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Population density, fertility, and demographic convergence in developing countries

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ABSTRACT

Whether the population tends towards a long-run stationary value depends on forces of demographic convergence. One such force is the result of fertility rates being negatively affected by population density. We test the existence of such an effect in 44 developing countries, matching georeferenced data from the Demographic and Health Surveys for half a million women with population density grids. We find a causal relationship from population density to fertility such that a rise in density from 10 to 1000 inhabitants per square kilometer corresponds to a decrease in fertility of about 0.7 children. The corresponding half-life for population dynamics is of the order of four–five generations.

1. Introduction

Long-run population projections are key to assessing the sustainability of our societies. The combination of current age structures and projected fertility levels produces relatively accurate projections with a horizon of 50 years, but longer-term predictions rapidly become uncertain (Livi-Bacci, 1997). In the projections made by the Population Division of the UN, fertility being estimated in terms of either a high or low scenario (United Nations, 2004; Gerland et al., 2014) determines the time and level at which global population will peak. The probabilistic projections of the UN (Gerland et al., 2014) or of IAASA (Lutz and Butz, 2014) would benefit from a reduction in the uncertainty surrounding fertility.[1] In general, the speed at which Africa experiences the demographic transition matters to determine the peak of the world population. Consequently, gaining a better understanding of the determinants of fertility is a priority in order to improve these long-run forecasts.

We study whether or not fertility behavior reflects spontaneous convergence forces that lead the population to a stable, long-run level. In the natural sciences, this property is called population *homeostasis* (Lee, 1987). In animal populations, predator–prey models may display such a property, depending on their parameters. In human populations, predators are absent, but human reproduction is subject to limited resources. If convergence forces are at work, one should observe a correlation between fertility and/or mortality and population density. At high levels of density, fertility should be low, and/or mortality high, for a population to stabilize. The contribution of this paper is to shed light on the existence of the channel relating fertility to population density in developing countries.[2]

There are different ways in which population density may affect fertility. For Malthus (1807), areas with higher population density have lower agricultural income, and marriage and fertility are delayed (preventive check) as compared to regions with lower densities. According to a more modern view, initiated by Sadler et al. (1830), while income is higher in more densely populated areas because of agglomeration externalities, fertility decreases with income, leading to the same final negative relationship between density and fertility. More densely populated areas may also yield decreased fertility because they offer more affordable or accessible education and health infrastructure.

Beyond these causal mechanisms, the sorting (selection) of individuals can generate an apparent correlation between density and fertility. This is the case when people who are less inclined to have

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[1] The difference between these two recent projections essentially stems from different assumptions about Chinese and Nigerian fertility rates.

[2] Mortality can also be affected by population density. For example, André and Platteau (1998) detail the path from population pressure to land conflicts, and, ultimately to violence and genocide in Rwanda.

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children migrate to more densely populated places to enjoy the greater income opportunities offered by cities (Courgeau, 1989) and/or those who are more inclined to have children move to regions where the population density is lower and where raising children costs less. In this case, population density may not have a causal relationship to fertility, but instead may only affect individual decisions with respect to where to live. The United Nations (2014) projects that 66% of the world's population will live in urban areas by 2050. In 1950, this figure was only 30%. This movement of people from rural to urban areas may be the result of a selection of individuals and may not reflect an effect of higher population density on individual decision-making.

To analyze the relationship between population density and fertility, we use different sources of data. Raster files for population density come from CIESIN et al. (2011). They are based on detailed population data from census administrative units.[3] Individual fertility data are from the Demographic and Health Surveys (DHS) for 44 developing countries. In the DHS data, individuals belong to clusters, which are georeferenced, allowing for mapping population density onto fertility. In order to control for geographic variables, the caloric suitability index developed by Galor and Özak (2014) is used to control for intrinsic land quality. We also use the CIESIN et al. (2011) data to control for the distance to large bodies of water. Satellite light data are used to control for income effects at a disaggregated level.

We first consider the cluster level (i.e. village or neighborhood), relating the average number of births in a given cluster to the population density of this cluster. Without any control apart from country fixed effects, geographic variables, and the mean age of women in the cluster, an increase in population density from 10 to 1000 inhabitants decreases fertility by about one child on average. When controlling for additional cluster characteristics such as education, mortality, and income, the size effect is divided by four but remains highly significant. Among all the controls, education seems particularly important, indicating that education is obtained more easily in densely populated areas, where traveling costs are lower, and the fixed costs of schools are more easily covered (Boucekkine et al., 2007).

This relationship could be biased due to an omitted variable problem. Places with greater unobserved amenities might be those to which individuals with certain traits moved in the past and where these traits have persisted. This could lead to a spurious relationship in which it is not population density that affects fertility rates, but rather the unobserved characteristics of the people living in areas with a specific population density. We therefore use the distance to buildings and cities belonging to UNESCO World Heritage Sites constructed between the Neolithic Revolution and 1900, as a proxy for past population density, to instrument current population density. Controlling for current income, the exclusion restriction is that this instrument has no effect on fertility, other than through population density. We argue that this instrument reflects incentives for people to move to these specific areas long ago. However, the main reason why people are still in these areas today is the persistence of population density. Using this instrument, we estimate an even larger effect of population density on fertility, showing that endogeneity biases have a tendency to attenuate its effect.

In order to further exclude the possibility that population density at the cluster level may proxy local spillovers that affect fertility, we analyze fertility behavior at the individual level, distinguishing between individual and cluster effects (e.g. for education). The results are similar to those at the cluster level. The individual-level analysis also allows us to study whether or not the relationship between population density and fertility is the result of selection. Controlling for migration does not alter the conclusion; estimates from a subsample of individuals who had not moved during their lifetime are very similar to those from the whole sample.

Other papers have documented a negative relationship between population density and fertility, but never at the individual level. Among others, Adelman (1963) and Heer (1966) showed such a pattern for country-level data. By today's standards, however, it would be hard to argue that the correlation they found does not reflect country-specific factors (e.g. institutions) that were not accounted for in their analyses. A more robust approach would be to use country panel data, as in Lutz and Qiang (2002) and Lutz et al. (2006), who emphasize the importance of including population density as a determinant of declining fertility rates. Another approach is to compare smaller entities within the same country. For example, Firebaugh (1982) shows that population density and fertility were negatively related across 22 Indian villages between 1961 and 1972. However, these approaches limit the analysis to aggregate level data. This increases the likelihood of endogeneity due to the presence of unobserved factors affecting both the fertility of a population and its density. Compared to this literature, this paper is based on a much broader set of data (490k women in 25k clusters from 44 developing countries). The analysis is also carried out at the individual level and provides support for a causal effect of density on fertility.

The paper is organized as follows: the data are presented in Section 2. Our cluster and individual analysis is provided in Sections 3 and 4 respectively. The interpretation of the results for population dynamics is provided in Section 5. The conclusions are presented in Section 6.

2. Data

We use a large data set including individual and household surveys carried out in 44 developing countries and estimate the relationship between fertility and other variables, among population density.

To relate population density to fertility, information from demographic surveys must be combined with geographical data on population density and other controls, such as the quality of the land or the distance to water. Individual and household characteristics are derived from Demographic and Health Surveys (DHS), which in most countries are geo-localized. We have incorporated all countries with “Standard DHS” type data sets available, selecting the waves that are closest to the year 2000. Households are grouped into clusters for which we have the latitude and the longitude from the DHS GPS file.[4] The raster files for world population density are taken from CIESIN et al. (2011), which provides information on population density in grids with a cell size of $30'' \times 30''$ (approximately 1 km^2).[5] To avoid a possible reverse causality from fertility to population density, we use density in 1990, which is the earliest year available. Corrections for other types of endogeneity will be implemented in the next two sections. Fig. 1 shows the position of all the DHS clusters in our sample and their respective population density. Unlike most of the recent literature using geographical data, our unit of analysis is not a cell but a point. The sample contains 24,769 points.

