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1. Introduction

Theoretical models of spatial distribution of economic activity following the seminal contributions of Krugman (1991) on the one hand predict that labour and capital should concentrate in and around centres generating economies of scale, and on the other, that the level of activity should weaken continuously as distance from the centres grows. In reality many forms of distortions including natural “first order” causes as well as man-made second order determinants, imply that the observed distribution of economic activity departs from these theoretical predictions. The latter group of factors includes in particular man-made boundaries which restrict the smooth operation of economic forces, and most importantly international borders, which impose limitations on trade and mobility of capital and labour. At the same time human interventions – through creation of physical links facilitating operation of these economic forces, may contribute to more even special distribution of economic activity by overcoming the obstacles generated by nature in the form of mountain ranges or rivers.

In parallel to models in new economic geography (Hanson 1996; Davis and Weinstein 2002; for surveys see: Fujita, Krugman and Venables 1999), modern theories of economic growth have for a long time suggested convergence in economic activity between countries and regions (see e.g., Barro et al. 1991; Bernard and Durlauf 1995; Acemoglu et al. 2001; Kline and Moretti 2013, for a partial critic see Quah 1997). Finally, also the international literature on trade has been concerned with convergence over national borders (Anderson and Van Wincoop 2003, 2004; Evans 2003). Overall, from the point of view of economic activity observed at the local level, these three strands of literature would thus suggest a process of catching up of weaker regions and convergence in economic performance in response to lifting of physical or man-made constraints.

In this paper we focus on the region along the Polish-German border. Adopting the perspective of the above broad theories we first examine the degree of regional level convergence by looking at medium term developments of municipalities along the river-delimited part of the border between Poland and Germany. For this purpose, we take advantage of satellite night-time illumination data which cover the period between 1992 and 2012, which is a time of dynamic changes in economic activity on both sides of the Oder-Neisse border. The seminal work by Henderson et al. 2012 was first to use night-time light intensity data, which covers the entire globe, to measure the intensity of economic activity. After this initial study this innovative approach has been used to analyse regional development by numerous other researcher and the data have been validated against traditional measures of economic performance (see, e.g., Zhao et al. 2011; Michalopoulos and Papaioannou 2013, von Ehrlich and Seidel 2014; see also Huang et al. 2014 for review; this data has also been used earlier in other sciences, e.g.: Elvidge et al. 2009; Ghosh et al. 2009).

This novel measure is of particular importance for our project as it allows consistent measurement of economic development to compare Poland and Germany over a long period of time. In addition to this, unlike the traditional regional economic indicators which are reported for specific administrative units and may be not comparable before and after administrative reforms, light intensity data is independent of administrative border reforms, which have occurred on both sides of the border.

Thus, the aggregate convergence between border regions in Germany and Poland is of prime concern in the first part of our results section. This overall picture is interesting to scientists and policy makers alike. Especially, the long-term period of our study makes it worthwhile as certain trends can be identified and related to the stages of the European integration process.

Given that the data can be disaggregated to very small geographical units (geographical raster of approx. 1000m x 1000m), we can provide more insights to the precise patterns of the geographical distribution in economic activity. Thus, apart from the overall trends, we also analyse how economic performance measured with night-time lights varies by the distance from the border. For the purpose of this analysis we matched the light data with recent regional administrative boundaries at the municipal level (*Gminas* in Poland and *Gemeinden* in Germany). Using the geographical centroid of those administrative units we can calculate the raw distance of the municipality to the German-Polish border. Moreover, we complemented the data with information on the exact geographical location of the 20 bridge border crossings along the river-delimited part of the border (bridges for individual transfer only).[2] With this geographical information, we can then also calculate more precise measures of distance between a municipal centroid and the closest border bridge. Also, we determined the exact travel time between each municipality and the closest

[2] We also considered pedestrian bridges in the beginning. However, economic activity from pedestrian bridges is necessarily locally very confined. Also, there are a number of bridges for train traffic. While those train bridges might generally be important for the economic integration between Germany and Poland, we believe that the exact locations of those train bridges are not as important (freight trains could easily take a longer detour without it mattering as much). As for train bridges, it is important to note that most train bridges in fact coincide with road bridges.

border bridge. While from the economic point of view the final measure appears the most appropriate one to measure distance, it unfortunate that we can only use recent travel time data (data accessed in July 2018). This is because we lack historical online maps of road infrastructure to make our travel time data historically accurate.

Equipped with these detailed information on the precise geographical distribution of economic activity, we can highlight the developments of economic performance by distance from the border on both sides of the river Oder-Neisse. In this respect, we turn to regression analysis using fixed effects estimation (country and year) to isolate the correlation between distance to the border and economic activity.

Related to research of direct border effects as well as the importance of distance to the border, economic theory provides an array of hypotheses guiding our empirical analysis. A number of related strands of literature can be identified. First, researchers have been interested in the argument of access to markets (see Redding and Sturm 2008). When restrictions on national borders are eliminated, municipalities close to the border effectively increase the potential market to trade with. From this literature, one would expect both German and Polish towns to economically profit from the elimination of boundary given by national borders. Second, a literature on local labour markets across national borders has shown that there are sorting effects as well as displacement effects of native workers (see Rosen 1979, Roback 1982, Dustmann et al. 2017). The prediction from interaction of local labour markets is mixed. One could argue that highly qualified Polish labourer would prefer migrating to the close German regions and thereby improve the German productivity. However, it could also be the case, that Polish workers (of all qualifications) migrate and the German native workers are displaced to other regions further inland (see Dustmann et al. 2017). Third, there are studies concerned with cross-border competition effects (see, e.g. Cassette et al. 2012). If Polish regions along the border are more competitive with lower wages and overall lower production costs, the elimination of restraints along the national border, would result in increased growth in the Polish border towns and stagnating or possibly reductions in economic prosperity on the German side. Finally, fourth, the literature on regional economic development across national borders highlights an argument denoted "death of distance". Along with better infrastructure (better and more roads and bridges) and along with the digitalisation of trade and services, this literature argues that distance becomes less of an economic factor (see Engel and Rogers 1996, McCallum 1995, Brun et al. 2005, Lin and Sim 2012, Jacks

2009). While the evidence for this phenomenon is mixed, with year-by-year cross country regressions of the gavity trade model usually underpinning the argument, but many local level studies still showing persistent border effects, the death of distance argument would imply, that the effect of distance to the border would depend on time and should become smaller or even insignificant.

Our analysis suggests that over the analysed period from 1992-2012 there has been essentially full convergence in economic activity between municipalities on both sides of the Polish-German border. While the average value of night-time illumination in our selected group of municipalities in 1992 was 3.7 (on a scale between 0 and 63) in Poland and 7.7 in Germany, by the time of 2012, the respective values were 9.0 and 9.7, and the latter difference is not statistically significant.. Since the German municipalities started the period with higher degree of night-time illumination, this convergence suggests a much stronger rate of growth in economic activity as measured by night-time lights in Poland. By examining the distance of municipalities on both sides of the border to bridge border crossing we identify that Germany and Poland show very different trends. Within Germany the distance to the border has much less relevance for economic activity. During the observation period, we observe little significant differences between towns far and close to the border. In contrast, the Polish side of the border shows strong trends. In 1992, towns further from the border showed significantly higher economic performance as measured by light emissions. This gap in economic performance within Poland has been significantly reduced by towns close to the border over the 20 year observation period with regions closer to the border growing much faster compared to those further away.

The paper is structured as follows. We provide a brief overview over the main historical events shaping the region along German-Polish border in the period under analysis. This is only to complement the economic analysis and put the time period into historical perspective. Then, we provide more details on the data used in our analysis as well as on how we calculated and determined our distance measures from the geographical information. In Section 4, we turn to our analysis and we discuss the results in two part. First, we focus on the aggregate development comparing German and Polish municipalities with a radius of 100 km from the border. Then, we investigate the more detailed patterns of the geographical distribution in Section 4.2. Section 5 concludes the analysis.

