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Population homeostasis in sub-Saharan Africa

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ABSTRACT

Global population growth remains one of the major challenges of the twenty-first century. This is particularly true for African countries which have been undergoing their demographic transitions. To investigate whether predicted increasing population density and urbanization can help to stabilize African population, we construct a database for 84 georeferenced Demographic and Health Survey (DHS) samples including 947,191 individuals in sub-Saharan Africa and match each location with gridded population density from NASA. We apply a proportional hazard model to evaluate the quantitative impact of local population density on the transitions from childlessness to motherhood, and from celibacy to marriage. Moving from the 5th to the 95th percentile of population density increases the median age at first birth by 2.2 years. This roughly decreases completed fertility by half a child. The same increase in population density increases the median age at first marriage by 3.3 years. These findings contribute to the understanding of why fertility has not dropped in Africa as fast as expected. One part of the answer is that population density remains low. Yet the total effect of increased density on fertility remains limited and counting on it to stabilize the population would be unrealistic.

1. Introduction

Projections by the United Nations (UN) or the International Institute for Applied Systems Analysis (IIASA) show that the global population will peak at the turn of the next century at around 10 billion individuals.[1] The bulk of the increase leading to this peak comes from sub-Saharan Africa (Population Division, 2019; Lutz et al., 2014). The African population is expected to double in the next 50 years, and triple by the end of the century. This is one key challenge that the global ecosystem will face in the upcoming decades.

On the one hand, the rise in the world's population strongly depends on how rapid fertility transitions will be. On the other hand, increasing population density is likely to trigger a drop in fertility – a property called population *homeostasis* (Lee, 1987). Population homeostasis requires the presence of spontaneous convergence forces that keep population close to a stable, long-run level.[2] A question of major importance is whether these forces are strong enough.

Our contribution here is to quantify the population *homeostasis* property. In detail, we analyze the relationship between population density and fertility in sub-Saharan Africa, in order to better understand whether spontaneous convergence forces are at work. To do so, we combine individual fertility data from Demographic and Health Surveys (DHS) with gridded population density data from NASA. They are based on detailed population data from census administrative units.[3] In DHS data, individuals belong to georeferenced clusters, which allow for mapping population density onto fertility.

Once the local population density is known for each woman, we can run a statistical model relating the key determinants of fertility to the population density of the cluster in which they live. We focus on the starting time of reproduction, using either the age at marriage or the age at first birth. In addition to birth spacing and the age at stopping, which we do not consider here, these two dates are, for any woman, important determinants of her overall completed fertility. Focusing on these dates allows us to assess how fertility reacts to population density *today*, without having to rely on synthetic *tempo* measures of fertility. The latter measures have indeed been shown not to have a strong predictive power

[1] To be precise, the peak is not foreseen by the UN within the projection period up to 2100, although it should happen soon thereafter. IIASA's projected population peaks at 9.7 billion as early as 2070. This is happening under the medium variant of the UN and the SSP2 scenario of IIASA.

[2] While homeostatis is a property of a dynamical system, it is related to the idea of the demographic transition (Wilson and Airey, 1999). The demographic transition is usually seen as a shift from one stable demographic regime with high fertility and mortality to another stable regime with low fertility and mortality – following some large shock – while the homeostasis property ensures the convergence of demographic variables to some constant levels in the new regime. These different notions are developed in the Appendix.

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

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for completed fertility, precisely because of the change in the timing of childbearing over time (Bongaarts and Feeney, 1998). Hence, we suggest that looking at these two main events, age at marriage and age at first birth, allows us to assess the population *homeostasis* property based on individuals' decisions today.

Compared to the previous literature that has studied the relationship between population density and fertility (Lutz and Qiang, 2002; Lutz et al., 2006), we are the first to document the negative effect of population density on fertility using estimates from individual level data. Our main contribution is therefore to show that homeostasis forces are at play for human population, at a fine grid level. More generally, we show that macroeconomic conditions can affect individual fertility behavior in a permanent way. We also challenge the common wisdom that the main driver of the last phase of the demographic transition is family limitation obtained by reducing high order parity progression ratios, a *stopping* strategy. We show that homeostasis also operates through the *entry* into sexual activity (marriage and motherhood).

