Is climate change driving urbanization in Africa?

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Abstract

This paper documents a substantial impact of climate variation on urbanization in sub-Saharan Africa. In a panel of over 350 subnational regions, we find that drier conditions increase urbanization in places most likely to have an urban industrial base. Total city income in such places also increases. When receiving cities have an export sector that is not wholly dependent upon local agriculture, migration to cities provides an "escape" from negative agricultural moisture shocks. However, in most places (75% of our sample) without an industrial base, there is no escape into alternative export-based employment. Drying causes reduced urban and rural incomes, with little overall impact on the urban population share. Finally, the paper shows that climate variation also induces employment changes within the rural sector itself. Drier conditions induce a shift out of farm activities, especially for women, into non-farm activities, and especially out of the measured work force. Overall, these findings imply a strong link between climate and urbanization in Africa.

JEL Codes: O10, O55, R12

Key words: Africa, Urbanization, Climate Change

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1. Introduction

Sub-Saharan Africa (hereafter Africa) is urbanizing quickly, with cities and towns growing at an annual rate of close to four percent over the last 20 years. Its urban population of nearly 350 million now exceeds the total population of the United States. Nevertheless, almost two-thirds of Africa's population still lives in rural areas. How urbanization evolves in Africa over the next decades will determine where people and jobs locate and where public services should be delivered. A longstanding debate in the global development literature about the relative importance of push versus pull factors in urbanization has focused recently on Africa. Papers have assessed the contribution of pull factors including structural transformation driven by human capital accumulation and trade shocks (e.g., Fay and Opal 2000; Henderson, Roberts and Storeygard 2013) and of resource rent windfalls spent in cities (Jedwab, 2011; Gollin, Jedwab and Vollrath 2013). Other papers examine push factors including civil wars (Fay and Opal 2000), poor rural infrastructure (Collier, Conway and Venables 2008), and our focus, climate variability and change (Barrios, Bertinelli and Strobl 2006).

This paper analyzes the consequences of climate variability and change for African urbanization and the transformation of the rural sector. Over the last 50 years much of Africa has experienced a decline in moisture availability. Figure 1 maps average moisture in the 1950s and 1960s, where moisture is measured by an index combining precipitation and potential evapotranspiration (which is a function of temperature). A moisture level under 1 indicates that there is less rainfall available than would evaporate at the prevailing temperature. This is the cut-off we use to define "arid" areas.[1] As Figure 2 shows, much of the strongest (10-50%) decline in moisture over the subsequent forty years occurred in parts of Africa that were initially relatively dry (moisture under 0.65 or between 0.65 and 1.0 in Figure 1), increasing the vulnerability of these already vulnerable areas. In a region with limited irrigation, this decline in moisture has surely affected agricultural productivity.

We address three related questions. The first question is whether adverse changes in climate push people out of rural areas because of reduced agricultural productivity. We find strong evidence of this, but only in particular and limited circumstances. The second question is whether that push increases the total income of local cities. We find evidence supporting this hypothesis, but again only in

[1] We use "arid" as shorthand for areas that also include dry-subhumid, semi-arid and hyper-arid climates (see UNEP 1992).

certain limited circumstances. Thus in these contexts, urbanization provides an “escape” of sorts from the effect of deteriorating climate on agricultural productivity. The final question is whether adverse climate change also alters occupation choices within the rural sector, pushing people away from farming. We find more general evidence of this.

We find consistent patterns when analyzing these issues over different temporal and spatial scales. Specifically, first we look at local, within-district urbanization for an unbalanced 50-year panel of census data for 369 districts in 29 African countries. Typical intervals between censuses in the panel are 10-15 years. Two types of heterogeneity are critical to our analysis defining the limited circumstances in which climate change affects urbanization. The first is whether the district is likely to produce manufactures for export outside the district, and the second is whether the district is arid.

Our model, which treats districts in essence as small open economies, implies that climate affects urbanization only in districts that have some industry, not in districts producing agriculture almost exclusively. When the local agricultural sector is competing for labor with an urban sector engaged in production of goods for export outside the district, declines in moisture encourage urbanization by offering alternative employment for farmers. If, however, local towns exist only to serve agriculture with local services not traded across districts, then a decline in moisture has little or no effect on city population because the two sectors are not in competition for labor for export activity. We also expect weaker climate effects in wetter areas where the marginal effect of reduced moisture may be less harmful to farmers.