2. Brief historical background

The period covered by our analysis is a time of dynamic socio-economic changes on both sides of the Polish-German border. After the political breakthrough of 1989 and the initial shock of the economic transformation, the 1990s were years which saw gradual economic recovery in Poland, while sustained support from the West German Länder started to take effect and provided a stimulus for economic development in the former GDR.[3] It is important to bear in mind though, that Poland's and GDR's GDP between 1989 and 1991 fell respectively by about 20% and 40%, with significant consequences for the situation on the labour market, incomes and welfare. While Poland had to face a set of strict policies to limit inflation and reorientate its trade, the challenge for the Eastern Länder became large flows of the population (around net 1.3m people moved westwards) and rapidly falling birth rates (Münz and Ulrich 1995). Recovery on both sides of the Oder-Neisse border begun already in the early 1990s, at about the time when our lights data begin, and Poland's GDP reached its pre-1989 levels already in 1996 (Keane and Prasad 2002).

The region we examine, which covers municipalities up to 100 km on each side of the Oder-Neisse border rivers, was no exception to the general macro trends, especially that prior to the transition the economic strategy in the bordering regions focused on development of industry. After the transition reforms started around 75% manufacturing jobs were lost in the Brandenburg area by 1995, while in the Gorzów voivodeship the number fell by 12% by 1993 (Kratke 1999). This massive difference in the negative impact of the transition process was party an effect of equalising the eastern and western currency, which resulted in a ten-fold wage difference between German and Polish workers in the early 1990s.

What is also interesting from the point of view of analysing the socio-economic processes along the border is how distant the neighbouring Poles and Germans were towards each other. For example according to a poll reported in Kratke (1999) only 2.7% of Germans in Frankfurt and Guben and 2.4% of Poles in their respective twin cities (Słubice and Gubin) in the 1990s would accept members of the opposite nationality as members of their family. These numbers have significantly changed since then with only 7% of Germans and 12% of Poles living in the border

[3] That said, it should also be noted, that the substantial transfers from West to East did not result in a uniform geographic distribution of economic activity. The reunification saw many East German trades (traditional industry or agriculture) heavily hit by the sudden level of competition, leading to vast differences in the development of regions.

regions declaring that they would feel uncomfortable having someone from the other side of the border as a family member (European Commission, Directorate-General for Regional and Urban Policy, and TNS Political & Social 2015).[4] This means that the integration processes which followed increases in cross-border trade and mobility among people, especially following Poland's entry in to the EU in 2004 and into Schengen in 2007, have not only contributed to economic development but also brought important social changes in the region.

The social process behind economic statistics is important from the point of view of interpretation of our results, in particular given the nature of the data we use. The night-time lights data is a proxy for a general level of activity thus covering also population movements in and out of the analysed areas. Yet from the point of view of understanding of the overall trend and general inter-regional convergence, it seems that such general measure is precisely what one should focus on.

3. Data

3.1 Night-time illumination data

An important advantage of the data source we use in our analysis – the night-time illumination data – is that it has been collected in a consistent format through two decades. The series, provided by the National Oceanic and Atmospheric Association (NOAA), starts as early as 1992 and continues to 2012. Moreover, the data is independent of administrative structure of local government, which over time changed on both sides of the border. This allows us to aggregate the night-time lights information for municipalities using the most recent available administrative borders. This data represents essentially the only source of information on economic activity which is consistently available on both sides of the border.

The night-time lights data have been recently widely used as a proxy of economic development on country level (Henderson, Storeygard, and Weil 2012; M. Pinkovskiy and Sala-i-Martin 2016) and a number of papers demonstrated its usefulness for sub-national analysis (Wang et al. 2019; Bickenbach et al. 2016; Mellander et al. 2015). Clearly, the intensity of night-time lights is unlikely to capture the entire spectrum of economic activity, and the format of the data available for the

[4] Own calculations using Eurobarometer 422 data aggregated for 3 cross-border regions: CB011 Germany/Brandenburg-Poland, CB018 Poland-Germany/Saxony and CB019 Germany (Mecklenburg-West Pomerania/Brandenburg)-Poland; http://data.europa.eu/euodp/data/dataset/S1565_422_ENG

analysed period suffers from top coding, bottom censoring, measurement error due to blurring and satellite sensitivity. However, in our paper we focus on mostly rural and sparsely populated areas where there is little top censoring and to correct for changes in satellite sensitivity we employ intercalibration across satellite/years using parameters obtained from the literature (Elvidge et al. 2009; Hsu et al. 2015; Elvidge et al. 2014, 1999). In this process recorded light pixel values (Digital Number, DN) for each satellite-year are adjusted according to a selected constant illumination area across the dataset.

Our dataset consists of municipalities, delineated according to municipal borders from 2012 (PL) or 2013 (DE), which are located within 100 km from the PL-DE border as measured from the centroid of the municipality. To focus specifically on the river-delineated border we only include municipalities below the last border bridge on the Odra/Nysa Łużycka river (53.33N). Additionally, to avoid the sensitivity of the analysis to top censoring we removed regional capital cities: Berlin, Dresden, Gorzów Wielkopolski and Zielona Góra. Moreover, since Berlin, as the German capital is the main agglomeration in the analysed region with strong implications for local development in municipalities around it, we additionally excluded municipalities within a 20 km radius around Berlin. This leaves us with 488 municipalities on the German side of the border and 193 municipalities on the Polish side.

3.2 Measures of distance

To identify the role of location vis-à-vis the border, we employ three measures of distance. First we use a simple measure of minimum distance of municipal centroids, regardless of whether a border crossing exists in the particular point of reference. Secondly, we measure the distance from municipal centroids to the closest available bridge border crossing. Finally to measure distance to bridges as expressed through travel time we measure the average time of travel from each municipality to the nearest road bridge on the Oder or Neisse rivers (footpaths and railroad bridges have been excluded, for more details on existing bridges along the Oder/Neisse rivers see: Trzciński 2018). To calculate travel time to road bridges we used the road network from OpenStreetMap (OpenStreetMap contributors, 2018).[5] The procedure involved importing the whole road network for the bordering regions (NUTS-2 level) from the OSM data into PostGIS. Following this the pgRouting's Dijkstra algorithm was used to find the roads to the nearest bridge

[5] Map data copyrighted OpenStreetMap contributors and available from https://www.openstreetmap.org

for each road fragment. For each municipality we calculated the average travel times to the nearest bridge from these fragments using road speeds conditional on OSM road types.[6] The interpolated map of average travel times to the nearest bridge for municipalities on both sides of the border is shown in Figure A1 in the Appendix. Such approach implies that the calculated travel time is the time on most recent road infrastructure which naturally calls for caution with regard to the interpretation of the results. Using this method it is impossible to construct respective travel times going backward in time which would have been our preferred approach.

As we can see in Table 1 the consequence of a relatively high number of bridge crossings along the river is that the mean distance to the border is not much greater than the mean distance to the nearest bridge with the average difference between the two of about 4 km. In both cases the distances are about 3 km greater in Poland and this translates also to slightly longer travel time on the Polish side of the border of 0.85 hours compared to 0.76 hours in Germany. Naturally travel times increase gradually for municipalities farther from the border, but as we can see on Figure A1 there is also some influence on travel time related to the quality of the road network with shorter times for municipalities lined up along the motorways and principal roads.

Table 1. Municipalities along the border: descriptive statistics

	Germany		**Poland**	
Number of municipalities	488		193	
Mean area [km^2]	57.9	(56.8)	144.4	(90.9)
Mean distance to border [km]	45.6	(29.9)	49.7	(28.7)
Mean distance to nearest bridge [km]	47.6	(29.0)	51.5	(28.1)
Mean travel time to nearest bridge [h]	0.76	(0.43)	0.85	(0.44)
Mean municipal total lights [DN/px]				
- 1992	7.728	(7.175)	3.700	(5.211)
- 2002	9.624	(8.045)	7.146	(6.618)
- 2012	9.710	(7.480)	9.024	(6.784)

Notes: municipalities along the PL-DE river border up to 100 km to the border; outlier municipalities excluded from analysis due to high proportion of top-coded lights pixels in 1992; municipality borders as of 2013 (DE) and 2012 (PL); mean municipal total lights calculated using average pixel values per municipality and weighted by municipality area.
Source: own calculations based on data from: GeoBasis-DE / BKG 2013, PRG 2012, DMSP OLS v4 and OpenStreetMap.