We also identify the plausible mediating variables responsible for a link between density and fertility. At the individual level, both higher education and health postpone marriage and motherhood. This is not surprising, but it is worth noting that these variables partly capture the effect of population density on fertility. At the collective level, higher education and health in the community to which an individual belongs also have the expected effects on fertility. Importantly, they also capture an additional part of the effect of population density on the probability of entering motherhood (ten percent). This paper thus relates to the more extensive literature on urbanization and economic development in general, and urbanization and demographic change in particular (Dyson, 2011; Flückiger and Ludwig, 2017).[4]

The magnitude of the overall effect of population density on fertility is sizable, but falls short of what is needed to foster a fertility decline towards the replacement level of the population. Moving from the 5th to the 95th percentile of population density increases the age at first birth by 2.2 years and the age at marriage by 3.3 years. From the observed relationship between the age at first birth and completed fertility, this roughly corresponds to a decrease by half a child at most.

The results are robust to the inclusion of controls for ethnicity, religion, proxies for household wealth, the education of spouses, and contraception knowledge. We show that the results are neither driven by selection of individuals, nor by measurement errors in the data.

2. Data

Our main source of data is Demographic and Health Surveys (DHS). We consider every sub-Saharan country for which GPS-coordinates information is available. This amounts to 34 countries. For the majority of these countries, survey data were collected during different DHS phases. We include every "standard DHS" type of survey for phases II and above.[5] The list of countries and DHS phases are provided in Table S.1. We use the individual recode, the household recode, and the GPS dataset. Households are grouped into clusters for which we know the latitude and the longitude from the DHS GPS file. The total number of individuals for each country is shown in the supplementary material, together with the list of variables used, and some descriptive statistics.

From the individual recode, we built a sample consisting of women between 15 and 49 years of age whose cluster of residence is known. We use information on: age, education, partner's education, total number of children ever born, total number of living children, religion, age at first birth, age at first marriage, whether she moved from her place of residence after 14, and ethnicity. 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 dataset, we use the geographical coordinates of each cluster.

The geolocation of DHS samples allows us to combine these data with three sources of geographical data. First, population density raster files are taken from the Center for International Earth Science Information Network (CIESIN) and International Food Policy Research Institute (IFPRI) and The World Bankand Centro Internacional de Agricultura Tropical (CIAT), (2011). They provide information on population density in grids with cell sizes of 30" × 30" (approximately 1 km^2). To avoid a possible reverse causality from fertility to population density, we use density in 1990, which is the earliest year available.

The second geographical information that we include is a measure for land productivity. We use one of the caloric suitability indexes developed by Galor and Özak (2016) which has a resolution of 5' × 5' (approximately 100 km^2). Galor and Özak (2015) show that the caloric suitability index performs better than conventionally used agricultural suitability data (Ramankutty et al., 2002) in terms of capturing the effect of land productivity. 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, rainfall, soil quality, terrain ruggedness, steepness, etc.

Finally, as a proxy for income per capita, we use the GDP measures from Ghosh et al. (2010), which are essentially based on nighttime light satellite data. Henderson et al. (2012) show that luminosity is a strong proxy of GDP. This proxy has two main advantages. First, it provides a harmonized measure for total economic activity across countries at a disaggregated level. And second, it allows to account for the informal sector, which is often important in developing countries and difficult to include in national statistics. The precision level of the raster is 30" × 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 nighttime light pixels. We therefore base our measure on an aggregated 20' × 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 inhabitants per km^2. For every cluster, we impute its GDP as the mean within a circle of 50km in radius.

3. Results

3.1. Demographics in sub-Saharan Africa

Fig. 1 shows the location of all clusters in sub-Saharan Africa from the Demographic and Health Surveys. The shade of green represents the population density in 1990 in these clusters from the gridded population density raster built by NASA.[7] Population density ranges from 0.01 inhabitants per square kilometer in the Karas region (Namibia) to 32,861 in Addis Ababa (Ethiopia).[8] As we have merged all the waves of the DHS,

[4] See Collier (2017) and Pariente (2017) for discussions on urbanization, infrastructure and productivity in Sub-Saharan Africa. Urbanization has mostly been studied as the migration process of individuals who change location in search of better economic possibilities, but it is also associated with an increase in population density of urban areas, which has been called the internal urban population growth (Fox, 2017; Jedwab et al., 2017). This paper naturally relates to this latter, and less explored, aspect of urbanization.

[5] We do not keep DHS data collected during the first phase because these took place prior to our measure for population density.

[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] Center for International Earth Science Information Network (CIESIN) and International Food Policy Research Institute (IFPRI) and The World Bankand Centro Internacional de Agricultura Tropical (CIAT). (2011).

[8] Fig. S2 shows the frequency distribution of $\log(1 + density)$ across all women in the sample.