Twenty-three percent of districts in our sample show evidence of an industrial base, and approximately half of these industrialized districts are in arid areas. For arid industrialized districts, we find that a one standard deviation increase in a district’s annualized moisture growth rate lowers the annualized growth rate of its urban share by about 63% of the mean growth rate for arid areas. Moreover, across the range of annualized growth in moisture (in a slightly trimmed sample), moving from the lowest to highest moisture growth rate lowers the annualized growth in urban share by over 250% of the mean, a huge effect.

We next consider whether adverse changes in climate raise total urban income and stimulate the development of the urban sector. The answer is theoretically ambiguous and again depends critically on the initial state of the urban sector. When the local agricultural sector is competing for labor with urban production of goods for export outside the district, total city population and also total income rise with a decline of moisture. However if cities only exist to serve agriculture, then a decline in moisture generally leads to a decline in total city income. Our empirical analysis is based on much more recent, annual data for 1992 to 2008 on city income growth and rainfall in their immediate agricultural hinterlands. City income growth is proxied by growth in night lights (Henderson, Storeygard, and Weil 2012). For the cities in arid regions most likely to have an export base, the point estimate of the elasticity of lights with respect to rainfall is about -0.17. However, when cities are likely to just provide services to farmers, the point estimate of the elasticity is positive, although small.

Finally, we ask how moisture changes affect a related margin of adaptation: occupational choice in the rural sector. This question is motivated by the little-noticed transformation of the rural sector over the last 20 years in many African countries, signified by a large shift into non-farm occupations.[2] For example, data for Benin, Malawi, and Niger in the period 1987-1996 all showed between 85 and 91% of the rural male labor force working in agriculture. This low proportion of rural workers in non-farm activity contrasts with countries like India or China, even 25 years ago. However Africa is now transforming. By 2006 to 2008, only 57-72% of the rural male labor force in these countries remained in agriculture.[3] Has climate played a role in this transformation? Based on individual-level observations from the Demographic and Health Surveys (DHS), we show that decreases in moisture decrease the probability of working in agriculture. For women, a one standard deviation (levels) decrease in moisture decreases the probability of working in farm activities by about 0.03 from a mean of 0.44, a 7% decrease, mostly through increased probability of not working (0.027). Decreasing moisture across its full range lowers the probability of working on the farm by 0.18, a 40% decrease. For men, a one standard deviation decrease in moisture induces is a similar (0.034) decrease in the probability of working on the farm. Most of these men enter off-farm work (0.028). When moisture declines, women are more likely to drop out of the measured rural labor force altogether, while men are likely to shift into non-farm activities.[4]

While our analysis necessarily focuses on the impacts of past climate variability, the specter of future climate change is a strong motivation. The combination of an already difficult climate, significant projected climate change and limited adaptation capacity has led some observers to state that Africa will be more affected than other regions by climate change (e.g., Collier, Conway and Venables 2008). Barrios, Bertinelli and Strobl (2010) argue that unfavorable rainfall trends may have already contributed to Africa's poor growth performance over the last 40 years, explaining between 15 and 40 percent of

[2] Concurrent work by McMillan and Harttgen (2014) has also noted this.
[3] We are comparing the 1996 and 2006 DHS surveys in Benin, the 1992 and 2006 DHS in Niger, and the 1987 and 2008 censuses of Malawi.
[4] While we acknowledge the difficulty of defining labor force participation in this context, we are simply comparing answers to the same questions asked to succeeding cohorts.

today's gap in African countries' GDP relative to other developing countries. While the precise pattern of future change for individual regions is highly uncertain, further drying is the most common prediction for parts of Africa. Overall, our results suggest that if future climate change will have the negative impacts on agriculture in Africa that many climate scientists and agronomists expect, there will be an increased pace of urbanization in some places. Where towns have started to industrialize, total town populations and incomes will likely grow, but we have no evidence about per capita income, and the transition may be more problematic in less industrialized regions. Transformation of the rural sector may also continue, as people move out of farming into non-farm rural production.