[6] We used osm2po http://osm2po.de/ to import OSM routing into PostGIS (for details see osm2po documentation).

4. Results

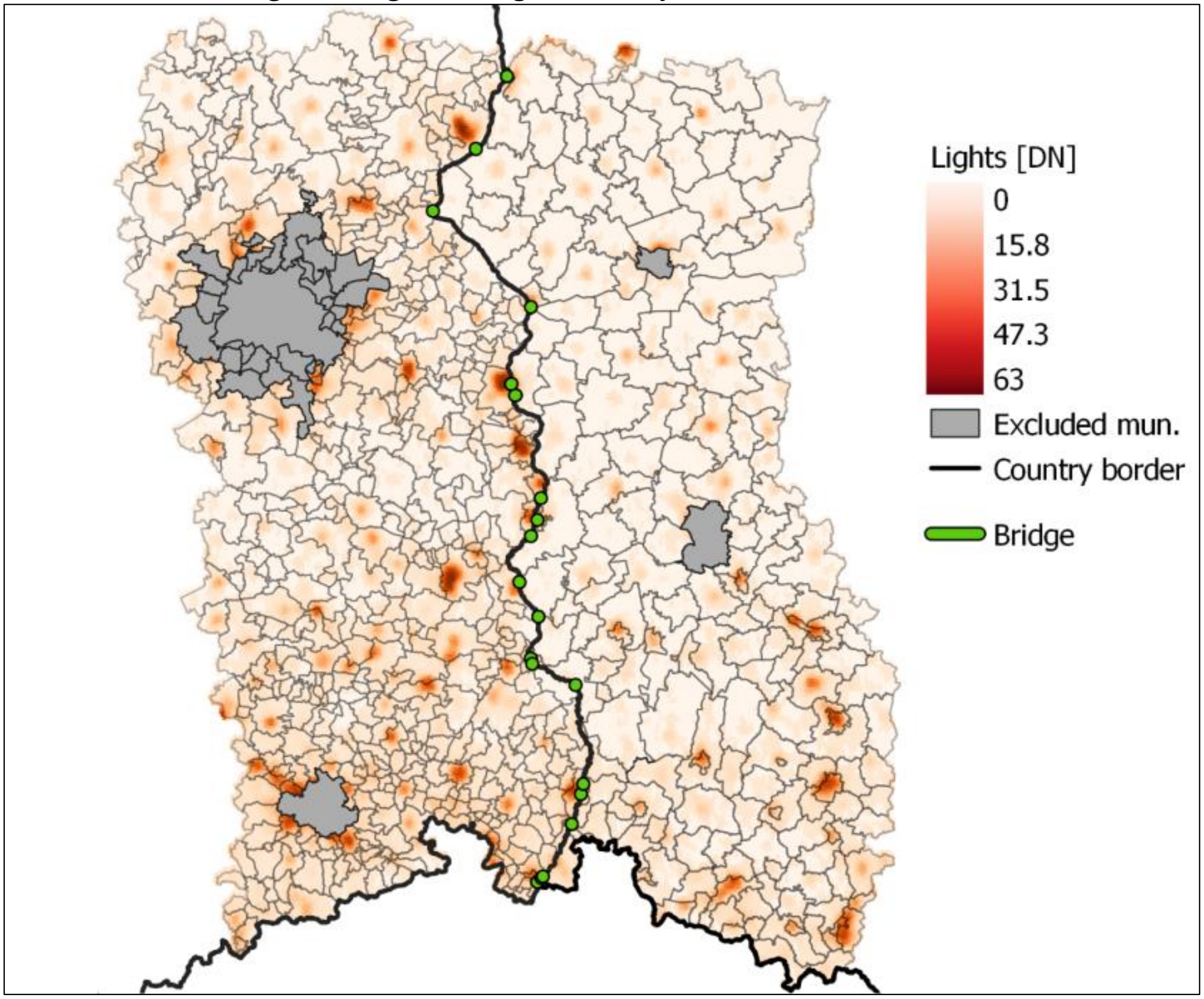
Results of our analysis are split into two parts. First, we evaluate the overall changes in the night-time light intensity in our observation period from 1992 to 2012. Here the focus is on the group of municipalities within 100 km from the border irrespective of the exact distance to the border. Second, we turn to the question about how important distance to the border is for economic performance. Here, we will provide graphical illustrations as well as estimation results on the importance of distance measured along the three dimensions discussed above (distance to border, distance to closed border bridge, travel time to closest border bridge).

4.1 Changes in night-time light intensity: 1992-2012

To understand the overall development of economic activity – as measured by night-time light intensity, we start by mapping the lights data for all municipalities within a 100 km distance from the Oder-Neisse border. Figure 1 highlights the light intensity as recorded in our earliest observation year, 1992. The light intensity is indicated by a scale of red (on an absolute scale between 0-63 points). A darker area implies higher light emissions and this in turn – as discussed above – serves as a proxy of higher degree of economic activity. We have marked the excluded municipalities (due to top-coding) in grey and we have superimposed the positions of the 20 border bridges with green dots.

The following observations can be made from the 1992 map. The average light intensity on the German side is higher. Consistent with the averages highlighted in Table 1, the German towns and municipalities appear significantly darker on the lights scale. The map also presents the expected pattern that local centres and larger towns show higher light emissions. On the German side, we for example observe high light emissions in Frankfurt/Oder, close to Cottbus (due to brown coal mining) and around the areas of Dresden. On the Polish side, we have clear economic centres of activity in Legnica and Lubin in the south and Stargard in the north.

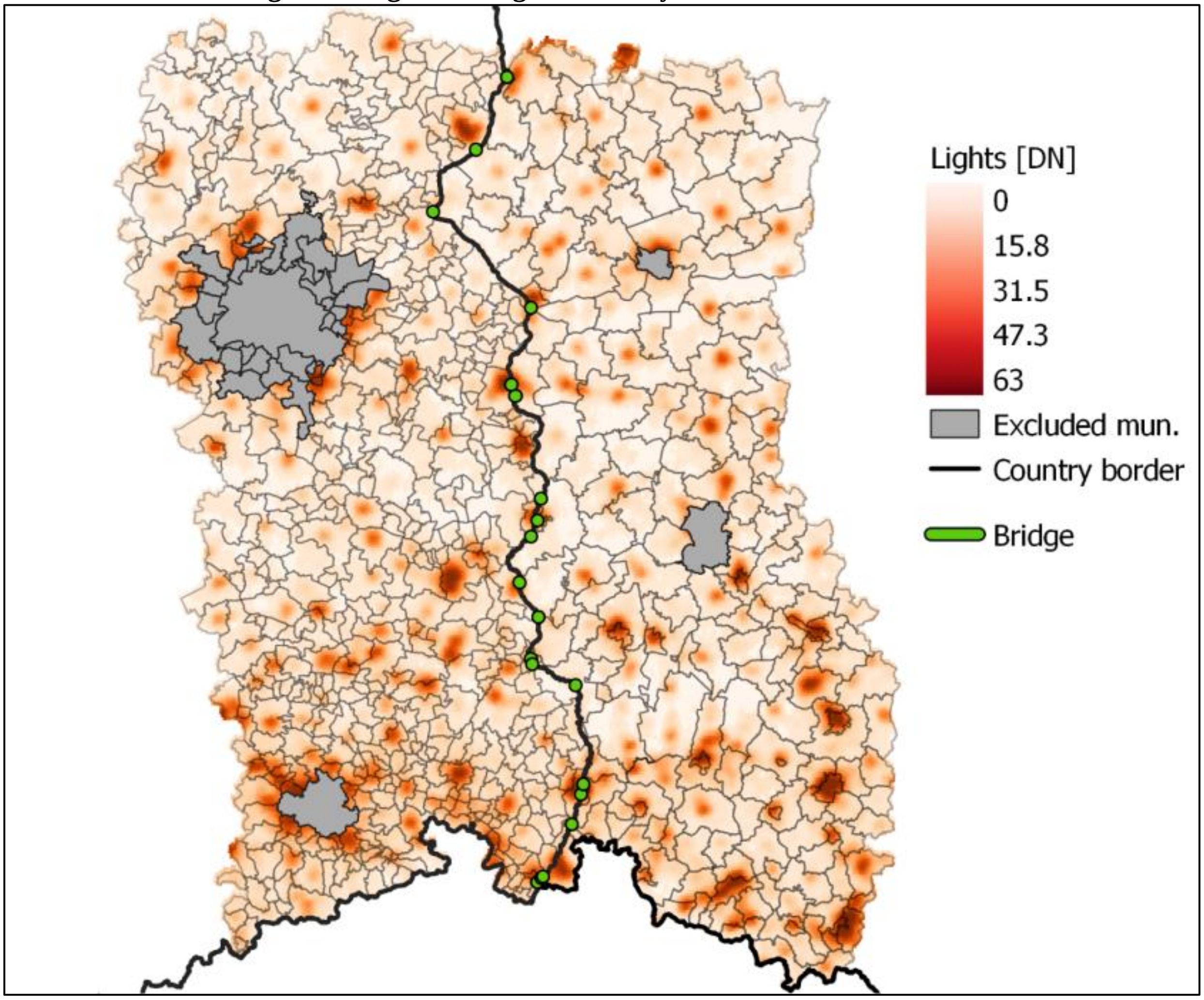
Figure 1. Night-time lights intensity: PL-DE border in 1992



