(11), 1011-1023.