To control for the geographical determinants of land productivity, we use one of the caloric suitability indexes developed by Galor and Özak (2014) which has a resolution of $5' \times 5'$ (approximately 10 km^2). Galor and Özak (2015) show that the caloric suitability index dominates the conventionally used agricultural suitability data (Ramankutty et al., 2002) in terms of capturing the effect of land productivity. In this paper, we use the raster file for the maximum potential caloric yield attainable given the set of all suitable crops in the post-1500 period. This yield varies across cells depending on their climatic and geographic characteristics, such as elevation, temperature,

[3] See URL http://sedac.ciesin.columbia.edu/downloads/docs/gpw-v3/balk_etal_geostatpaper_2010pdf-1.pdf for methodological details.

[4] DHS are built to be representative of a country's population. However, even if they are not representative, it would not affect our study, since we do not consider country-level total fertility rates.

[5] A map of the population density of the relevant region is provided in Fig. B.1, Appendix B.

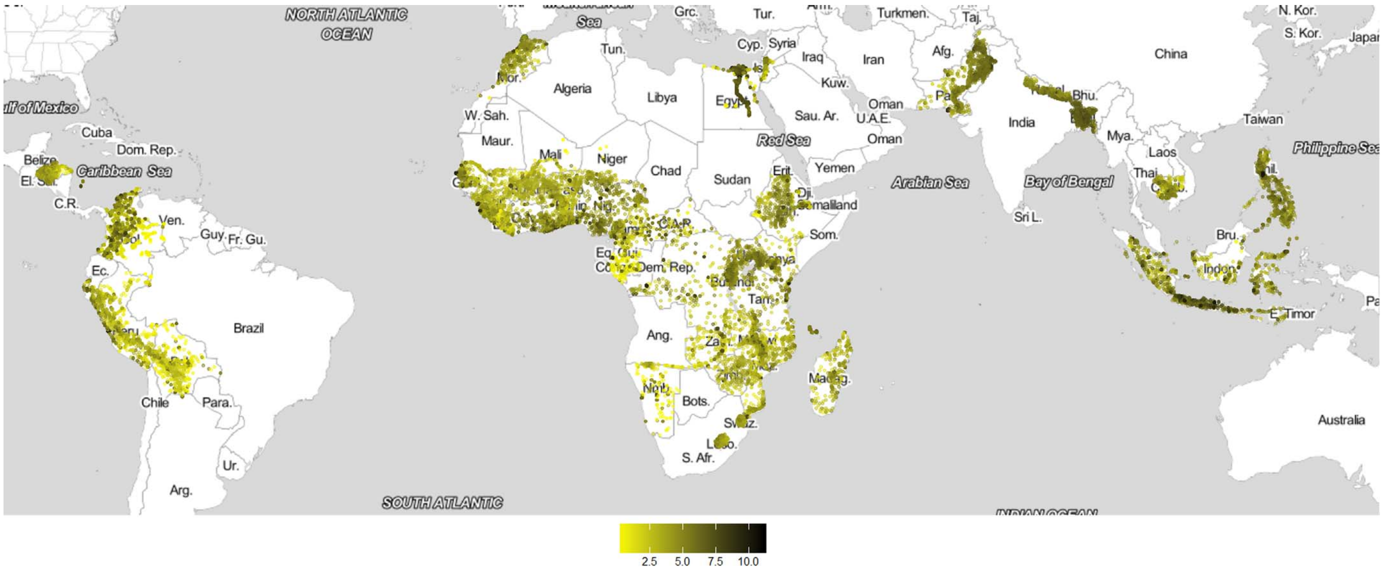

Fig. 1. Cluster localization and population density. *Note*: Population density is reported as $\ln(1 + \text{population density})$.

rainfall, soil quality, terrain ruggedness, steepness, etc. Fig. B.2 represents this variable.

Finally, as a proxy for income per capita, we use the GDP measures from Ghosh et al. (2010), which are essentially based on night-time light satellite data. Henderson et al. (2012) show that luminosity is a strong proxy for GDP. Apart from the fact that there is no standardized method to account for national income across countries, and that informal sectors, which are often important in developing countries, are difficult to include in national statistics, the major advantage of using this data is that it allows us to capture total economic activity at a disaggregated level. The precision level of the raster is $30'' \times 30''$; however, measurement errors at the pixel level are large.[6] Ashraf et al. (2015) argue in favor of measuring GDP on the basis of a continuum of a larger number of night-time light pixels. We therefore base our measure on an aggregated $20' \times 20'$ raster. To obtain a per capita variable, we divide GDP by our measure of population density taken at the same level of aggregation and discarding pixels with fewer than 0.1 inhabitant per km^2. For every cluster, we impute its GDP as the mean within a 50 km-radius circle. The resulting measure is shown in Fig. B.3. As an alternative measure, we also directly take the satellite light data averaged over 1992–2013, and compute a per capita measure as above, after having removed the areas affected by gas flares (from NOAA's "Global Gas Flaring Estimates").

Let us come back to the DHS data and provide more details on the data itself. We use the individual recode, the household recode, and the GPS data set. The list of the DHS data sets, with the corresponding years and phases, are shown in Table B.1, in Appendix B. The total number of clusters and individuals included in the sample are also provided at the end of the table.

Table 1 provides the list of variables used, and some descriptive statistics. From the individual recode, we build a sample consisting of women between 15 and 49 years of age whose cluster we know.[7] We drop the observations for which the number of years of education is unknown or is higher than 30. All dates are expressed in Century Month Code (CMC).[8] Mortality rates are computed as the ratio between the total number of living children and the total number of children ever born. Marital status is coded as either ever married (includes living with a partner, currently married, divorced, or widowed) or single (never married). Data on religion is available for almost all countries, except the following six: Bolivia, Colombia, Egypt, Morocco, Pakistan, and Peru. For countries for which we do have this information, we divide the sample into Muslims, Christians, Hindus, Buddhists, and others.[9] Except for Burundi, Comoros, Lesotho, Liberia, Madagascar, Rwanda, Swaziland, Tanzania, Zimbabwe, Egypt, Jordan, Morocco, Bolivia, Bangladesh, Cambodia, and Indonesia, we also know the ethnicity each woman belongs to (not reported in the table). Fig. B.6, in Appendix B, shows the histogram of the variables: age, education, infant mortality, and number of births. We observe strong age heaping at ages ending in 0 and 5, which is evidence of women's ignorance of their actual age. Finally, it is worth noting that the quality of the data on the number of children ever born and their date of birth is subject to misreporting errors, as stressed in the literature on demography (Schoumaker, 2014). We address this issue in Section 4.4.

From the household recode, we use the information on whether or not the household has electricity or/and a refrigerator. These two variables are used as additional controls to proxy for income.

From the GPS data set, we use the geographical coordinates of each cluster. From these, we can infer population density, land productivity, and income per capita in each cluster. In order to ensure the anonymity of respondents, urban clusters contain a minimum of 0 and a maximum of 2 km of positional error. Rural clusters contain a minimum of 0 and a maximum of 5 km of error, with a further 1% of rural clusters displaced a maximum of 10 km.[10] To account for this error in urban clusters, we set the density in a cluster to the average density in the 2 km radius around the center of this cluster. For rural clusters, we set the radius at 5 km.[11] Finally, as the raster for the caloric

[6] For example, they can be due to over-glow and blooming. We also check whether one should correct for gas flares, but the measure from Ghosh et al. (2010) seems to have filtered them out.

[7] In a majority of DHS, eligible individuals include women of reproductive age (15–49). Some countries provide information for older women, but we did not keep these observations in the sample.