Notes: municipalities along the PL-DE river border up to 100 km to the border; municipalities marked in grey treated as outliers and excluded from analysis due to high proportion of top-coded lights pixels in 1992; municipality borders as of 2013 (DE) and 2012 (PL).
Source: GeoBasis-DE / BKG 2013, PRG 2012, DMSP OLS v4, OpenStreetMap, own calculations.

Figure 2 then maps the night-time light intensity in the year 2012. Most notably, the light emissions have increased significantly both in Germany and in Poland, reflecting the positive economic development in both countries. The effect of higher light emissions is quite universal. Earlier centres indicate stronger light emissions, new centres have emerged and even in the very rural parts of both Germany and Poland, the lights intensity has increased. However, while municipalities in both countries show higher light emissions, the Polish side seems to have caught up entirely in terms of light intensity. From visual inspection of the map, we can no longer observe a notable average difference in the night-time light intensity data. This is consistent with the average measures highlighted in Table 1.

Figure 2. Night-time lights intensity: PL-DE border in 2012

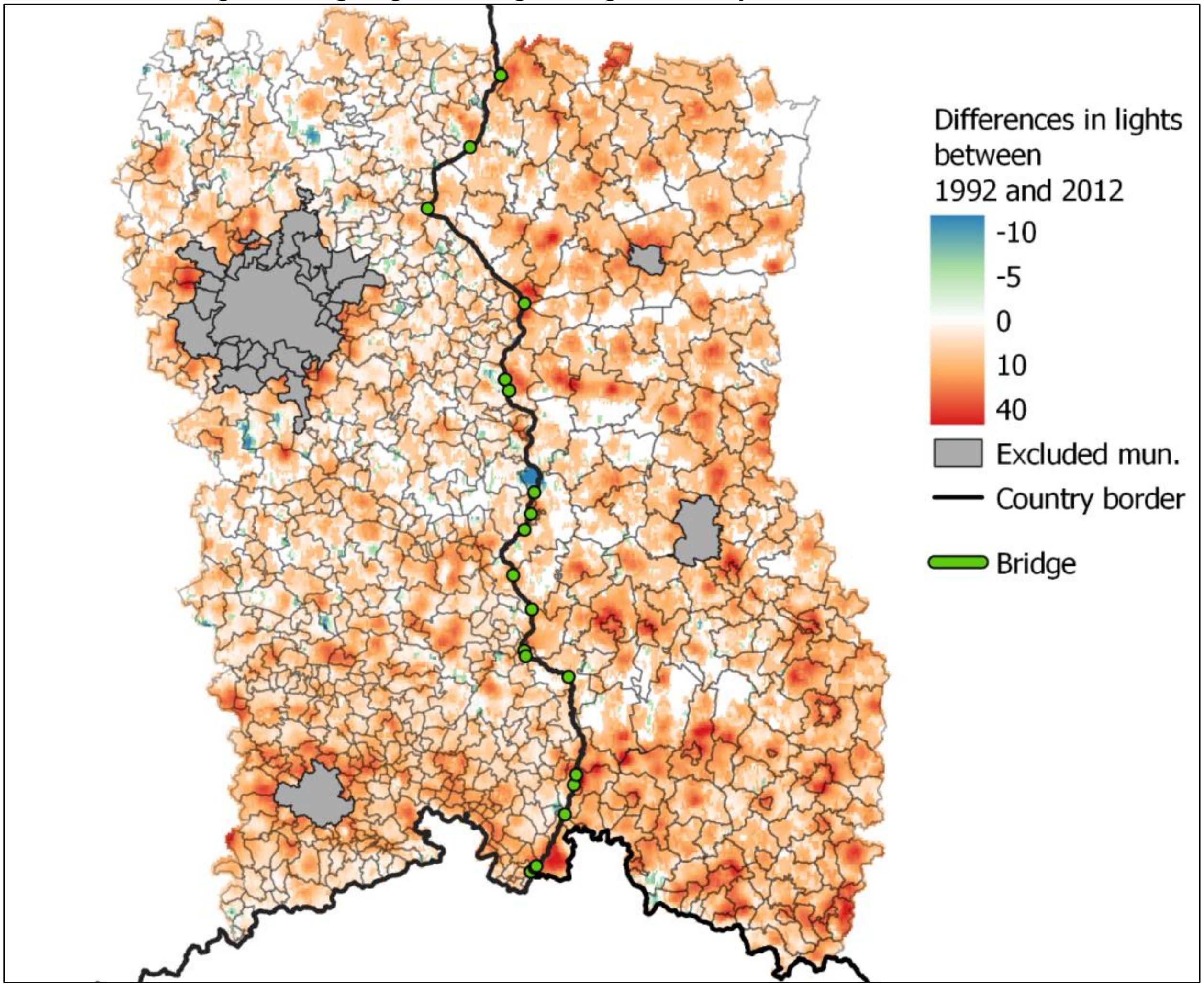


Notes and source: see Figure 1.

To understand the development over the time period from 1992 to 2012 in more detail, we graph the changes in the night-time light intensity between 1992 and 2012 in Figure 3. The new scale of (the absolute) differences between light emissions from 1992 to 2012 now ranges between -10 and 40, a negative value indicating a reduction and a positive value highlighting an increase in the light intensity.[7]

[7] A measure of -10 for example implies that the local light emission has been reduced by 10 points (originally measured on a scale between 0 and 63).

Figure 3. Nightlights: changes in light intensity between 1992 – 2012



Notes and source: see Figure 1.

To graphically distinguish local reductions and increases, we coloured negative values in a green-blue scale and positive values in a red scale. As notable in Figure 3, the red areas are predominant. This exemplifies that the overall economic development for the majority of municipalities has been positive during the time period. For the German side, we have a few areas that exhibit a negative development. This is probably due to the extreme economic upheaval in the 1990s in which certain economic trades and hence certain regions (agriculture and traditional industries) saw a dramatic downturn as they were unable to compete with West-German technology and productivity.[8]

[8] One notable area in Germany where the reduction of light is very large is the town of Neißemünde (formerly named Wellmitz) located at the border south of Frankfurt/Oder – right in the centre of Figure 2. Here we observe the largest drop. While this area is traditionally characterized by above ground brown coal mining and the drop in intensity could represent a closed mine, we have been unable to specifically locate the reason for the recorded drop in the light

In Poland, green to blue areas are extremely sparse, illustrating the universally positive economic development in Poland. Overall, the convergence of Polish municipalities to a comparable level to the German villages and towns (Figures 1 and 2) is notably marked by the higher growth in light intensity shown in Figure 3.