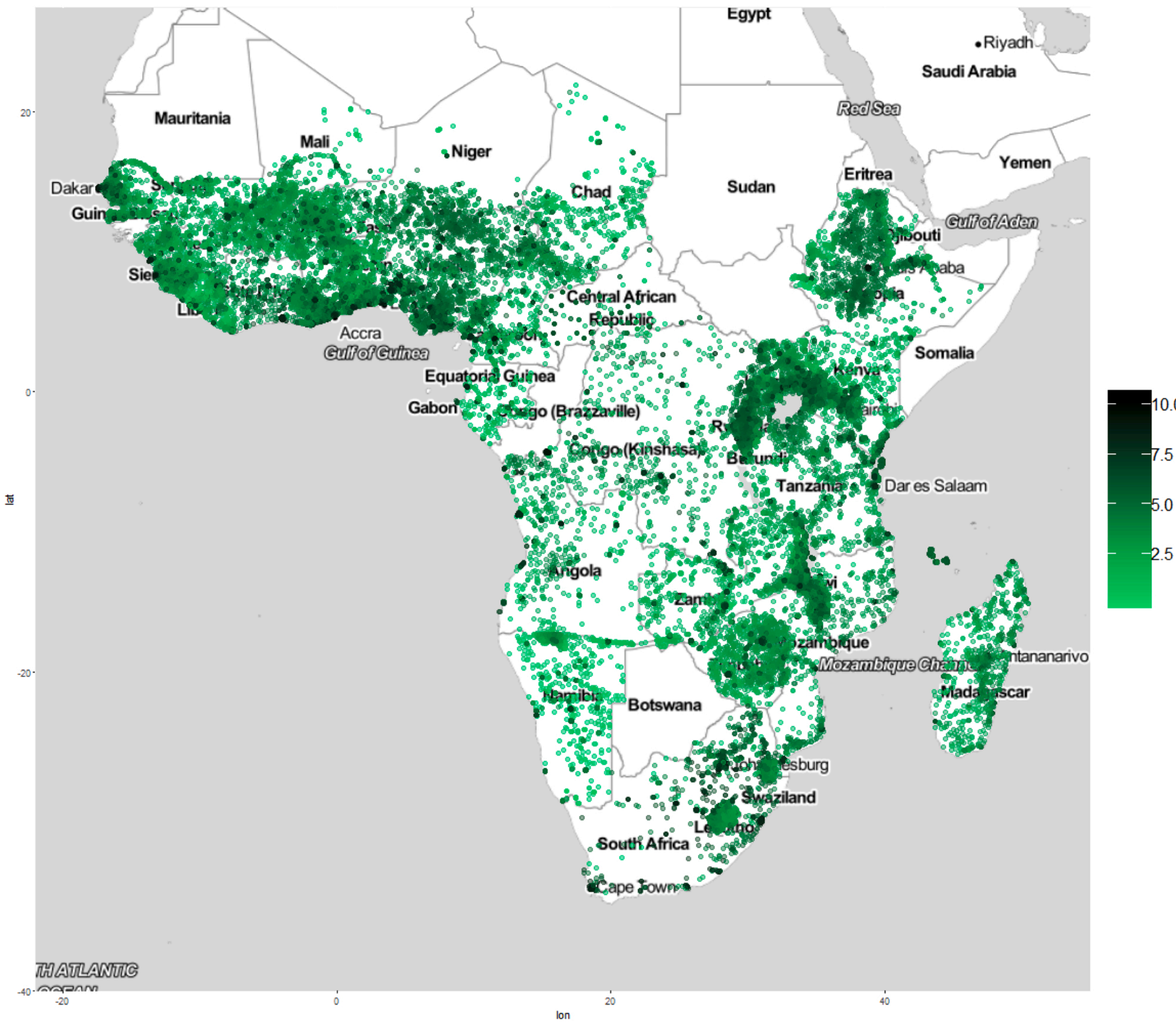

Fig. 1. Cluster Localization and Population Density. *Note*: Population density is reported as $ln(1 + \text{population density})$.

we obtain a comprehensive coverage of Africa, both across countries and across urban/rural areas.

The sample includes 947k women, with an average age of 28. The average total number of children ever born is 2.9. The average age at first birth is 19, and the average age at first marriage is 18.[9] In practice, variations in the number of children per woman depend on the age at marriage and first birth, on the time between each birth (spacing), and/or on when the last child occurred (stopping). Standard DHS provide the complete history of birth for each woman. The weaknesses of these surveys, as reported in Schoumaker (2014), are particularly relevant to analyzing the spacing between births. We can however still check for the first proximate determinant of fertility - birth and marriage postponement - by studying the determinants of age at first birth and age at first marriage. In Section 3.3 we will show that these two dates are very strong predictors of completed fertility.