[8] CMC is the usual way in which dates are coded in DHS. Time is counted in terms of months and starts with the value 1 for January 1900.

[9] Christians include those who belong to the Roman Catholic Church, the Evangelical Church, the Anglican Church, Protestants, Seventh Day Adventists, Pentecostalists, Methodists, the Salvation Army, Kimbanguists, the "Églises Réveillées", Presbyterians, the Apostolic Sect, the "Iglesia Ni Kristo", the Aglipay (Philippine Independent Church), and those coded as "other Christians" by DHS.

[10] DHS do not precisely define the urban–rural variable of the GPS data set. In each country, they adopt a definition that can depend on the size of the population or on the breadth of infrastructures. See more at URL: http://dhsprogram.com/What-We-Do/GPS-Data-Collection.cfm.

[11] Due to the DHS displacement, two clusters in Uganda appear to be inside Lake Victoria. We give each point the minimal radius so as to have positive population density:

Table 1
Descriptive statistics.

Variable	N. obs.	Mean	St. dev.	Min	Max
From the individual recode					
Date of the interview (in cmc)	490,669	1262.56	103.64	1110	1899
Date of birth of the respondent (in cmc)	490,669	904.29	154.18	511	1717
Age (in completed years)	490,669	29.41	9.68	15	49
Education (in single years)	490,669	5.41	4.77	0	27
Partner's education	360,543	6.16	5.27	0	26
Desired number of children	455,194	3.90	2.42	0	30
Total number of children ever born	490,669	2.71	2.69	0	21
Total number of living children	490,669	2.34	2.27	0	16
Children's mortality rate	490,669	0.08	0.18	0	1
Births in the last five years	490,669	0.67	0.83	0	8
Motherhood rate	490,669	0.74	0.44	0	1
Marriage rate	490,669	0.77	0.42	0	1
Islamic (%)	355,361	0.34	0.47	0	1
Christian (%)	355,334	0.51	0.50	0	1
Hindu (%)	355,495	0.03	0.17	0	1
Buddhist (%)	355,487	0.04	0.20	0	1
Date of first birth (in cmc)	360,520	1108.72	151.22	669	1898
Age at first birth (in years)	360,520	19.62	4.01	7	45
Age at first birth (in months)	360,520	47.96	47.94	90	543
Date of first marriage (in cmc)	375,104	1099.40	157.38	622	1898
Age at first marriage (in years)	375,255	18.47	4.35	5	49
Age at first marriage (in months)	375,255	226.82	52.20	60	591
Moved from place of residence after 14 (%)	383,733	0.42	0.49	0	1
Ethnicities	313,255	242 categorical variables			
From the household recode					
Has electricity (percent)	467,150	0.51	0.50	0	1
Has a refrigerator (percent)	441,984	0.31	0.46	0	1
From CIESIN et al. (2011)					
Population density in 1990 (pop. per km^2)	24,769	1249	3321	0.012	60987
From Galor and Özak (2014)					
Caloric suitability index post 1500 (/10000)	24,769	8.38	3.86	0	17.98
From Ghosh et al. (2010)					
GDP per capita	24,769	0.006	0.012	0.00001	0.333
Own computation					
Distance to a large body of water (deg)	24,769	1.749	1.756	0.000	11.157
Alternative GDP per capita	24,763	0.023	0.081	0.000	2.498

suitability index described above has a lower resolution than the population density raster, we impute the land productivity in each cluster from the value of the index in its given position.

3. Cluster-level analysis

We proceed in three steps. First, we show the relationship between population density and development across clusters. Then, we show estimates for the correlation between fertility and population density with ordinary least squares (OLS). Then we discuss possible endogeneity issues, and support a causal relationship between population density and fertility using an instrumental variable estimation. The whole section uses cluster-level analysis.

(*footnote continued*)
13km for one cluster and 33km for the other. A similar issue arose for an urban cluster in Palau Belitung (Indonesia). We allowed the radius to be 6km for this cluster. There are also six clusters, all in Egypt, for which the population density at their given location is nil. We gave these clusters the mean density based on a radius of 20km.

For each cluster, we compute the average value of the number of children ever born, level of education, marriage rate, infant mortality, and the number of Muslims, Christians, Hindus, and Buddhists from the individual recode. From the household recode, we also compute the average electricity rate and the share of households with a refrigerator in the cluster. We take into account individual or household weights for each woman or household respectively.[12] Figs. B.4 and B.5 in Appendix B show the histograms of the important variables.

The mean number of women per cluster is 19.8. The average mean age of women is 29.4 years. The average marriage rate within clusters is 77%. The average population density in a cluster in 1990 is 1249 inhabitants per square kilometer. The mean level of education is six years. 51% of the households in the clusters have electricity and 31% have a refrigerator. On average, 51% of the individuals in the clusters are Christians, 34% are Muslims, 4% are Buddhists and 3% are Hindus.

3.1. Population density and development

Before turning to a multivariate analysis and, later, a causal analysis, we first describe how population density correlates with the level of economic development. We divide the sample of 24,769 clusters into 20 quantiles. For each of these quantiles, we compute the mean level of GDP per capita, years of education, infant mortality rate, marriage rate, and children ever born. Fig. 2 shows the results. If we abstract from the two extreme quantiles, Q01 and Q20, the correlation between population density and the level of development is very strong (and significant given the large number of observations in each quantile). Density correlates positively with GDP per capita, as measured from satellite light data, and with the mean years of education of the women interviewed by DHS. It is negatively correlated with the surveyed infant mortality rate, marriage rate, and number of children ever born. On the whole, population density and development are positively correlated across space. This is also in line with the result according to which urbanization and income per capita are strongly correlated across countries (see Fig. 1 in Gollin et al., 2015), although urbanization is not synonymous with industrialization.

The rest of the analysis is devoted to understanding the relationship between population density and children ever born by controlling for other determinants of fertility, such as education, mortality, marriage, and unobserved variables.

3.2. Multivariate analysis (OLS estimation)

The following equation describes the relationship between fertility and population density at the cluster level, j:

$$E[n_j] = \beta_0 + \beta_1 \ln(1 + \text{density}_j) + \sum_{i=2}^{N} \beta_i X_{ij} \tag{1}$$

where $n_j \in \mathbb{R}_+$ denotes the average number of children born to the women of cluster j. The population density in 1990 in cluster j, density_j, enters the equation in logs which allows us to interpret β_1 as a partial elasticity.[13] X_{ij} are control variates that also affect fertility.

We present the results for all countries in Table 2. In all regressions, we include country fixed effects in order to account for income differences across countries, as well as unobserved characteristics like

[12] Each observation has a weight that is intended to adjust for the probability of selection and is used in order to make the sample data representative of the entire population. We use these weights to compute the descriptive statistics included in Table 1, and to compute the mean value of the variables at the cluster level, but not for the regression analysis at the individual level, as indicated in Rutstein and Rojas (2006). Appendix G.1 includes weights for regression analysis at the individual level and shows that, if anything, the results are stronger.

[13] The log formulation allows us to tackle the strong skewness in the distribution of density. We add 1 to density_j in order to avoid attributing too much weight to the few observations in which density is close to zero.