The following section reviews the literature on predicted impacts of climate change in Africa and on the link between climate and development outcomes including urbanization. Section 3 develops a model of how changes in climate will affect (a) the division of population between the urban and rural sector and (b) urban incomes. Section 4 describes the construction of the core climate and urbanization indicators used in the main analysis in Section 5. Other data sets used are described in the relevant empirical sections. Section 5 presents the analysis of the impact of changes in moisture availability on local urbanization. Section 6 examines the effects on urban incomes. Section 7 analyzes work activity responses within the rural sector. Section 8 concludes.

2. Literature on climate change and its impacts in Africa

2.1 Urbanization, local city growth and climate

The most closely related paper on climate change and urbanization in Africa is Barrios, Bertinelli and Strobl (2006), who estimate an increase in the national urban share of 0.45 percent with a reduction in national rainfall of 1 percent. Henderson, Roberts and Storeygard (2013) revisit the question and find a more imprecise effect of rainfall. Both papers have two limitations we overcome in the present work. First, they use national data, when there is significant within-country variation in climate change and most migration in Africa is local (Jonsson, 2001). We exploit within-country heterogeneity for a more nuanced and precise analysis of the effects of climate changes on urbanization. Second, those papers examine national urbanization using population data at regular 5- or 10-year intervals. Such data rely heavily on interpolation, especially in Africa where many censuses are infrequent and irregularly timed. We construct a new data set of urban growth for sub-national regions based on actual census data, not interpolations.

Related studies use micro data to study the effect of rainfall on migration per se, rather than urbanization. They are informative and examine issues not covered in our approach, including movement across rural areas and between countries, as well as from rural area to cities (see Henry, Schoumaker, and Beauchemin 2004 on Burkina Faso) and temporary or circular movement (Parnell and Walawege 2011).[5] These studies typically interview rural residents about their migration history, thereby omitting permanent moves to cities, though the Demographic and Health Surveys could be useful for that purpose (Young, 2013). We limit our scope to net effects on urbanization within districts over long time periods of climate change. This approach allows us to consider a broad swath of African countries.

Two other papers indirectly consider how climate change might affect African urban incomes. Jedwab's (2011) historical study of Ghana and Cote d'Ivoire suggests that conditions in agriculture have a strong effect on nearby market towns that serve them. Gollin, Jedwab, and Vollrath (2013) explore how natural resource income affects urban development, extending the simple two-sector model of the rural-urban divide to include multiple urban economic sectors that may be differentially affected. We will model the effect of climate change on district urban incomes using insights from these two papers.

2.2 Climate change in general

Like other large world regions, sub-Saharan Africa has a highly diverse and variable climate. Moisture availability ranges from the hyperarid Sahara and Kalahari deserts to the humid tropics of Central Africa. In places like the West African Sahel, long droughts have followed extended wet periods. Africa's climate is shaped by the intertropical convergence zone, seasonal monsoons in East and West Africa, and the multi-year El Nino/La Nina Southern Oscillation (ENSO) phenomenon in which changes in Pacific Ocean temperatures indirectly affect African weather (Conway 2009). These processes influence temperatures and precipitation across the continent including extreme events like meteorological droughts, especially in the Sahel, the Horn of Africa and the Southern African drylands, as well as severe floods, such as in Kenya in 2013. Climate records indicate a warming trend over Africa during the 20th Century, continuing

[5] We have focused in the text on papers of immediate relevance. We note that migration may be affected by the development of networks in destinations (Munshi, 2003). Recorded urban versus rural population growth may be affected by differential fertility rates and by the classification of what is urban (McGranahan, Mitlin, Satterthwaite, Tacoli, and Turok 2009). Recent macro-level studies have investigated the role of climate factors in African migration including international migration (e.g., Naudé 2010 and Marchiori, Maystadt, and Schumacher 2012). Marchiori et al. (2012) divide drivers of migration into those related to (dis-)amenities (potential spread of disease; risk of floods or heat waves) and economic geography (most importantly, agricultural performance). They find both channels to be important, estimating that temperature and rainfall anomalies have triggered 5 million migration episodes between 1960 and 2000. There has been much less consideration of year-to-year climatic variability in such models, despite evidence that the length of growing period, for instance, varies considerably in much of Africa (Vrieling, de Beurs and Brown 2011; Vrieling, de Leeuw and Said 2013). An exception is Marchiori, Maystadt and Schumacher (2013) who suggest that environmentally induced income levels—proxied by per capita GDP—may be more important for migration decisions than variability.

at a slightly faster pace in the first decade of the 21st Century, independently of ENSO impacts (Collins 2011; Nicholson et al. 2013; see also Giannini, Saravanan, and Chang 2003 and Held et al. 2005).