The unconditional probability (hazard rate) of becoming a mother and of marrying changes with density. Fig. 2 plots the hazard rates[10] as a function of age dividing the sample into four groups of equal size, according to the population density in their area. These are unconditional probabilities, i.e. we do not control for anything but age. Fig. 2 displays two salient features. First, there is a postponement in the mean age at first birth when population density is higher: the probability of becoming a mother peaks at 18 years (220 months), and drops quickly after this peak for the first quartile. In the last population density quartile, the probability peaks over the range between ages 20 and 28 (240-340 months). Second, high density areas have lower risks associated to childbearing at each age. The same description applies to the probability of marrying (right panel).

3.2. Average effect of population density on population dynamics

We study how population density affects birth or marriage postponement through a proportional hazard model. The unit of observation is a woman. The probability that woman j living in cluster c will exit childlessness or singlehood at time a, denoted $\lambda_{jc}(a)$, is

$$\lambda_{jc}(a) = \lambda_0(a)\exp\left\{\tau_1 \ln(1 + \text{density}_c) + \sum_{i=2}^{N} \tau_i X_{jci} + \sum_{i=N+1}^{N_c} \tau_i X_{ci}\right\}. \tag{1}$$

According to Equation 1, the baseline hazard rate, $\lambda_0(a)$, is shifted

[9] Fig. S3 shows the frequency distribution of both ages across all women in the sample.

[10] Computed in R with the package `muhaz` which estimates a hazard function from right-censored data using kernel-based methods.

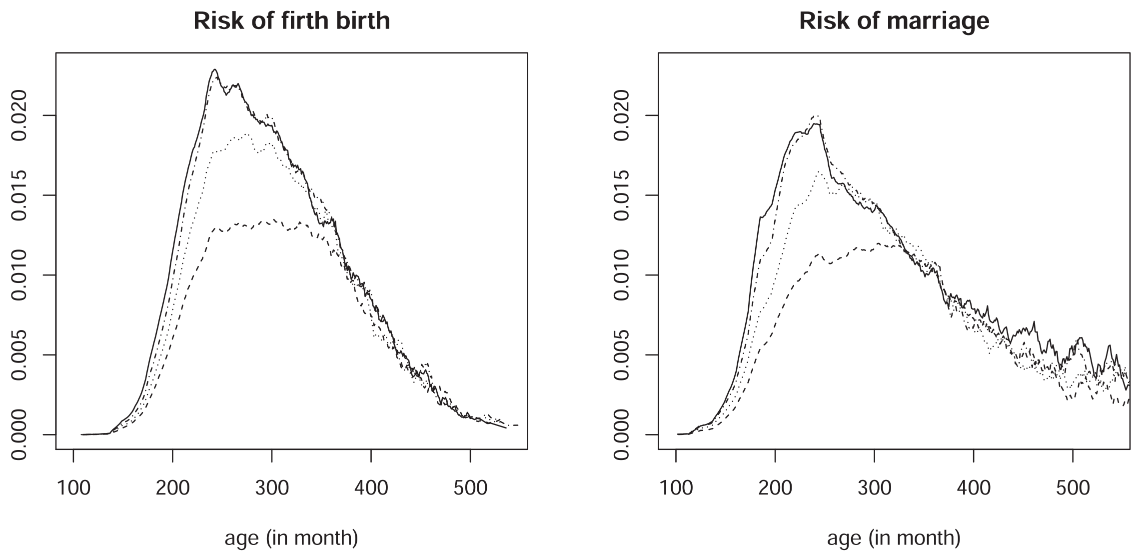

Fig. 2. Unconditional Probability of Becoming a Mother (Left) and Marrying (Right) as a Function of Age (in Months) by Population Density Quartile (Q1 - solid line, Q2 - dashed-dotted line, Q3 - dotted line, Q4 - dashed line. Kaplan-Meier estimates.