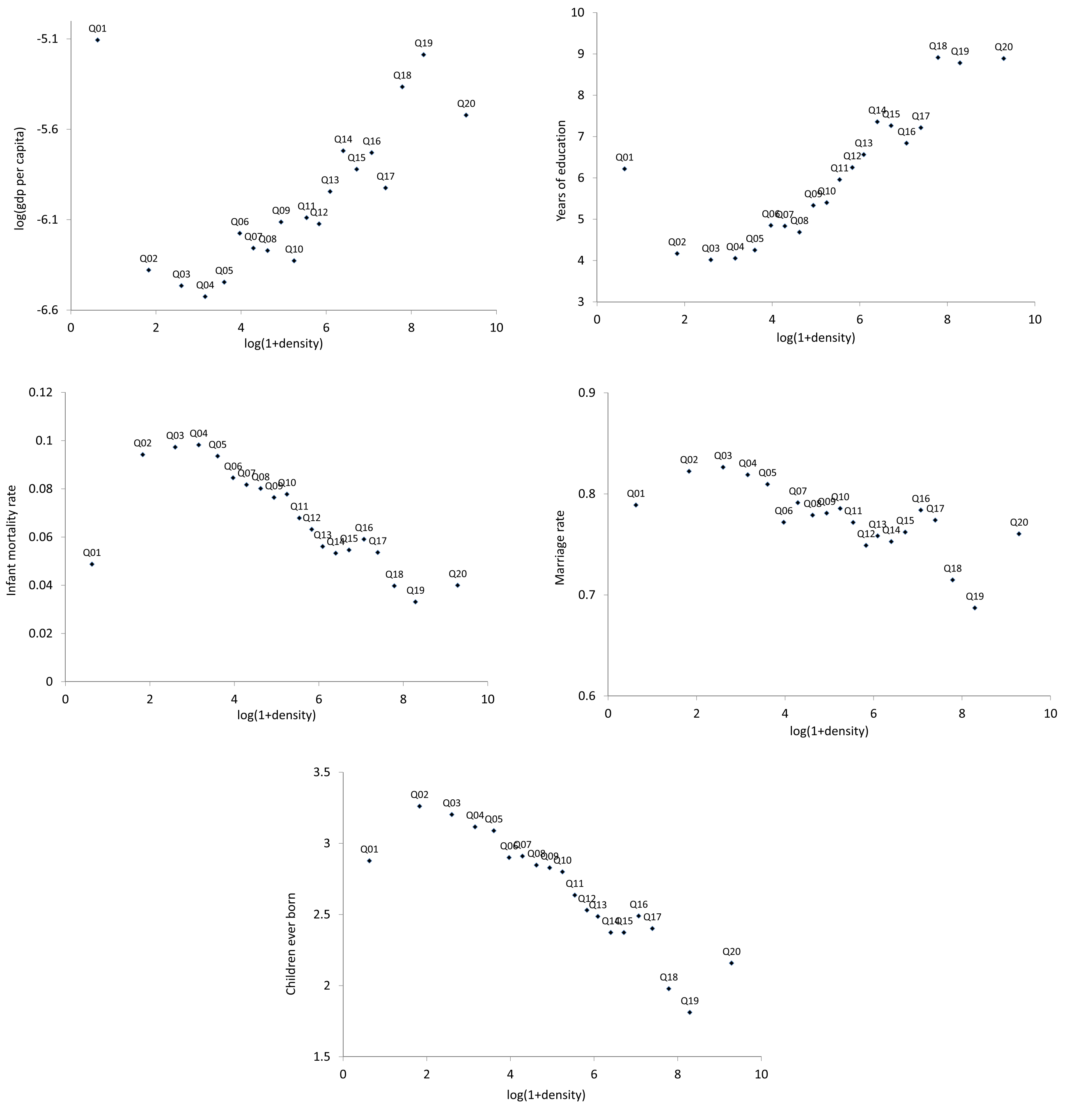

Fig. 2. Bivariate correlations at the cluster level between population density and: ln(GDP per capita) (top-left panel), years of education (top-right panel), infant mortality rates (middle-left panel), marriage rates (middle-right panel), and children ever born (bottom panel).

institutions. Standard errors are clustered at the country level.

Column (1) of Table 2 shows the effect of population density on fertility, controlling for nothing but the mean age in the cluster, geographical controls (land quality and distance to a large body of water), and country fixed effects. Controlling for land productivity accounts for the Malthusian argument according to which more productive land leads to the fathering of more children by means of an income effect. In other words, it allows us to control for the carrying capacity of each location. The point estimates imply that if population density increases from 10 ind/km^2 to 1000 ind/km^2, then the women in a cluster would have 0.86 fewer children on average.[14] To clarify this further, Appendix D plots the maps of locations with densities ranging from 0.01 to 10, 000 ind/km^2.

The introduction of marriage rates in Column (2) diminishes the direct effect of population density. This may reflect the fact that people marry later in more densely populated areas, which reduces the observed marriage and birth rates in the cluster. In Column (3), we introduce the infant mortality rate at the cluster level as a determinant of fertility. A higher mortality is purported to increase fertility as a result of the child replacement effect (Doepke, 2005). The impact of density on fertility is reduced by the inclusion of mortality (the reduction is statistically significant, but small in size). Infant mortality captures part of the effect of density: as the provision of health services is higher in more densely populated areas, mortality is lower, decreasing the need to have a large number of children.

In Column (4), we also control for differences in GDP per capita

[14] $-0.191 \times (\ln(1001) - \ln(11))$.

Table 2
OLS estimates at the cluster level.

	Dependent variable: Children ever born, per woman (average in cluster)				
	(1)	(2)	(3)	(4)	(5)
ln(1+density)	−0.191***	−0.142***	−0.125***	−0.119***	−0.050***
	(0.001)	(0.007)	(0.007)	(0.007)	(0.005)
Marriage		2.204***	1.842***	1.818***	1.102***
		(0.101)	(0.079)	(0.081)	(0.085)
Infant mortality			4.238***	4.133***	2.635***
			(0.484)	(0.480)	(0.314)
ln (GDP per capita)				−0.076***	−0.047***
				(0.013)	(0.011)
Women's education					−0.091***
					(0.024)
(Women's education)^2					−0.004**
					(0.002)
Observations	24,769	24,769	24,769	24,769	24,769
Adjusted R^2	0.569	0.631	0.667	0.669	0.740

Notes: Robust standard errors, clustered at the country level, in parentheses. All specifications include country fixed effects, geographical controls (the caloric suitability index and distance to a large body of water) and a polynomial of order 2 in mean age. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

across clusters as wealthier places could for example have higher returns to human capital and therefore a lower fertility, which would be in line with Beckerian theory (Doepke, 2015) . The impact of density on fertility is not altered significantly when controlling for the GDP per capita of the cluster, as shown in Column (4). Using the satellite light data over 1992–2003 as a proxy for GDP per capita does not lead to a different estimated correlation coefficient between fertility and population density. Finally, in Column (5) we add mothers' level of education as a control. The squared term is significant, showing a stronger negative effect of education on fertility for higher education levels. A similar argument to the one used to discuss mortality can be applied here. The provision of education services is higher in more densely populated areas, enabling mothers to become more educated. More education leads to lower fertility rates either because the opportunity cost of having children is higher, or because women are more aware of contraception. The estimate in Column (5) provides a lower bound on the partial correlation between density and fertility, as all the main controls have been introduced. Under this specification, fertility decreases by 0.23 children when population density increases from 10 ind/km^2 to 1, 000 ind/km^2.

Appendix E provides the results pertaining to the relationship between population density and fertility for each continent. The magnitudes of the relationships between fertility and population density across different contexts remain remarkably similar to the estimates at the global level, shown in Table 2. The coefficients of ln (1+ density) in Model (5) are −0.044 in Sub-Saharan Africa, −0.040 in the Middle East and North Africa, −0.025 in Asia, and −0.052 in Latin America (all significant at the 1% level, except for Asia, where the significance is at the 10% level). Finally, in order to account for the fact that some regions have transitioned to the modern growth regime, while others remain in the Malthusian stage, we also group countries according to two income levels: countries belonging to the least developed economies according to the United Nations Economic and Social Council ($N = 25$), and the remaining, wealthier, countries ($N = 19$). The results are presented in Appendix F. The effect of density is significant in both samples, with a size of −0.030 for the poorest countries, and −0.056 for the richest.