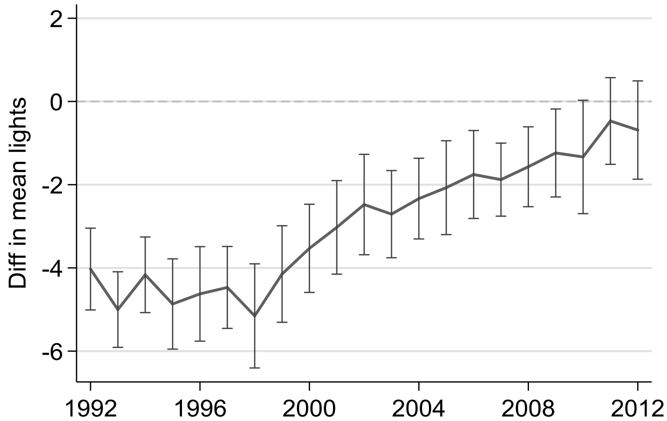
Figure 4 presents the difference between the night-time light intensity in Germany and Poland in all years between 1992 and 2012 and provides a test for its statistical significance. The estimation is done on mean pixel values per municipality (Figure 4a), mean log pixel values per municipality (Figure 4b) and log total lights per municipality (Figure 4c). For each of the measures the Figure clearly highlights the steep path of convergence between Polish and German municipalities. In the early nineties the difference in mean light intensity was around 100 percent. Already 10 years later the difference had been reduced to around 50 percent and it disappears by the end of the analysed period. It is notable that, after an initial steep convergence, the difference in light intensity had a period of stagnation between 2002 and 2008. Interestingly, the full convergence which follows coincides with the entry of Poland to the Schengen agreement in December 2007. As we can see on Figure 4b already in 2009 the difference in the average night-time light intensity between Poland and Germany was statistically insignificant (the zero baseline falls within the 95% CI) and it is essentially zero since 2009.

To summarize, this first set of evidence has exemplified two main points. First, the economic activity – as measured by light intensity – has increased in our observed municipalities in Germany and in Poland. Second, this overall increase has been markedly steeper in Poland, to an extent that the initially significant difference in mean light intensity is nullified at the end of our observation period. In terms of night-time light emissions, the average German and Polish municipality (in the extended border regions) are no longer statistically significantly different.

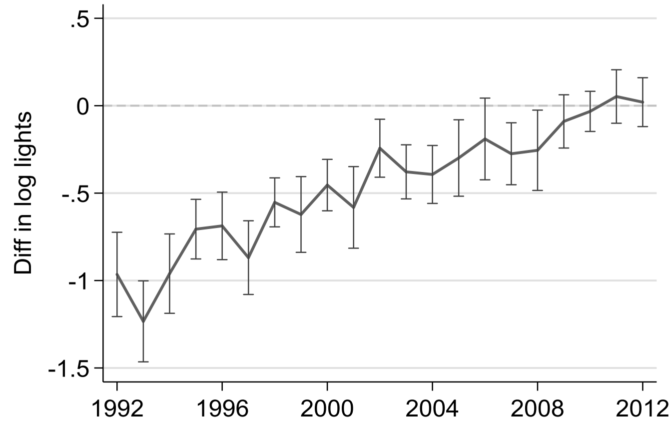
intensity. We have double checked the data and found the Wellmitz light emissions to be high in 1992 and in several subsequent years. They subsequently gradually fall to take consistently low values after about 1997.

Figure 4. Difference in mean night-time lights between Germany and Poland over time

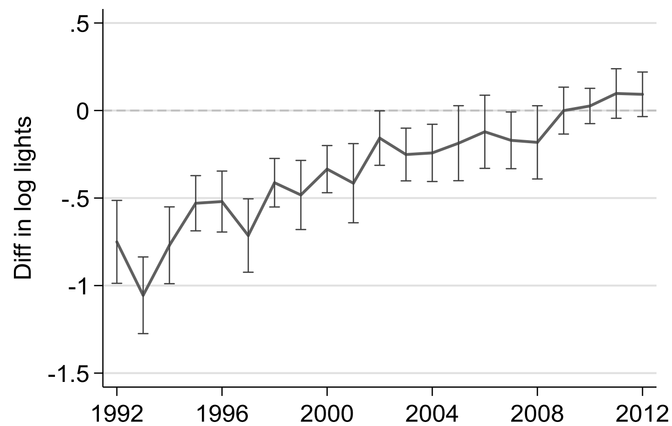
a) Average lights



b) (Log) average lights



(Log) total lights



Notes: Sample as defined in Table 1; a) difference in average pixel values per municipality, b) difference in log of average pixel values per municipality, c) difference in (log) total night-time lights; in all cases measured through coefficients on country*year interaction in a linear regression; year fixed effects included; regressions in (a) and (b) weighted by municipality area; standard errors clustered on municipality level; 95% CI.
Source: see Figure 1.

Despite the fact, that we have argued that light emissions are a valuable way to compare economic activity across borders, and the fact that we believe that light emissions might indeed be the best available measure to highlight regional differences in economic prosperity over long periods of time, we still have to issue a note of caution. Even with light intensity being levelled on average across the border, it does not necessarily imply full convergence in other economic measures. Averages in light intensity might to some degree be influenced by systematic differences in e.g. production technology (indoor or outdoor production, night-time work or not, etc.) as well as differences in infrastructure (street lights, energy production). They will also be affected by external (but within one country) transfers. For example if an area is a net recipient of welfare benefits (from outside of the analysed region) this is likely to be reflected in the intensity of lights as people continue to live in the area while relying on transfers. This would not however imply higher productive capacity of the region. While a full economic convergence might thus not be implied by our data, the findings certainly highlight the remarkable development that the Polish municipalities underwent during the time period between 1992 and 2012.

4.2 Distance from the border and changes in economic activity

While the first result section focussed on the average development in the lights data, we now turn to the analysis on the importance of distance to the border. This analysis is important for four reasons: 1.) We are interested in the importance of the national border for economic development. This is an empirical question, as economic theory in inconclusive as to whether we should expect increases or reductions in economic activity in municipalities directly at the border. The argument of access to markets may clearly point to increases at both sides of the border. As the labour market is also fully integrated, it is similarly possible to make an argument that skilled labour may exit the Polish local labour markets and increase productivity at the German side. Finally, one can plausibly argue that German local markets close to the border may suffer from increased competition with Polish markets in which labour and other goods are comparably cheaper. 2.) As mentioned in the introduction, economists are also interested in the significance of distance. With improving infrastructure (e.g. highways) and changes in how businesses are conducted (digitalisation of tasks and services), the argument goes that distance to borders becomes insignificant. 3.) While the average effects presented above may be hampered by aggregate differences in infrastructure or production, this should be less important for differences between towns and villages within the same nation. Comparing the economic activity in municipalities closer and further from the borders may therefore provide valuable insights into the regional patterns of economic prosperity. Illustrating those patterns may be inherently important for national policy makers when deciding on policy tools to foster or hamper further economic integration. 4. As our state of the art data analysis also allows us to measure distance in different dimensions (raw distance to border as well as distance to closest border bridge and travel time to closest border bridge), we are able to draw conclusions on the importance of infrastructure connecting the two nations and highlight differences in the importance of these different dimensions of distance.