proportionally by the density in the cluster $\ln(1+\text{density}_c)$, by N individual controls X_{jc}, and by N_c cluster level controls X_c, both listed in the following paragraph. For the age at first marriage and the age at first birth, the hazard rates λ are computed from women's data, where one observes for an individual j the couple $(y_j; I_j)$, where $y_j = \min(t_j; c_j)$ is the minimum between the age at first event t_j (i.e. the survival time) and the age at interview c_j (i.e. the censoring time). The event indicator I_j equals 1 if the event, either a birth or a marriage, has been observed (i.e. $t_j \leq c_j$), and zero otherwise. The estimation uses the Breslow method to handle tied failures. Standard errors are clustered at the DHS cluster level, accounting for the possibility that observations might not be independent within each DHS cluster. Tables 1 and 2 present the results of the estimated coefficients using either the age at first birth or the age at marriage as dependent variables. Column (1) shows the results for the total effects of population density when we only include survey fixed effects to the model. Column (2) includes a second-order polynomial on individual education. Column (3) adds individual-level covariates. These covariates are the marriage status of the respondent (only when the dependent variable is the birth hazard) and the proportion of children that have died, as observed at the time of the survey. This variable can proxy the overall health of a woman and her income status. Finally, Column (4) adds cluster-level variables that might influence the age at first birth or age at marriage. The first is land productivity, proxied by the amount of calories that the land can provide. This allows us to control for the carrying capacity of each location. Land productivity can positively affect the probability of having a first birth or marrying if a Malthusian-type of argument is at play. The average mortality in the cluster allow us to capture the effect of health institutions. We also control for the average GDP per capita in logs and the average education in the cluster. The coefficients for GDP per capita suggest that richer places are associated with a lower probability of marrying. As shown by Kravdal (2002), average education is an important factor affecting women's birth rates, above their individual education level. Recently, Kebele et al. (2021) also show that average fertility has a negative effect on fertility intentions. This is in line with Beckerian theory, according to which more educated places are associated to economies where the returns to human capital are higher.

Table 1
Cox model estimates for age at first birth.

Dependent variable:	*Probability of becoming a mother*			
	(1)	(2)	(3)	(4)
ln(1+density)	-0.099***	-0.038***	-0.024***	-0.014***
	(0.001)	(0.001)	(0.001)	(0.001)
education		0.018***	0.046***	0.052***
		(0.001)	(0.001)	(0.001)
(education)^2		-0.007***	-0.008***	-0.008***
		(0.000)	(0.000)	(0.000)
married			1.271***	1.268***
			(0.007)	(0.007)
infant mortality			0.627***	0.583***
			(0.007)	(0.007)
calories				0.014***
				(0.001)
mean mortality				0.577***
				(0.036)
log(GDP per capita)				-0.002
				(0.003)
mean education				-0.011***
				(0.001)
Observations	947,191	947,191	947,191	947,191

Notes: *p< 0.1; **p< 0.05; ***p< 0.01. Standard errors clustered at the cluster level. All specifications include survey fixed effects.

Table 2
Cox model estimates for age at marriage.

Dependent variable:	*Probability of marrying*			
	(1)	(2)	(3)	(4)
ln(1+density)	-0.136***	-0.059***	-0.057***	-0.017***
	(0.001)	(0.001)	(0.001)	(0.002)
education		-0.062***	-0.057***	-0.036***
		(0.001)	(0.001)	(0.001)
(education)^2		-0.003***	-0.003***	-0.003***
		(0.000)	(0.000)	(0.000)
infant mortality			0.537***	0.441***
			(0.008)	(0.008)
calories				0.007***
				(0.001)
mean mortality				1.249***
				(0.049)
log(GDP per capita)				-0.010***
				(0.003)
mean education				-0.051***
				(0.001)
Observations	947,191	947,191	947,191	947,191

Notes: *p< 0.1; **p< 0.05; ***p< 0.01. Standard errors clustered at the cluster level. All specifications include survey fixed effects.

The magnitude of the total effect of population density (Column (1)) can be interpreted as the difference between the median age at first birth and the median age at first marriage for a hypothetical individual living in a low- vs. high-density area. We set low-density areas to those in the first decile of the distribution of density (4.7 ind/km^2), and high density areas to those in the tenth decile (3,750.8 ind/km^2). For a given age, the chance of becoming a mother (resp. of being married) in a high-density area is 52.5% (resp. 41.3%) of the chance of becoming a mother in a low-density area. We can also translate these probabilities into median age at first birth and at marriage. In a low-density area, the estimated median age at first birth is 19.0 years. In a high-density area, it is 21.2 years (+2.2 years). For marriage, these ages are 17.7 and 21.0 respectively (+3.3 years).

We also identify the plausible responsible mediating variables in Columns (2), (3), and (4). We distinguish between candidates for mediating effects at the individual (Columns (2) and (3)) and collective level (Column (4)). At the individual level, higher education postpones marriage and motherhood. This result is well known in the literature (Kravdal, 2002). What matters here is that introducing these variables partly captures the effect of population density on fertility. In detail, sixty percent of the overall effect of population density on the probability of becoming a mother are captured by individual education. This is confirmed when computing the magnitude of the effect of population density at constant education as the difference between the median age at first birth and the median age at first marriage for a hypothetical individual living in a low- vs. high-density area. In a low-density area, the estimated median age at first birth is 19.5 years. In a high-density area, it is 20.3 years (+0.8 years). For marriage, these ages are 18.3 and 19.7 respectively (+1.4 years).