3.3. Causal inference (two-stage least squares)

One might suspect that the coefficient of density estimated by OLS is plagued by an endogeneity bias due to a local omitted variable affecting both population density and women's fertility. This could lead to a spurious relationship between these two variables without causal effect. Reverse causality is unlikely for two reasons: (i) we take the earliest available data for population density and the latest available for fertility rates. Therefore, fertility cannot affect past density and (ii) fertility is measured at the individual level while population density is measured at the cluster level.

Three candidates for omitted variables could affect both fertility rates and population density. First, favorable economic conditions can affect both fertility and population density, as people are more likely to want to live in these places. We control for income in several ways. In the specification of Column 5 in Table 2, we control for GDP per capita using satellite night-light data, individuals' education, and country fixed effects as proxies for income. Therefore, income is unlikely to affect fertility rates via a channel other than population density.

A second omitted variable could be the existence of norms related to fertility. These could be linked to certain ethnicities rather than countries, as we already control for country fixed effects. A region inhabited by groups of individuals that observe a pro-natalist norm or experience higher fecundity will have a higher population density as a result. If our instrument cannot account for this persistence, then the bias introduced reduces the estimated impact of population density on fertility. This leads to a conservative estimate and therefore does not invalidate the claim that population density has a causal impact on fertility. A similar argument can be made in the presence of unobserved fecundity factors specific to ethnicities.

Lastly, unobserved amenities at the local level can lead to the migration of people with certain characteristics whose persistence could affect fertility rates.

If the omitted variables we have just described affect both population density and fertility *positively*, then they will attenuate the measured effect of density on fertility in the regressions without instrumentation. Instrumenting population density should therefore *increase* the effect of population density on fertility rates.

The generally accepted means of dealing with omitted variables is to instrument the suspected endogenous variable. Density is a commonly used variable in studies on firm productivity, as a way of capturing agglomeration effects. As surveyed by Combes and Gobillon (2015), the literature has adopted different strategies to address this issue. Two strategies dominate: using the historical value of population density and using geographical and geological variables that were important with regard to human settlements centuries ago, but only have negligible effects on outcomes today. The exogeneity of both types of instruments may depend on whether or not one is able to control for local permanent characteristics that may have affected past location choices and still affect fertility locally.

We instrument historical density with the distance to buildings and cities belonging to UNESCO World Heritage Sites constructed between the Neolithic Revolution and 1900. Appendix C shows the list of these sites and maps the computed distance to each cluster in our sample. Notice that we only retain man-made structures and not natural habitats. Proximity to a UNESCO World Heritage Site is likely to increase population density on average since these sites were trade, religious, or political centers. While these were all good reasons to reside close to these locales at the time, they no longer apply since they are not used for their original purpose anymore. However, if population density is persistent over time, then this is a strong instrument. There are reasons to believe that some of these sites may still affect income today. For example, Valencia Caicedo (2014) shows that Jesuit Missions on Guarani land have had a persistent effect on the education and income of those who live close to them today. As we control for

Table 3
IV estimates at the cluster level.

	Dependent variable:		
	n_j	ln(1+density)	n_j
	(5)	1st stage	2nd stage
ln(1+density)	−0.050***		−0.141***
	(0.005)		(0.027)
Distance to UNESCO site		−0.180***	
		(0.023)	
Marriage	1.102***	−1.744***	0.941***
	(0.085)	(0.304)	(0.115)
Infant mortality	2.635***	−0.263	2.597***
	(0.314)	(0.406)	(0.307)
ln(GDP per capita)	−0.047***	−0.263***	−0.019
	(0.011)	(0.074)	(0.013)
Women's education	−0.094***	0.341***	−0.063**
	(0.024)	(0.050)	(0.025)
Women's education^2	−0.004**	−0.001	−0.004**
	(0.002)	(0.003)	(0.002)
Observations	24,769	24,769	24,769
Adjusted R^2	0.740	0.469	0.722
F-test		61.029***	

Notes: Robust standard errors, clustered at the country level, in parentheses. All specifications include country fixed effects, geographical controls (the caloric suitability index and distance to a large body of water) and age polynomials. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

both the mean education and income of clusters, this should not lead us to violate the exclusion restriction.

A potential issue that could invalidate the instrument may be that the proximity to UNESCO World Heritage Sites affects fertility by way of an institutional channel, namely the antiquity of the state. These monuments could indeed symbolize great societies of the past whose effects persist today via norms. Indeed, Chanda and Putterman (2007) show that ancient states such as Egypt, China, and India still have an advantage today, perhaps as a result of culture and institutional capabilities. Most of this effect is controlled for by the inclusion of country fixed effects. Finally, one may still wonder whether some endogeneity bias may persist despite instrumentation through enduring norms. This type of bias would, however, play out in our favor. Indeed, since this persistence leads to a positive relationship between population density and fertility rates, our estimate from the second-stage instrumental variable regression is a lower bound for the effect of population density on fertility. In all cases, the presence of country dummies helps satisfy the exclusion restriction, as many historical and geographical determinants of institutions possibly affecting fertility are controlled for.

Table 3 presents the results. Column (5) of Table 3 is the same as that of Table 2. The second column shows the estimates for the first stage, and the third the estimates of the second stage. The F-test for the first stage is greater than the various threshold values proposed in the literature. We therefore reject the hypothesis that the instrument is weak. We see that the effect of population density on fertility is, as expected, stronger than in the benchmark of Column (5). The effect of increasing density from 10 to $1,000$ ind/km^2 now leads to a drop of 0.64 children, instead of 0.23 in the model without instrumentation. The endogeneity bias is therefore an attenuation bias, arising from the positive correlation between an unobserved variable and both density and fertility.

4. Causal inference at the individual level

The analysis above reveals the main determinants of fertility rates at the cluster level. Moving to the individual level allows us to disentangle the effects of personal variables, like one's education, from the effect of the environment, like the mean education in the cluster. Kravdal (2013) argues that there are strong educational spillovers from cluster-level data to individual behavior.

To exclude the fact that population density at the cluster level may proxy such spillovers, thereby influencing individual fertility, in this section we study fertility at the individual level. We also look at whether the selection of migrants with different fertility behaviors into more or less dense areas might have biased the results of the previous section. We then add further controls in order to account for individual differences in religion, ethnicity, and additional income levels. Finally, we discuss the quality of the fertility responses in DHS. We conclude this section with a discussion of the identified mechanisms that link population density to fertility rates.

4.1. Poisson and IV Poisson

Since the dependent variable, children ever born n_j, is a count variable, we estimate a Poisson regression model to predict the impact of density on births. The model is:

$$E[n_j] = \exp\left\{\pi_0 + \pi_1 \ln(1 + \text{density}_j) + \sum_{i=2}^{N} \pi_i X_{ij}\right\} \tag{2}$$

where $n_j \in \mathbb{N}$ is distributed according to a Poisson distribution. The estimated coefficients π cannot be directly compared to the β's of the OLS. They are related through $\beta_i = \pi_i E[n_j]$. Building on Eq. (1), in Eq. (2), we add controls for average education, marriage, and mortality rates in the cluster where the woman lives. The results are shown in Table 4. To facilitate comparison with the regression at the cluster level, Column (x) of Table 4 has the same set of variates as Column (x) of Table 2. Column (5-IV) shows the estimates of an IV Poisson regression in which we instrument population density with the same instrumental variable used in Section 3.3, i.e. the distance to a UNESCO World Heritage Site, using the GMM estimation method described in Windmeijer and Santos Silva (1997).