Climate researchers predict future climate change using various emission scenarios as inputs to several different assessment models. The underlying scenarios range from aggressive mitigation of greenhouse gases to a continuation of current trends. While there is fairly broad consensus about global average temperature trends, regional scenarios of temperature and particularly of precipitation patterns remain quite uncertain. Researchers from the Potsdam Institute for Climate Impact Research recently reviewed the predictions of a number of credible climate models for regional climate change in Africa (World Bank 2013). In general, average summer temperature is expected to increase by 1.5°C by 2050 in Africa under an optimistic (2°C) global warming scenario. The area exposed to heat extremes is expected to expand to 45 percent of the region by 2050.[6] Under a more pessimistic (4°C) global scenario, these trends would be exacerbated. Falling precipitation and rising temperatures would likely worsen agricultural growing conditions in large parts of Africa, especially in coastal West African countries and in Southern Africa.

Agriculture worldwide will feel the effects of climate change more directly than any other sector, but extreme climate conditions on the continent mean that many African farming systems operate in fairly marginal conditions even in the best of times.[7] A significant literature on climate change and African agriculture is emerging and helps inform and motivate some of our specifications. The majority of studies predict yield losses for important staple and traded crops of 8 to 15 percent by mid-century, with much higher losses of more than 20 percent and up to 47 percent by 2090 for individual crops (especially wheat) under more pessimistic climate scenarios (Kurukulasuriya, Mendelsohn, Hassan, et al. 2006, Kurukulasuriya and Mendelsohn 2008; Lobell, Burke, Tebaldi, et al. 2008; Schlenker and Lobell 2010; Thornton, Jones, Ericksen and Challinor 2011; Calzadilla, Zhu, Rehdanz, Tol and Ringler 2013; the meta-analyses by Piguet 2010; Roudier, Sultan, Quirion and Berg 2011; and Knox, Hess, Daccache and Wheeler 2012).[8] Assessing potential effects has been challenging in part because adaptation in the agricultural sector appears to be more difficult in Africa. Fertilizer use, for instance, has stagnated in Africa at low levels since 1980, while it has risen tenfold in Asia and Latin America

[6] The report defines heat extremes as 3-sigma events with respect to the 1951-1980 local distribution.
[7] A number of studies have estimated the impact on the value of crop and livestock production under various scenarios, with a focus on the United States (Mendelsohn, Nordhaus and Shaw 1994, Schlenker, Hanemann and Fisher 2006, Deschênes and Greenstone 2007).
[8] Some studies find modest or even positive impacts under optimistic scenarios of limited climate change and successful adaptation (Kurukulasuriya, Mendelsohn, Hassan, et al. 2006, Kurukulasuriya and Mendelsohn 2008; Calzadilla, Zhu, Rehdanz, Tol and Ringler 2013).

(Cooper, Stern, Noguer and Gathenya 2013), and only 4 percent of agricultural land is irrigated compared to 18 percent globally (You, Ringler, Nelson, et al. 2010). These studies motivate some of the specifications we test below.[9]

3. A Model of the impact of climate variability on local urbanization

We model movement of workers between an urban and a rural sector which together comprise a district. While migration across district boundaries, for example to capital cities, clearly plays a role in this context, our focus is on local migration, which is very important in many African countries (Jonsson, 2010). Our goal is to model the effect of a change in moisture in a district on the urban-rural division of population and on city total income. The model treats districts as small open economies, facing fixed prices of exports to other districts or internationally. We would find more nuanced but similar qualitative effects if districts faced finite external demand elasticities. However, as we note below, if districts were closed economies theoretical results could be quite different. What we find empirically fits our formulation. Finally we note that the model does not address occupational choice as considered in our final empirical exercise.