We can compare the effect of population density with the effect of education. First, using the coefficients of Column (2), a raising density from the first to the last decile (at given education level) has the same effect on the probability of becoming a mother as raising female education from 6 years to 8.9 years.[11] Second, using the coefficients of Column (1) for the total effect of density and of Column (2) for the effect of education, a raising density from the first to the last decile has the same effect as raising female education from 6 years to 12 years.[12]

In Column (3), better health (proxied by the inverse of the ratio between child deaths and total births) also postpones marriage and motherhood. Finally, at the collective level (Column (4)), GDP is negatively associated to both the probability of a first birth and of marrying, although it is only significant for the last. This points towards a Beckerian effect of income on fertility, rather than a Malthusian effect. The no significance might also witness that GDP is poorly measured by satellite lights at the cluster level. Higher education and better health in the community to which an individual belongs have the expected effects on fertility. Importantly, they also capture an additional part of the effect of population density on the probability of entering motherhood. After accounting for both individual and collective plausible mediating variables, a residual effect of population density on the age at first birth and the age at marriage remains. Non-observable variables, such as the price of space or unobserved income effects, could further mediate the relationship.

3.3. Implications for the demographic transition

We have shown in the previous subsection that the magnitude of the overall effect of population density on fertility is sizable. Here we will show that it however falls short of what is needed to foster a fertility decline towards the replacement level of the population.

First, we provide evidence that both the age at first birth and the age at first marriage are excellent predictors of completed fertility. To illustrate this, Fig. 3 shows the relationship between the average number of children ever born for each age at first birth (left panel) and for each age at first marriage (right panel) in months. The average number of children ever born is computed for the subsample of mothers aged 40 and more, being thereby (almost) at the end of their reproductive period. There are 151,190 women in this sample. For each age at first birth and age at first marriage, we then compute the average number of children ever born. For both the age at first birth and the age at first marriage, the relationship with completed fertility is linear over the age range 14-32. The corresponding regression lines are:

$$\text{number of children ever born} = 11.42 - 0.25 \times \quad \text{age at first birth} \tag{2}$$

$$\text{number of children ever born} = 10.13 - 0.21 \times \quad \text{age at first marriage.} \tag{3}$$

Hence, postponing birth by one year reduces fertility by one fourth of a child on average.

Second, we can use the relationship between ages at first birth and at marriage and fertility to link population density to the number of children ever born.

From Table 3 we see that moving from the 5th to the 95th percentile of population density increases the age at first birth by 2.2 years (from Column (3)) and the age at marriage by 3.3 years (from Column (5)). From the observed relationship between the age at first birth and completed fertility, this corresponds to a decrease by 0.6 children (from Column (4)). From the observed relationship between the age at marriage and completed fertility, this corresponds to a decrease by 0.7 children (from Column (6)).

One can also use Table 3 to evaluate the effect of population size on population growth in the coming century. Africa's population is expected to triple. Starting from median density, the last two lines show the effect of this tripling on ages at first birth and at marriage, as well as their implication for fertility. Obviously, the expected increase in population density will have a limited effect on fertility in Sub-Saharan countries, although negative. This further suggests that population homeostasis is a slow-moving process. This is in line with recent estimates of population dynamics in a Malthusian economy found by Bouscasse et al. (2021).

To be more precise, we can compute the half-life of population dynamics implied by our estimates. Regressing population density (Column (2)) on fertility (Column (4)), we get a coefficient of -0.0836. This implies that the dynamics of population are given by $P_{t+25} = 0.9164 P_t$ (assuming one generation is 25 years, and mortality is constant). The half life of these dynamics are $ln(0.5)/ln(0.9164) = 7.94$ generations, i.e. 198 years. We can compare this number to the literature. For pre-industrial England, Bouscasse et al. (2021) find a half-life of 150 years, higher than the previous estimate by Lee and Anderson (2002) of 107 years. Lagerlöf (2019) finds a half life of 356 years for pre-industrial Europe. For the developing world as a whole, De la Croix and Gobbi (2017) find a value of 102 years. For Japan, Sato (2007) estimates a value of 156 years. All these estimates point towards very slow dynamics. Africa is rather on the slow side.

3.4. Robustness

To assess the robustness of our findings, we do three robustness exercises. First, we include other potential determinants of the age at marriage and the age at first birth. These are religion fixed effects, ethnicity fixed effects, proxies for family income and wealth, the education of spouses, and knowledge about contraception methods. The inclusion of these additional control variables does not alter the significance of the effect of population density. The size of the effect also remains the same overall, except when including the proxies for

[11] Solving $-0.038(8.23 - 1.74) = 0.018(e - 6) - 0.007(e - 36)$ for e gives 8.9.