The relationship between density and fertility estimated in Column (1) is close to that at the cluster level. Indeed, $\pi_1 \times E[n_j] = -0.069 \times 2.711 = -0.187$ can be compared to $\beta_1 = -0.191$. The estimate from Column (5) is not statistically different from that at the cluster level either. As in the cluster analysis, instrumentation leads to a greater effect of density on the number of children born; when population density goes from 10 to $1,000$ ind/km^2, we estimate that fertility decreases by 0.7 children at the individual level. This again reflects the attenuation bias brought about by the omitted variables.

Among the additional control variables included at the individual level, it is worth noting the coefficient of education. At the cluster level, the effect of education on fertility is negative, with an increasing impetus given by the quadratic term as the level of education increases. As stressed in Kravdal (2002), this measured effect combines both individual and aggregate effects. When one distinguishes between the two, the individual effect first increases and then decreases. Baudin et al. (2015) and Vogl (2016) find evidence of positive income effects affecting the fertility of the uneducated in a large number of developing countries. This may explain the hump-shaped relationship between education and fertility found at the individual level. The other controls have the same effect as at the cluster level, with the exception of the cluster-level marriage rate.[15]

The results shown in Table 4, and in all subsequent tables, do not account for individual weights. Appendix G.1 reproduces Table 4 introducing individual weights. Table G.1 of this appendix shows that

[15] In the last two columns of Table 4, the coefficient of the average marriage rate in the cluster is negatively related to the fertility of individuals. This might be the result of the following: in clusters where marriage rates are higher, the chance of finding a partner in the event of divorce is lower and women may therefore choose to have fewer children in order to limit the cost of divorcing.

Table 4
Poisson and IV Poisson estimates at the individual level.

	Dependent variable: children ever born					
	(1)	(2)	(3)	(4)	(5)	(5-IV)
ln(1+density)	−0.069***	−0.050***	−0.045***	−0.043***	−0.018***	−0.058***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.005)
Married		1.497***	1.487***	1.487***	1.422***	1.422***
		(0.014)	(0.014)	(0.014)	(0.014)	(0.014)
Mean marriage		0.309***	0.154***	0.142***	−0.065***	−0.149***
		(0.013)	(0.014)	(0.014)	(0.012)	(0.017)
Mortality			0.470***	0.470***	0.427***	0.428***
			(0.006)	(0.006)	(0.006)	(0.006)
Mean mortality			0.579***	0.541***	0.161***	0.170***
			(0.030)	(0.030)	(0.028)	(0.029)
ln(GDP per capita)				−0.029***	−0.018***	−0.007***
				(0.002)	(0.002)	(0.002)
Woman's education					0.003***	0.003***
					(0.001)	(0.001)
(Woman's education)^2					−0.003***	−0.003***
					(0.0001)	(0.0001)
Education in cluster					−0.009***	0.004
					(0.002)	(0.002)
Education^2 in cluster					−0.001***	−0.001***
					(0.0001)	(0.0001)
Observations	490,669	490,669	490,669	490,669	490,669	490,669

Notes: Robust standard errors, clustered at the cluster level, in parentheses. All specifications include country fixed effects, geographical controls (the caloric suitability index and distance to a large body of water) and age dummies. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

accounting for them leads to an even higher estimated effect of population density on fertility.

To be sure that our estimation is not only capturing a tempo effect, but that completed fertility also decreases with density, we restrict the sample to women aged 40+. The IV Poisson estimates are presented in Table G.2 of Appendix G.2. The sample size is very much reduced as a result: 95k women instead of 490k. However, most coefficients, including the effect of density, are remarkably stable. Finally, we also look at the impact of population density on the number of births in the last five years, which can also be used as a variable to analyze fertility behavior. The last column in Table G.2 shows the result of the IV Poisson regression. The impact of population density is even stronger with this variable.

4.2. Additional controls for selection

Density may be correlated with fertility because of a selection problem: women with a lower desire for children or lower fecundity may migrate from rural to urban areas.[16] In addition to the instrumentation methods discussed above, we control for selection in two different ways.

First, we run the IV-Poisson regression as specified in Column (5) removing from the sample: (a) those we know have moved (keeping those for whom information on the years lived in the place of residence is not available (NA) in the sample) and (b) everyone but those we know did not migrate (we also exclude those for whom we do not have information on migration). We consider a migrant to be a person who arrived to their place of residence when they were between age 15 and their age at the time of the interview. The results are shown in Columns (5a) and (5b) in Table 5. Alternatively, instead of removing observations, we introduce a dummy variable into the regression that takes the value one if the woman is a migrant and zero otherwise and another dummy that is equal to one when there is no information on migration for the woman and zero otherwise. This prevents us from losing observations unnecessarily. The results are shown in Column (5c).

[16] One example of how this selection might operate is that barren women tend to move to more densely populated areas in order to hide their childlessness (Lesthaeghe, 1989).

Table 5
IV Poisson estimates at the individual level, without migrants (5a), without migrants when restricting the sample to individuals with information on migration status (5b), and controlling for migration status (5c).

	Dependent variable: children ever born			
	(5-IV)	(5a)	(5b)	(5c)
ln(1+density)	−0.058***	−0.070***	−0.097***	−0.058***
	(0.005)	(0.007)	(0.013)	(0.005)
Married	1.422***	1.477***	1.578***	1.425***
	(0.014)	(0.016)	(0.019)	(0.014)
Mean marriage	−0.149***	−0.160***	−0.213***	−0.147***
	(0.017)	(0.021)	(0.034)	(0.017)
Mortality	0.428***	0.449***	0.457***	0.428***
	(0.006)	(0.008)	(0.009)	(0.006)
Mean mortality	0.170***	0.234***	0.200***	0.171***
	(0.029)	(0.036)	(0.047)	(0.029)
ln(GDP per capita)	−0.007***	−0.001	0.000	−0.006***
	(0.002)	(0.003)	(0.004)	(0.002)
Education	0.003***	0.002**	0.005***	0.003***
	(0.001)	(0.001)	(0.001)	(0.001)
Education^2	−0.003***	−0.003***	−0.003***	−0.003***
	(0.000)	(0.000)	(0.000)	(0.000)
Mean education	0.004***	0.009***	0.012**	0.004*
	(0.002)	(0.003)	(0.005)	(0.002)
(Mean education)^2	−0.001***	−0.001***	−0.001***	−0.001***
	(0.000)	(0.000)	(0.000)	(0.000)
Migrant				−0.015***
				(0.002)
Migrant (NA)				−0.023
				(0.028)
Observations	490,669	328,871	221,935	490,669

Notes: Robust standard errors, clustered at the cluster level, in parentheses. All specifications include country fixed effects, geographical controls (the caloric suitability index and distance to a large body of water), and age dummies. DHS data on the years lived in the place of residence is not available for Burundi, Comoros, Ivory Coast, Gabon, Guinea, Honduras, Indonesia, Mozambique, and Pakistan. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 6
IV Poisson estimates at the individual level, controlling for religion (1), ethnicity (2), and other controls for income: electricity (3) and refrigerator (4).