3.1 The basic model

3.1.1 Urban sector

The urban sector (city) produces services and manufacturing. Output per unit labor is b in services and cL_M^{ε} in manufacturing, where L_M is total labor units in manufacturing and $\varepsilon > 1$. Services, produced with constant returns to scale, represent non-agricultural items produced and sold locally, but not traded outside the district. Scale economies in manufacturing, represented by ε, can come from information spillovers or from diversity of local intermediate inputs in a monopolistic competition framework.[10] Final output of manufactures is tradable nationally or internationally at fixed prices to the city. The wage rate per unit labor in the city is thus

[9] Besides urbanization and local city development, an emerging literature is finding broader impacts of variations in temperature and rainfall on a variety of human capital, economic, and political outcomes. These include birth weight effects with long term consequences (Deschênes, Greenstone and Guryan 2009), childhood effects on health, schooling and socioeconomic status (Maccini and Yang 2009), later childhood effects on schooling (Shah and Steinberg 2013), and effects on the risk of conflict in Africa (Burke, Dykema, Lobell, Miguel and Satyanath 2009; Hsiang, Meng and Cane 2011; O'Loughlin, Witmer, Linke, et al. 2012).

[10] In the latter context, output of any final goods firm is $m = \left(\int_0^n z(h)^{1/(1+\varepsilon)} \, dh \right)^{1+\varepsilon}$ where output of any intermediate input producer employing $l(h)$ workers is $z(h) = \gamma l(h) - \lambda$ and n is the number of local intermediate input

$$w = p_S b = cL_M^{\varepsilon} \qquad (1)$$

where p_S is the price of services and manufacturing is the numeraire.

Following standard urban models (Duranton and Puga, 2004), workers live in a city where they must commute to work in the city center. Each worker is endowed with 1 unit of labor and commuting reduces time spent working at a rate of $4t$ per unit distance commuted. Those living far from the city center spend less on land rents to compensate for their higher commuting costs, or lost labor earnings. City land rents are redistributed to urban workers. Per worker net income, after commuting and land rents are paid and land rent income is redistributed, is

$$y = w(1 - tN_U) = p_S b(1 - tN_U) \qquad (2)$$

where N_U is city population.[11]

City effective total labor supply net of time spent commuting, L, is

$$L_S + L_M = L = N_U(1 - tN_U) \qquad (3)$$

where L_S is the labor force in services.

3.1.2 The rural sector and equilibrium conditions for the district

The other part of the district is the rural sector producing agricultural products, sold at a fixed price p_A in international markets. Per worker income in the agricultural sector is given by

$$p_A f(N_A, R), \quad f_1 < 0, \; f_2 > 0 \; . \qquad (4)$$

The rural (agricultural) population is N_A and the total land area is shared equally among that population. Per worker output (either marginal or average output depending on how agricultural rents are distributed) is declining in total farm workers and increasing in moisture or rainfall, R.

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producers a city can support. Solving the monopolistic competition problem, the equilibrium wage of a worker in the manufacturing sector has the form cL_M^{ε}.

[11] Following Duranton and Puga (2004), in a linear city, where each worker is endowed with 1 unit of time and working time is $1-4tu$ where u is distance from the city center and $4t$ unit commuting costs, it is easy to derive expressions for city labor force L as a function of population N_U (by integrating over the two halves of the city each of length $N_U/2$), for the city rent gradient (equating rent plus commuting costs for a person at *u* with that of a person at the city edge where rents are 0, so they are equally well off in equilibrium) and for total rents. These have forms respectively:

$$L = N_U(1-tN_U); \quad R(\mathrm{u}) = \mathrm{wt}(2N_U - 4u); \quad \text{total rents}=wtN_U{}^2$$

where w is the wage rate. A person living at the city edge and paying zero rent earns in net $w(1-2tN_U)$, with the diseconomy arising from increasing commuting distances reducing time available to work. After getting a share in urban rent income their net income is $y = w(1-tN_U)$.