[12] Solving $-0.099(8.23 - 1.74) = 0.018(e - 6) - 0.007(e - 36)$ for e gives 12.

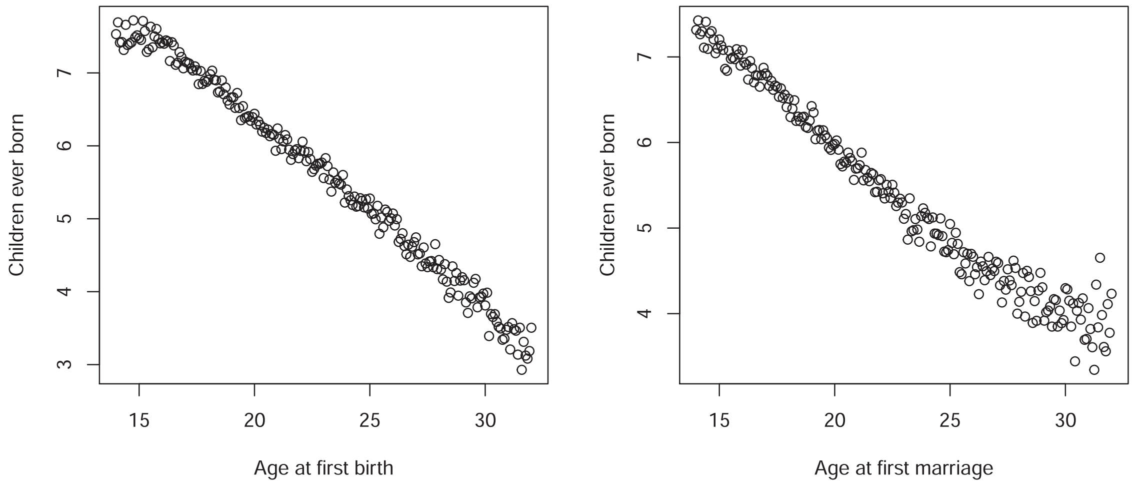

Fig. 3. Age at first birth, age at first marriage, and children ever born for women aged 40+.

Table 3
Density and completed fertility.

density quantile (1)	ln (1+ density) (2)	median age at first birth (3)	children ever born from (2) (4)	median age at marriage (5)	children ever born from (3) (6)
0.05	1.74	19.0	6.6	17.7	6.5
0.15	2.77	19.3	6.5	18.1	6.4
0.25	3.44	19.5	6.5	18.3	6.3
0.35	3.99	19.7	6.4	18.6	6.3
0.55	5.01	20.0	6.3	19.1	6.2
0.45	4.51	19.8	6.4	18.8	6.2
0.65	5.59	20.2	6.3	19.4	6.1
0.75	6.15	20.3	6.3	19.8	6.0
0.85	7.09	20.7	6.2	20.3	5.9
0.95	8.23	21.2	6.0	21.0	5.8
median	4.75	19.9	6.4	19.0	6.2
density x3	5.85	20.3	6.3	19.5	6.1

household income and wealth, which lowers the effect of density further. Second, we look at whether the results might be driven by migration, which could lead to biased estimates due to a selection of individuals into places with higher or lower population density. Dropping the women who changed residence after the age of 14 from the sample leaves the results unaffected. Finally, DHS might suffer from quality issues regarding the reported timing of some events. Dropping countries known to have poor quality data (Schoumaker, 2014) amplifies the magnitude of the effect of density. Hence, our results might be seen as providing a lower bound on the true effect. Details are provided in the supplementary material.

4. Discussion and concluding remarks

Rather than starting from a unique theory and estimating a structural model derived from it, we estimated a reduced form, whose results can be compatible – or not – with different theories. Several theories originating in different fields have been put forward to understand population dynamics. Our analysis based on individual survey data can be read in light of these theories.

Biological and ecological mechanisms: Populations are simultaneously affected by two classes of mechanisms going in opposite directions (Fowler and Ruxton, 2002): some lead to a decrease in fertility with increasing population size (called the *competition effect* by biologists), while others lead to an increase in fertility with increasing population size. An example of the latter is the *Allee effect*: in this instance, the harmful consequences of inbreeding reduce the fitness of a population as its size decreases. Our results clearly indicate that the competition effect is the dominant one for human reproduction in sub-Saharan Africa.