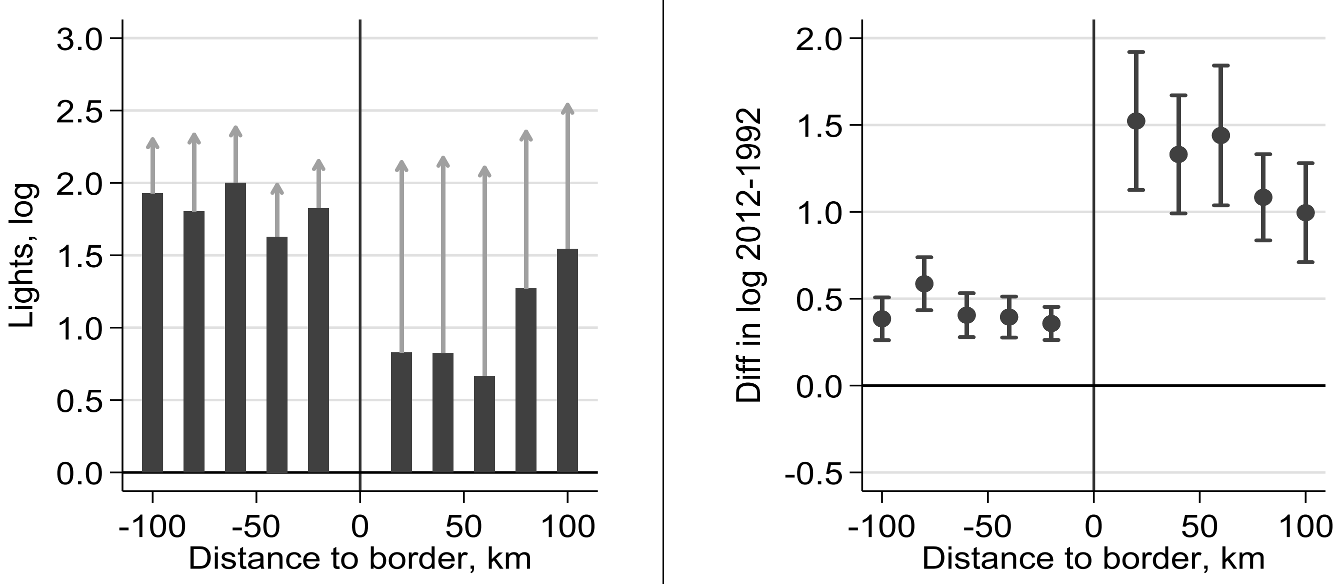
We start the analysis on the importance of distance with a descriptive illustration of average light intensity by grouping municipalities in bins by their distance to the border. Panel (a) of Figure 5 presents the results of this statistical exercise. The grey vertical line marks the border at 0. The bins to the left show the average log light intensity grouping all German municipalities by distance (centroid to border) within 0 to below 20 km, 20 to below 40 km, etc. To the right, the graph groups the Polish municipalities accordingly. The figure always shows the average night-time light emissions for 1992 (bars) as well as the emissions in 2012 (arrows). The difference between 1992 and 2012 can also be observed in Panel (b), in which we have singled out the differences over time to highlight the clear geographic pattern.

The emerging developments are different in the two countries. In Germany, we have no clear geographic pattern in 1992 (Figure 5a). Municipalities closer to the Polish border (within the set of observations in the 100 km radius) are not better or worse off in terms of observed night-time light intensity. From 1992 to 2012, all groups of German municipalities saw light intensity moderately increase (see also Figure 5b). Again, we observe no differences by distance to the border.

The results for Poland are markedly different. In 1992, the municipalities closer to the border had notably less economic activity as measured by light intensity (Figure 5a, see also Figure 1). In terms of log light the group closest to the border (0-20 km) only had about half the light emissions compared to the group in the range (80-100 km). In 2012, the geographical pattern changed. The border municipalities have almost caught up with the level of light at more distanced towns. Panel (b) also highlights the difference in geographical development. Even though the differences in growth do not seem to be statistically significant between the different groups, the point estimates for the direct border municipalities is about 0.5 difference in logs larger than for the group furthest from the border.

Figure 5. Distance to the PL-DE border and night-time lights intensity: levels and growth, 1992 and 2012

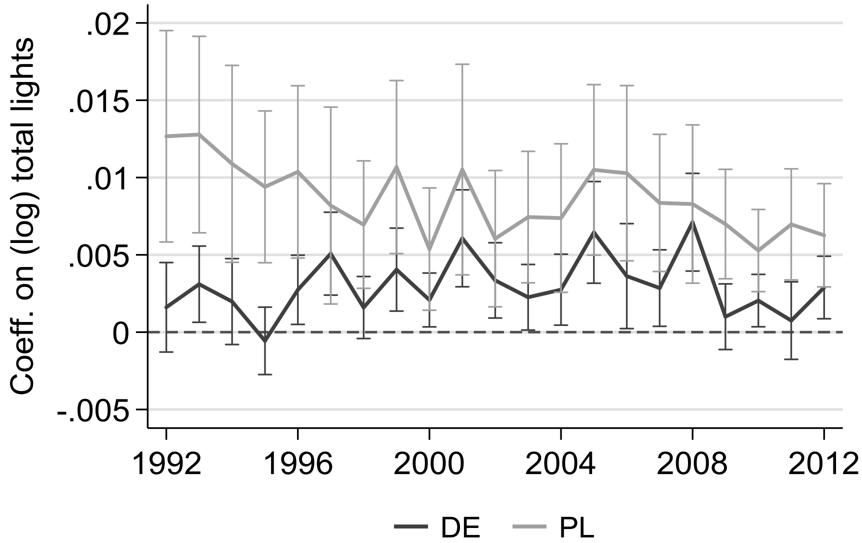
a) (Log) total night-time lights: 1992 (bars) and 2012 (arrows)	**b) Changes in (log) total lights**



Notes: Distance from the border measured from centroids of municipalities, expressed geographically with Germany on the left (negative numbers) and Poland on the right (positive numbers); municipalities with bridges on the border excluded; other selection criteria as in Table 1; averages calculated within 20km bins.
Source: own calculations based on GeoBasis-DE / BKG 2013, PRG 2012, DMSP OLS v4 and OpenStreetMap data.

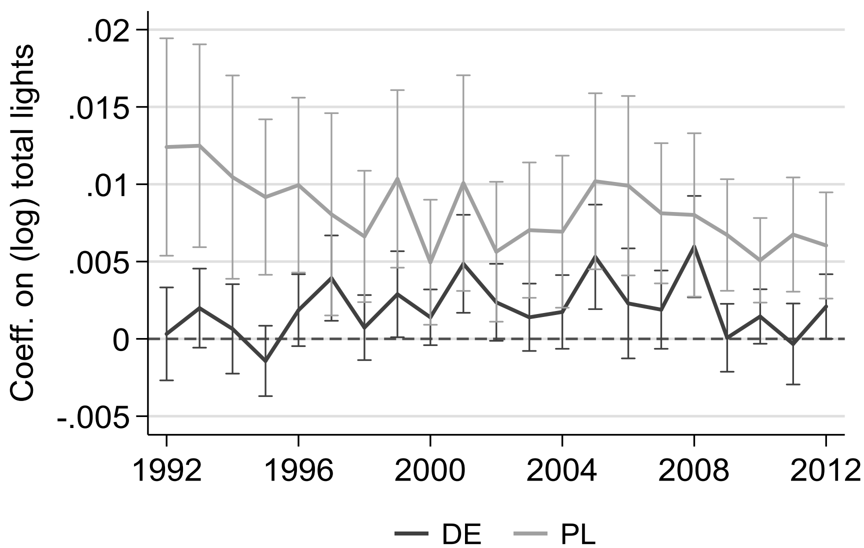
In Figures 6-8, we provide a more detailed analysis of the importance of distance. The Figures show the country and year-specific coefficients from a regression using a measure of distance as the explanatory variable and the log of light intensity as the outcome variable. Here, we show the full development over time and we distinguish our three different measures of distance. Figure 6 uses the raw distance to border (in km) and is hence directly comparable to Figure 5. In Figure 7 we instead use distance from the centroid of the municipality to the closest border bridge. Finally, in Figure 8, we use the average travel time from the municipality to the closest border bridge (in hours). We should note again, that while travel time might seem like a preferable measure, we have only been able to measure this in recent data (July 2018) which may not reflect the actual travel times in the past due to significant changes in road infrastructure.

Figure 6. Night-time lights and distance to PL-DE border: year-by-year developments



Notes: Distance to the border measured from centroids of municipalities; municipalities with bridges on the border excluded; other selection criteria as in Table 1; coefficients and confidence intervals (at 90%) obtained from year and country interactions; year fixed effects included; standard errors clustered on municipality level.
Source: own calculations based on GeoBasis-DE / BKG 2013, PRG 2012, DMSP OLS v4 and OpenStreetMap data.