Migration arbitrage between the urban and rural sector equalizes incomes and there is full employment in the district so that

$$p_S b(1-tN_U) - p_A f(N_A, R) = 0 \qquad (5)$$
$$N_A = N - N_U \qquad (6)$$

N is district total population. The model is closed by noting that the untraded services market must clear. Total production is bL_S and total demand is $N\ D(y, p_A, p_S)$ for the individual demand function $D(y, p_A, p_S)$. Thus we know using (2) and (5) that

$$bL_S = N\ D(p_A f(N_A, R),\ p_A,\ p_S) \qquad (7)$$

3.2 Comparative statics when the local urban sector exports manufacturing.

We seek the effect of moisture change on city (or conversely agricultural) population and total city income. That is, we want to solve for dN_U / dR and $d(y\, N_U)/dR$.

3.2.1 Changes in urbanization

First we solve for the effect on the population allocation. We differentiate (1), (7), (3) and (5), having used (6) to substitute for N_A. We define income and own-price elasticities of demand for services, $\eta_y > 0,\ \eta_{p_S} < 0$ in the usual fashion. The results are

$$\frac{dp_S}{p_S} = \varepsilon \frac{dL_M}{L_M} \qquad (8a)$$
$$\frac{dL_S}{L_{sS}} = -\eta_y \frac{f_1}{f} dN_U + \eta_y \frac{f_2}{f} dR + \eta_{p_S} \frac{dp_S}{p_S}, \quad \eta_{p_S} < 0 \qquad (8b)$$
$$dL_S + dL_M = (1-2tN_U)dN_U \qquad (8c)$$
$$\frac{dp_S}{p_S} - \frac{t}{1-tN_U} dN_U + \frac{f_1}{f} dN_U - \frac{f_2}{f} dR = 0 \qquad (8d)$$

Using (8a) and (8b) to substitute for dL_M and dL_S in (8c) and solving for dp_S / p_S we get

$$\frac{dp_S}{p_S} = \varepsilon\ [1+\varepsilon \frac{L_S}{L_M} \eta_{p_S}]^{-1} \left(\left[\frac{1-2t\,\mathrm{N}_U + L_S \eta_y \dfrac{f_1}{f}}{L_M} \right] dN_U - \frac{L_S}{L_M} \eta_y \frac{f_2}{f} dR \right) \quad (9)$$

We substitute (9) into (8d) to get

$$\frac{dN_U}{dR} = \frac{f_2}{f} \quad \frac{L_M + \varepsilon L_S(\eta_y + \eta_{p_S})}{Z} \tag{10}$$

$$Z \equiv \frac{f_1}{f}[L_M + \varepsilon L_S(\eta_y + \eta_{p_S})] - \frac{t}{1-tN_U}(L_M + \varepsilon L_S \eta_{p_S}) + \varepsilon(1-2tN_U)$$

To sign this expression we first need to sign Z. Stability of migration between the urban and rural sector requires that the differential in (5) be decreasing in N_U, and therefore that the expression in (8d) divided by dN_U is negative when $dR = 0$. This reduces to

$$Z(L_M + \varepsilon L_S \eta_{p_S})^{-1} < 0. \tag{11}$$

As long as the local urban manufacturing sector is not negligible (i.e. L_M / L_S is not too small) then $(L_M + \varepsilon L_S \eta_{p_S}) > 0$. For example if $\eta_{p_S} = -1$, we require that $L_M / L_S > \varepsilon.$ Estimates of ε in the literature are typically 0.05 or less (Combes and Gobillion 2015), so as long as the local city has a modicum of manufacturing, $L_M + \varepsilon L_S \eta_{p_S} > 0$, and stability implies $Z < 0$. We focus on this case here, and the opposite case in section 3.3.

Returning to (10), given $L_M + \varepsilon L_S \eta_{p_S} > 0$ and therefore $Z < 0$, $dN_U / dR < 0$ follows directly. The magnitude of response depends on the magnitude of f_2 / f. Of course, as moisture changes all variables change, but we can say that as f_2 approaches zero, so does the response. f_2 / f plays a role in the empirical formulation in Section 5.