	Dependent variable: children ever born			
	(1)	(2)	(3)	(4)
ln(1+density)	−0.049***	−0.051***	−0.053***	−0.055***
	(0.006)	(0.005)	(0.006)	(0.006)
Married	1.295***	1.290***	1.412***	1.394***
	(0.016)	(0.015)	(0.015)	(0.014)
Mean marriage	−0.124***	−0.088***	−0.147***	−0.129***
	(0.019)	(0.017)	(0.017)	(0.018)
Mortality	0.387***	0.397***	0.426***	0.435***
	(0.006)	(0.007)	(0.006)	(0.007)
Mean mortality	0.177***	0.119***	0.176***	0.189***
	(0.032)	(0.033)	(0.030)	(0.031)
ln (GDP per capita)	−0.011***	0.000	−0.005**	−0.002
	(0.003)	(0.003)	(0.002)	(0.002)
Woman's education	0.007***	0.002**	0.005***	0.001*
	(0.001)	(0.001)	(0.001)	(0.001)
(woman's education)^2	−0.003***	−0.003***	−0.003***	−0.003***
	(0.000)	(0.000)	(0.000)	(0.000)
Mean education	−0.001	0.015***	0.004*	0.013***
	(0.003)	(0.003)	(0.002)	(0.002)
(Mean education)^2	−0.001***	−0.002***	−0.001***	−0.001***
	(0.000)	(0.000)	(0.000)	(0.000)
Islam	0.019***			
	(0.006)			
Christian	−0.014***			
	(0.005)			
Buddhism	−0.048**			
	(0.021)			
Hinduism	−0.151***			
	(0.014)			
Electricity			−0.045***	
			(0.004)	
Mean electricity			0.011	
			(0.013)	
Refrigerator				−0.072***
				(0.003)
Mean refrigerator				−0.063***
				(0.013)
Ethnicity dummies	NO	YES	NO	NO
Observations	355,334	313,255	458,591	430,374

Notes: Robust standard errors, clustered at the cluster level, in parentheses. All specifications include country fixed effects, geographical controls (the caloric suitability index and distance to a large body of water) and age dummies. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Comparing these results to the benchmark Column (5-IV), we see that although the sample size is very much reduced after removing migrants, the effect of population density on children ever born is still significant and larger in (5b). Controlling for migration status in (5c) does not change the size of the coefficient. The coefficient of the dummy identifying those women who moved ("migrant" in the table) is significant and negative; fertility rates among these women are therefore lower on average.

A limitation of the above approach, based on the observed migration status, is the following: if the desire for children is transmitted over generations and it is the parents of the woman who moved and not the woman herself, then we are missing part of the selection channel. We cannot measure this effect based on the data we use.

4.3. Additional controls for religion, ethnicity, and income

Here, we investigate whether or not adding additional controls alters the estimate for the causal relationship between population density and fertility. By doing so, however, we lose some observations for which these control variables are not available.

Column (1) of Table 6 provides the estimates when controlling for the religious composition of the cluster. Information on the religion of an individual is not available in Egypt, Morocco, Pakistan, Bolivia, Colombia, and Peru, while in Jordan, women are either Muslims or Christians in the DHS. The results show that Islam is the most pro-birth religion, followed by Christianity, Buddhism, and Hinduism.[17]

Controlling for ethnicity is a way to control for unobserved norms and values. Column (2) of Table 6 adds dummies for the ethnicity of women. The countries for which we do not have information on ethnicity are Burundi, Comoros, Lesotho, Liberia, Madagascar, Rwanda, Swaziland, Tanzania, Uganda, Zimbabwe, Egypt, Jordan, Morocco, Bolivia, Bangladesh, Cambodia, and Indonesia. For other countries, we add a dummy variable denoting which ethnicity a woman belongs to. This adds up to 236 different ethnicities. Notice that some ethnicities can be present in more than one country.

As additional controls for income, Columns (3) and (4) add controls for the electricity availability rate in the cluster and refrigerator ownership rate in the cluster, respectively. DHS data on refrigerator ownership is not available for Ethiopia and Malawi. Higher electricity or refrigerator rates are negatively associated with fertility,[18] perhaps as a result of the effect of modernization and access to other norms, as shown by La Ferrara et al. (2012) in the case of television-transmitted soap operas in Brazil, for example.

The estimate of the effect of population density on fertility does not change significantly in any of the four alternative specifications in Table 6.

4.4. Quality of the data

Another possible issue is that our data might include misreported births, as detailed in Appendix G.2. In particular, older women with low or no education, are more likely to omit first births, thereby reporting fewer children than they actually have. The third column of Table G.2 shows the IV-Poisson estimates taking into consideration only those countries with the "best quality" data, as suggested by Schoumaker (2014). By doing so, we drop more than half of the observations. Comparing the results, we see that when we restrict the analysis to these countries, the overall impact of population density on fertility rates is unchanged. The effect of some covariates differs, however. In particular, the impact of individual education on fertility is now systematically negative and significant.

The results obtained so far suggest that several mechanisms are at play. First, an *augmented Beckerian* model allowing for an effect of density through education captures parts of the relationships revealed in the data. Indeed, controlling for education and health (mortality) reduces the correlation between density and fertility, suggesting that some of its impact is brought to bear through education and health. Moreover, distinguishing individual variates from cluster-level variates highlights the importance of agglomeration externalities entailed by higher population density. These externalities play an important role in reducing fertility, as population density increases when for instance education, health, and electricity are provided. Second, even when controlling for education, mortality, income, and marriage, there remains a direct effect of density on fertility, which might be related to *Malthusian scarcity mechanisms* still at work today. As we control quite extensively for income, these mechanisms are likely to affect the cost of having children, for example by making space (land and housing) more expensive, such as in Murphy et al. (2008) and de la Croix and Gosseries (2012). Third, the negative causal effect of density on fertility persists when estimated on samples from which migrants are excluded. Hence, the selection model does not appear to explain a large part of the correlation between density and fertility.

[17] This ranking is in line with de la Croix and Delavallade (2015) who study the role of religion in both the quantity and quality of children in South East Asia.

[18] Contrary to what would be expected by Greenwood et al. (2005) who explain the baby boom in terms of better home production technology.

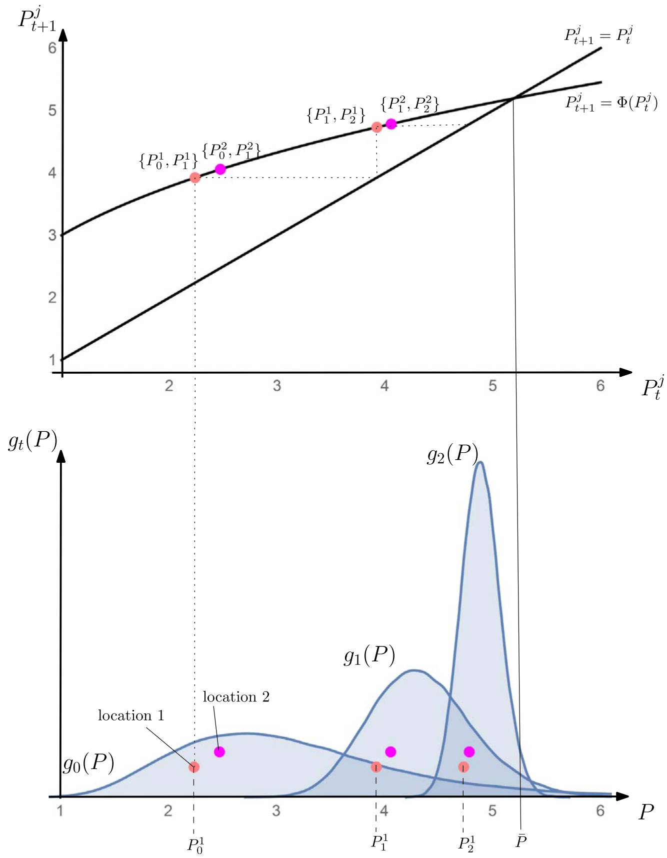

Fig. 3. Dynamics and convergence of population in Malthus or Sadler models.

5. Demographic convergence

To relate our cross-sectional empirical results to population dynamics, consider the following proposition.

Proposition 1 (*Population dynamics*). *If population dynamics follow $P_{t+1} = \Phi(P_t)$, given P_0, with $\Phi'(\cdot) > 0$ and $\Phi''(\cdot) < 0$, then population growth is negatively correlated with population density over time.*

P. roof: See Appendix A.

To map the relationship between population density and population growth over time as a relationship across space, one can follow the standard approach provided by growth theory (Galor, 1996).