Figure 7. Night-time lights and distance to nearest bridge on PL-DE border: year-by-year developments



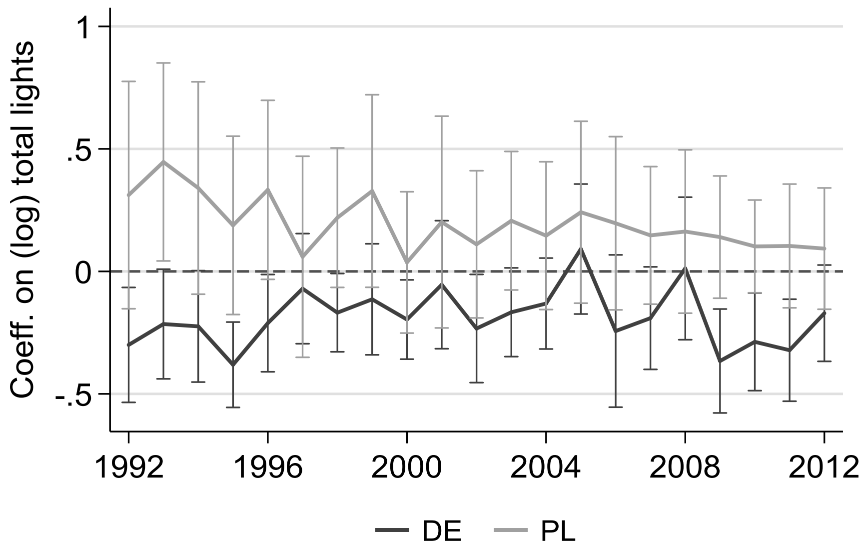
Notes: Distance to nearest border bridge measured from centroids of municipalities. For other notes and source see Figure 6.

The results from the analysis in Figures 6-8 are threefold: First, for the early nineties, we can now verify that Polish municipalities further from the border indeed had statistically significant higher light intensity (Figures 6 and 7, see also Figure 5). In 1992, an additional kilometre from the border implied an average increase in night-time light intensity by about 1 percent. Moreover the results indicate that distance has been of much less significance in Germany throughout the observation period, although we find a positive statistically significant relationship for some of the years, in particular between 2000 and 2008.

Second, the yearly estimates show that the importance of distance to the border within Poland declined steadily between 1992 and 2012. While municipalities further from the border are consistently better off, this difference declined and by 2012 was about half the size of the value estimated for 1992 (coefficient values change from 0.013 to 0.006 in case of distance to border) and cannot be statistically distinguished from the coefficients estimated for Germany. Does that imply that the distance to the national border has become irrelevant? Not necessarily. Before 1992, the German-Polish border had been economically not as important. What our data show is that over time, municipalities close to the border have caught up with formerly more prosperous towns further inland. And it seems plausible to speculate that it is exactly the (closer) distance to the border that has helped those towns develop faster. However, we can only observe the convergence of the light intensity levels. This convergence is also expected if the national border is of no importance per se, and the argument of the death of distance holds. For a final say, whether distance to the border matters for economic activity today, we would expect that border towns grow to be economically stronger than the formerly strong municipalities inland.

Third, we can analyse importance of distance using the different distance measure. Comparing Figures 6 with raw distance and Figure 7 with exact distance to the closest border bridge, we find virtually no important differences. This suggests that in conditions where there is a significant number of bridges – like in the case of the Polish-German border further research can knowingly ignore geographical specialities with national borders (as long as they are not too special) in its analysis and use simple raw distance to border. Our analysis using average time travel remains somewhat inconclusive, which is surprising given the results in Figures 6 and 7 and the fact that one would generally consider travel time as a better measure of economic distance which should improve the precision of our estimates. For Germany, we observe a few instances in which distance (measured in hours travel time to the closest border bridge) is negative and significant. This suggests that municipalities closer to the border are somewhat better off. The pattern for Poland suggests otherwise, with a positive correlation between travel time and night-time light intensity, although the estimates are only statistically significant in 1993. The problem with these estimates is that our travel time measure is only available for the current time calculation (as of 2018) and therefore does not reflect the actual time in the year in which economic activity was recorded. Since there has been massive investment in transport infrastructure since the early 1990s in Germany and since the early 2000s in Poland, the current travel times are likely to be an inaccurate measure for the earlier years of analysis. This might explain both lack of precision of the estimates but it could of course also invalidate the estimated developments of the relationship over time.

Figure 8. Night-time lights and travel time to nearest bridge on PL-DE border: year-by-year developments



Notes: Average time of travel to nearest bridge calculated for most recent conditions using OpenStreetMaps (for details see description in the text). For other notes and source see Figure 6.

In Table 2 we show results of regression analysis which aggregates the results presented in Figures 6-8. We examine the relationship between distance to the border and economic activity as proxied by night-time lights across the years from 1992 to 2012, and look at three-years windows at each end of the analysed period. Finally, we examine the role of distance to the border for the rate of change of the intensity of night-time lights, once again differentiating between the full period and the two time windows on either end (Table 3).

Table 2. Total night-time lights along the Polish-German border, 1992-2012

	(Log) total lights: 1992-2012			**(Log) total lights: 1992-1994**			**(Log) total lights: 2010-2012**		
	(1)	**(3)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**
DE * time to bridge	-0.0483			-0.0785			-0.103		
	(-0.50)			(-0.72)			(-1.17)		
PL * time to bridge	0.370*			0.534*			0.254*		
	(2.00)			(2.10)			(2.02)		
DE * distance to border		0.00296*			0.00223			0.00190	
		(2.17)			(1.42)			(1.56)	
PL * distance to border		0.00863**			0.0121**			0.00617**	
		(3.04)			(3.17)			(3.21)	
DE * distance to bridge			0.00195			0.00098			0.00107
			(1.38)			(0.60)			(0.85)
PL * distance to bridge			0.00831**			0.0118**			0.00596**
			(2.84)			(2.99)			(3.01)
Constant	1.813***	1.640***	1.683***	1.836***	1.674***	1.729***	2.638***	2.471***	2.507***
	(21.28)	(20.75)	(20.67)	(20.04)	(19.56)	(19.52)	(39.63)	(42.22)	(40.38)
N	13499	13499	13499	1917	1917	1917	1944	1944	1944
R-squared	0.109	0.120	0.116	0.111	0.123	0.119	0.0977	0.105	0.102

Notes: Municipalities up to 100km from the PL-DE border; municipalities with border bridges and those within range of 20 km from Berlin excluded; OLS results with standard errors clustered at municipality level; country, year and year*country fixed effects included, *t* statistics in parentheses, statistical significance: $^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Source: own calculations based on GeoBasis-DE / BKG 2013, PRG 2012, DMSP OLS v4 and OpenStreetMap data.

Table 3. Changes in night-time lights along the Polish-German border: 1992-2012

	(Log) total lights: 1992-2012			**(Log) total lights: 1992-1994**			**(Log) total lights: 2010-2012**		
	(1)	**(3)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**
DE * time to bridge	0.123^{+}			0.131*			0.0589^{+}		
	(1.74)			(2.47)			(1.75)		
PL * time to bridge	-0.288			-0.0581			0.0545		
	(-1.63)			(-0.67)			(1.42)		
DE * distance to border		0.00157^{+}			0.00161*			0.00085^{+}	
		(1.68)			(2.37)			(1.73)	
PL * distance to border		-0.00672**			-0.00183			0.00099^{+}	
		(-2.60)			(-1.53)			(1.73)	
DE * distance to bridge			0.00209*			0.00169*			0.00064
			(2.15)			(2.37)			(1.28)
PL * distance to bridge			-0.00668*			-0.00200			0.00096^{+}
			(-2.53)			(-1.63)			(1.65)
Constant	0.326***	0.348***	0.320***	-0.0931*	-0.0676^{+}	-0.0743^{+}	-0.442***	-0.436***	-0.428***
	(6.01)	(7.29)	(6.46)	(-2.13)	(-1.78)	(-1.85)	(-14.60)	(-15.24)	(-14.49)
N	639	639	639	637	637	637	650	650	650
R-squared	0.220	0.228	0.228	0.0171	0.0170	0.0176	0.0136	0.0142	0.0121

Notes and source: see Table 2.