A non-monotonic relationship between fertility and population size has also been described by Lotka and Volterra (Lotka, 1925; Volterra, 1926) with their predator-prey model. In the original Lotka-Volterra model, it is mortality that channels the link between population density and population growth. Further extensions, as for instance De la Croix and Dottori (2008), show that the same type of interaction may occur through fertility. Instead of being eaten by predators, the preys refrain from procreating. Such a model implies a positive effect of density on the age at first birth and the age at marriage for low levels of density, and a negative effect of density for high levels of density. We test for such effects in the supplementary material. A positive effect is only found on the age at first marriage, when population density increases from the first to the second decile. More importantly, we find that the stabilizing force of population density is stronger when population density is larger (for deciles 8 to 10). This suggests that the demographic transition in sub-Saharan Africa will accelerate once population density has reached a certain threshold.

Demographic mechanisms: The idea that human fertility adjusts to population density precedes the research of biologists and ecologists. Montesquieu (1749) described the view of Greek philosophers on the issue (emphasis added): “In a small and flourishing territory, the number of citizens must soon augment, so as to become *a burden*. This people of consequence omitted nothing which might prevent an *undue increase of children*. Their politics were more immediately confined to the regulation of the number of citizens.” The negative effect of population density on fertility was also explained by Malthus (1807). For the latter, when food is expected to become scarce, people limit their fertility. Malthus expressly stressed the role of marriage in regulating fertility. Following the Malthusian theory, other types of scarcities, such as land or housing, lead to the same effect (Ashraf and Galor, 2011).

The link between population density and fertility was made explicit by Sadler (1830), who wrote against Malthus *The Law of Population – in disproof of the superfecundity of human beings, and developing the real principle of their increase*. His Law simply states that “The prolificness of human beings, otherwise similarly circumstanced, varies inversely as their numbers.” The mechanism by which density influences fertility is the opposite of the Malthusian logic. For Malthus, higher density reduces resources per person, leading to a decline in fertility as a result of preventive (marriage is delayed) and positive checks (mortality increases). In the words of biologists, Malthus refers to the competition effect. For Sadler, on the other hand, affluence increases with population density, as it is purported to in theories of agglomeration externalities since Marshall (1890). When comparing Sadler's and Malthus's theories, both imply that fertility rates should be lower in more densely populated areas, but for different reasons. For Sadler, it is because those areas are richer than others, while for Malthus, it is the opposite.

The link we find between density and age at marriage supports either Sadlerian or Malthusian mechanisms, at least in the versions of the regression in which we do not control for income. When controlling for income (through calories and GDP per capita), under a strict Sadlerian or Malthusian model, density should not matter, because its effect should always go through income. We still find some residual effect of density, which might be because we do not perfectly control for individual income. Moreover, the negative effect of GDP per capita on the risk of marriage reflects the fact that regions with higher income have less marriages than poorer regions, keeping education and health constant across them. This points towards Sadlerian views.

Economic mechanisms: In economics, fertility choices are analyzed following the work of Becke (1993), who claims that the more productive an economy is, the more expensive the time spent on children is, and hence, the lower fertility will be. The Beckerian approach can be "augmented" to account for the effects of population density on fertility by introducing one of the following three features: the housing market, the provision of public infrastructure (education or health system), and an endogenous technology. For the first feature, higher density entails an agglomeration effect and a congestion effect (Sato, 2007). The agglomeration effect leads to higher productivity which negatively affects fertility, in line with the Sadler model that we described previously. The congestion effect implies that the price of land and the cost of living are higher, similarly to Malthus's intuitions. Both effects diminish fertility. The second feature introduces the provision of public infrastructure (Boucekkine et al., 2007; Becker et al., 2010). When population density increases, it is easier to cover the fixed cost of infrastructure such as schools, and their provision increases (Boucekkine et al., 2007). An increased provision of schools encourages parents to substitute quality for quantity, hence having fewer but better educated children (Becker et al., 2010). Hence, higher density leads to more education and lower fertility. The third feature is based on technological progress (Galor and Weil, 2000). A denser population increases the pace of technological progress, allowing for faster growth. Higher human capital is therefore required more acutely in the production process in order to deal with fast technical change. The return to education increases, and parents are led to invest more in the quality of their children, at the expense of quantity.

Our results provide strong support for mechanisms linking density to fertility through both health infrastructure and education. Individual education delays birth for education levels above 4 years, because of the quadratic term. Education in the community also leads to birth postponement. Both are plausible mediating variables for population density, because the provision of education is higher in denser places. The same reasoning holds for health. However, all these effects do not appear strong enough to lead to an automatic stabilization of the African population.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ehb.2021.101102.

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