Corollary 1. *Consider a world consisting of different locations, each location isolated from the rest, and following the same law of motion, $\Phi(P_t)$, described in Proposition 1 (up to a multiplicative constant). If each location starts from a different initial condition P_0, then population growth is negatively correlated with population density across space.*

Fig. 3 illustrates this point. The bottom panel represents the distribution of population across locations, j, for three points in time, $t = 0, 1, 2$. $g_t(P)$ is the distribution of the population at time t. For the initial period, we represent two locations, 1 and 2, with initial population ${P_0}^1$ and ${P_0}^2$ (bottom panel). Projecting them on the top panel, which represents the dynamic function $P^j_{t+1} = \Phi(P^j_t)$, allows us to compute the populations in the next period ${P_1}^1$ and ${P_1}^2$. After having applied the function Φ to all locations, one can then compute the new distribution of population $g_1(P)$. Given that function Φ is concave, we see that the rise in population in location 1, $P^1_1 - P^1_0$, is larger than the one in location 2, $P^2_1 - P^2_0$, which was initially the more densely populated location. As time passes, all populations tend toward a stable steady state $\bar{P}$ and the distribution becomes degenerate.

To interpret this result in terms of causality, let us consider two different locations identical in all respects, but starting with different population densities for historical reasons (initial conditions). Reasoning in terms of the Malthusian model for instance, the location with the higher density will have, at all future dates, a lower income and a more expensive space than the location starting with the lower density. This location will also have lower fertility rates. Higher initial density causes lower income and more expensive space, which in turn cause lower fertility.

The assumption that function Φ is the same across locations up to a multiplicative constant amounts to assuming that the demographic growth rate is the same in two locations that share the same distance (in %) from their steady state.

The speed at which a population tends toward its steady state depends on the slope of Φ.[19] The lower the slope, the faster the convergence. In our context, if fertility reacts strongly to population density, the convergence is fast.[20]

Sections 3.3 and 4.1 show that, on average, greater population density reduces fertility rates. Assuming that population dynamics are governed by the same function Φ, the size of this negative impact of population density on fertility determines the speed at which the *global* population level converges to its steady state. Let us now compute the speed of convergence[21] of a population, which we call demographic convergence, using our model of fertility. The law of motion of the global population at time $t + 1$ (time represents a generation) is:

$$P_{t+1} = n_t P_t + (1 - d)P_t \tag{3}$$

where d is the death rate, which is assumed to be constant. Based on the previous section, the following equation describes the fertility rate:

$$n_t = b_0 - b_1 \ln\left(1 + \frac{P_t}{L}\right)$$

where P_t/L is population density. Replacing n_t in (3) we have:

$$P_{t+1} = f(P_t) = \left(b_0 - b_1 \ln\left(1 + \frac{P_t}{L}\right)\right)P_t + (1 - d)P_t$$

At steady state $\bar{P}$, births necessarily balance deaths: $n_t - d = 0$. The rate of convergence of the population is the derivative of $f(P_t)$ at the steady state:

$$f'(\bar{P}) = 1 - \frac{\bar{P}/L}{1 + \bar{P}/L} b_1 \approx 1 - b_1.$$

Hence, it is simply one minus coefficient β_1 of $\ln(1 + \text{density})$ from the OLS regression, or $1 - E[n]\pi_1$ in the case of the Poisson regression.

Table 7 summarizes our results. The first column reports coefficients b_1 produced by the 2SLS and IV-Poisson specifications at the cluster and individual levels respectively. The last two columns of Table 7 show the time it takes to close half the gap with the steady state, and standard errors. From the specification at the cluster level, the half-life estimate lies in the confidence interval of the coefficient obtained using Sato's (2007) data for Japanese regions in 2000.[22] Our estimates suggest that half of the gap with the steady state is filled in between four and five generations.

This result is obtained from the regressions in which all control variables are included. If density also influences fertility through education and health, the effect is stronger, and Table 7 can be seen

[19] See Sato (1966) for an early analysis of adjustment speed in growth models, and Barro and Sala-i Martin (1986) for an empirical application to convergence of income per person across U.S. states.

[20] Notice that this result no longer holds if function Φ is convex-concave rather than globally concave, as is the case with a logistic function, unless all locations are close enough to their steady state, in which case only the concave portion of Φ is relevant.

[21] In Appendix A, we remind the reader of the basic definitions used in convergence analysis.

[22] We thank Professor Yasuhiro Sato for kindly sharing the data with us.

Table 7
Summary of the estimates at the cluster and individual levels.

	$-b_1$	Half-life	(s.e.)
Cluster instrumented	−0.141	4.78	(1.190)
Woman instrumented	−0.157	4.08	(0.395)
Sato (2007)	−0.110	6.23	(1.580)

Note: s.e. computed using Monte Carlo simulations.

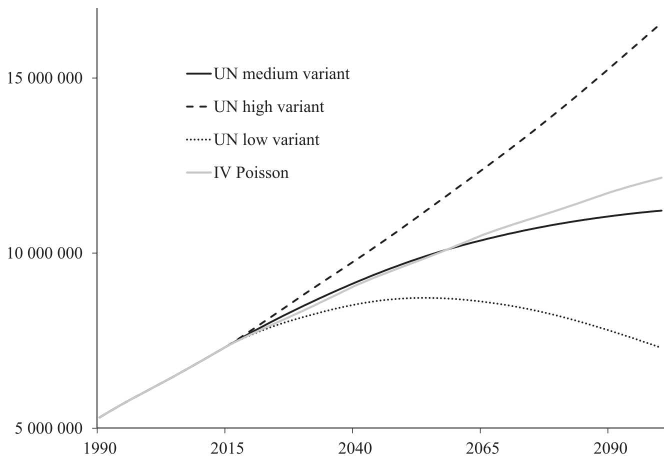

Fig. 4. World population projections – U.N. and ours from the IV Poisson estimates.

as providing an upper bound on the actual half-life for population dynamics.

To provide an idea of what it implies for population projections, let us forecast population as follows. Suppose one generation is 25 years. In a first step, we compute $\overline{P}$ to solve:

$$P_{2015} - \overline{P} = (1 - \beta_1)(P_{1990} - \overline{P}).$$

In a second step, we take as initial conditions P_i with $i = 1990\ldots2015$, and we use the following equation:

$$P_i - \overline{P} = (1 - \beta_1)(P_{i-15} - \overline{P}) \quad (4)$$

to compute P_i, with $i = 2016\ldots2100$. Fig. 4 compares UN population projections (2015 revisions) with our hypothetical dynamics solely based on the reaction of fertility to population density. We take the estimates of the IV-Poisson specification for the analysis.

The medium variant scenario put forward by the UN follows our projections closely until 2065. Beyond that point, it estimates a world population below the one implied by the IV-Poisson regression. This may reflect the fact that their fertility rates adjust more than what is predicted by the spontaneous convergence forces we have estimated. Notice also that our dynamics decrease less than theirs, implying a population peak at 12.2 billion individuals, around one billion higher than the UN medium variant scenario predicts.

6. Conclusion

Using data from DHS and raster files from CIESIN et al. (2011), this paper provides empirical evidence of the negative impact of population density on fertility in developing countries.

Comparing the impact of density on fertility at the cluster level and at the individual level sheds light on the importance of the consequences of agglomeration on fertility. Among the components of agglomeration, higher education, better health services, and access to public infrastructure play a role in decreasing fertility. We also find nuanced evidence supporting the view that scarcity and congestion affect fertility rates.

A contribution of this paper is also to relate the microeconomic estimate of the effect of density on fertility to the macroeconomic notion of convergence applied to the demographic context. The total effect of density, including an increase in education, better access to services such as healthcare, and the changes in cultural norms that come with it, imply a relatively rapid rate of convergence: population levels take four to five generations to fill half the gap with their long-run levels.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jdeveco.2017.02.003.

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