Results in Table 2 confirm the strong positive relationship between economic activity and distance to the border on the Polish side of Oder-Neisse rivers. Overall regions farther from the border show greater degree of economic activity, though as we saw on Figures 6 and 7 this relationship is stronger in Poland where it has substantially diminished over time. On average in Germany economic activity was higher in regions further from the border increasing at the rate of about 0.3% per km. In Poland the rate of increase was on average about 3 times higher and it fell from about 1.2% per km in years 1992-94 to 0.6% in years 2010-2012.

In Table 3 we find some interesting, and perhaps disconcerting results regarding the relationship of distance to the border and changes in light intensity. While the coefficient on the distance measures in the Polish case for the full period 1992-2012 are negative, suggesting that regions closer to the border were catching up behind those more developed regions farther away, the relationship in the final three years is negative. Although the coefficients are small the estimates point to faster development of municipalities farther from the border with the change in the final three years growing by about 0.1% per kilometre of distance to the border. Moreover the values of the estimated coefficients for Poland in 2010-2012 are also slightly higher in absolute terms than those estimated for Germany in the same period.

5. Conclusions

This paper uses high-quality satellite night-time light intensity data to evaluate regional development in municipalities on the German and the Polish side of the Oder-Neisse border. Light emission data provide an innovative, comparable and reliable measure to proxy for economic activity on both sides of the border consistently over a long period, from 1992 to 2012, covering the time during which European integration measures have been implemented on both sides of the border.

In the analysis, we supplemented the original light data with geo-information on municipal administrative units at the local level (*Gminas* in Poland and *Gemeinden* in Germany) in order to aggregate the light data from raster data at meaningful socio-economic units. We focus on municipalities within 100 km from the Polish-German border. From these geo-data we calculate the raw distance of the municipal centroid to the border. We also geo-located all available road bridges to calculate more detailed distances between the centriods and these key access points.

Finally, we also determined travel times instead of physical proximity, with the caveat that only recent travel times are available for this purpose.

Our empirical interest focuses on several aspects. First, we are interested in descriptive evidence on the overall state of the economic integration along the Polish-German border and using night-time light intensity as proxy for economic activity opens a new avenue for research in this respect. Here, we find that the convergence in economic activity has been – somewhat surprisingly – complete. Driven by a rapid growth by the Polish municipalities and somewhat sluggish growth on the German side of the border, the light intensity levels across the Oder-Neisse border show no significant differences by the end of our observation period. This is despite significant and economically enormous initial differences just 20 years earlier and despite the fact, that municipalities on the German side also experienced increases in economic activity.

Second, night-time lights data allows us to study the detailed geographical patterns within each country. Here, different national patterns emerge. In Germany, distance to the border does not manifest to be an important driver of the economic activity as proxied by light emissions, either in 1990s or in the 2000s. In Poland, however, distance from the border shows some intriguing patterns. In 1992, our regressions show that distance is strongly and positively correlated with light emissions, hence indicating that municipalities further from the border show higher average economic activity. In 2012, however, the border regions have closed most of the gap and distance to the border is a much weaker predictor of economic activity. To evaluate the question whether the Polish evidence is consistent with the theory of the death of distance (as a general convergence is driving the results), or whether the actual border is still driving the results, future research has to evaluate whether the differential in growth by distance is still present in future time periods.

Finally, we use our different measures of distance (raw distance, actual distance to closest border bridge as well as travel time) to investigate whether these measures and hence the related infrastructure are of great importance. In this respect we find no significant differences. Our results remain qualitatively comparable using all three of the distance measures. For the comparison between raw distance to the border and actual distance to the closest border bridge, the analysis stays practically unchanged. This may be of important value to other researchers as our results indicated that – in similar circumstances as along the Polish-German border future research can use the better available raw distance measures.

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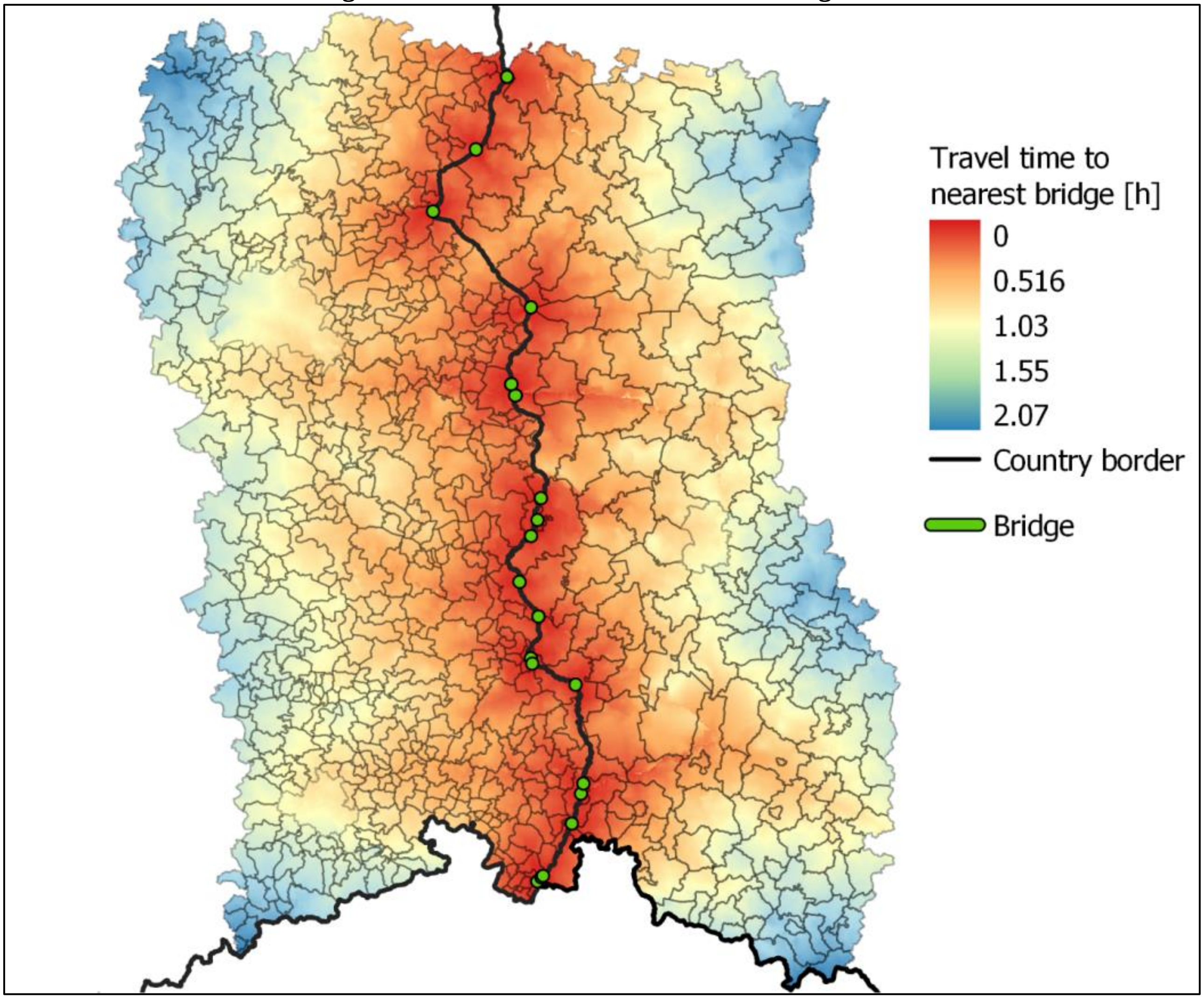
Appendix

Figure A1. Travel times to the nearest bridge.



Notes: Shortest travel times calculated using pgRouting and then interpolated in GQIS.
Source: own calculations using data from GeoBasis-DE / BKG 2013, PRG 2012, DMSP OLS v4 and OpenStreetMap.