3.2.2 Changes in city income

Next we turn to the effect of moisture on city income. Total city income is $yN_U = p_A f(N - N_U, R) N_U$. Thus

$$\frac{dyN_U}{dR} = p_A f_2 Z^{-1}(1-tN_U)^{-1} * M \tag{12}$$

where $M \equiv [L_M + \varepsilon L_S(\eta_y + \eta_{p_S})](1-2tN_U) + tN_U \varepsilon L_S \eta_y + N_U \varepsilon(1-2tN_U)(1-tN_U)$

Under the current assumption that $L_M + \varepsilon L_S \eta_{p_S} > 0$, $Z < 0$. If we further require that city earned incomes ($1-2tN_U$) be positive, M must be positive. Given that *Z* is negative, dyN_U / dR is negative. . Income is nominal in a context where the price of services will change, but for a broad class of utility functions, the city's sum of utilities is affected in qualitatively the same way as city income.[12]

In sum we have the following proposition relevant to our empirical work:

Proposition 1. *If the city has a tradable manufacturing sector that is not too small relative to its local service sector so that* $L_M + \varepsilon L_S \eta_{p_S} > 0$*, a decline in moisture will lead to an increase in urban population and total city income.*

For completeness, the expression for the change in city per capita income is:

$\frac{dy}{dR} = p_A f_2 Z^{-1}[-(L_M + \varepsilon L_S \eta_{p_S})\frac{t}{1-tN_U} + \varepsilon(1-2tN_U)]$. In the current situation, given $Z<0$, $L_M + \varepsilon L_S \eta_{p_S} > 0$, and the definition of *Z*, $dy/dR > 0$. In our empirical work, total income or expenditure in the city will be measured by night lights data, which are recorded over time periods incompatible with the bulk of the population data

3.3 Comparative statics with minimal local manufacturing.

If the local traded good manufacturing sector is very small so $L_M + \varepsilon L_S \eta_{p_S} < 0$, then the fortunes of the city are tied to the local agricultural sector, as in Jedwab (2011).[13] Stability thus requires $Z > 0$, and the sign of dN_U / dR in eq. (10) is ambiguous. If $\eta_y + \eta_{p_S} \geq 0$, then $dN_U / dR > 0$. Ambiguity arises if $\eta_y + \eta_{p_S} < 0$ and $L_m > 0$. If $L_m = 0$, the sign of dN_U / dR is the same as the sign of $\eta_y + \eta_{p_S}$. If $\eta_y + \eta_{p_S} = 0$, as $L_M \to 0$, $dN_U / dR \to 0$. Then there is no effect of rainfall on the rural-urban population allocation because migration effects only come through changes in demand for services (and the effect of reduced price on demand for services is exactly offset by the effect of reduced per person income).

Total urban income from (12) is more generally increased by rainfall. Given $Z > 0$, if $\eta_y + \eta_{p_S} \geq 0$, we can unambiguously show that $dyN_U / dR > 0$. Increased rainfall raises local farm

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[12] We examine the sum of utilities based on a log linear indirect utility function, but it applies to any indirect utility function where doubling income doubles utility. For $V(y,\vec{p})N_U = AN_U y p_S^{-\sigma_s}$ where σ_s is the expenditure share of services and differentiating we can show that

$$\frac{d(N_U y p_S^{-\sigma_s} A)}{dR} = p_S^{-\sigma_s} A N_U y \frac{f_2}{f} Z^{-1}\left[(1-\sigma_s)\varepsilon(1-2tN_U) + \frac{(1-2tN_U)(L_M + \varepsilon\eta_{p_S} L_S) + [1-(1+\sigma_S)tN_U)]\varepsilon\eta_y L}{(1-tN_U)N_U}\right].$$ If $Z<0$ this expression is negative.

[13] We describe this case assuming the local manufacturing sector exists, but the situation is analogous in the case where there is no manufacturing at all and per worker output of the service sector is given by $bL_S^{\varepsilon_S}, \varepsilon_S \geq 0$.

productivity and all local incomes.[14] With city population modestly affected, total city incomes must rise. However, if $\eta_y << |\eta_{p_S}|$, so that city population declines a lot, then urban incomes may decline as well.

Proposition 2. *If the city has a traded good manufacturing sector that is tiny or non-existent so that* $L_M + \varepsilon L_S \eta_{p_S} < 0$ *< 0, the effect of a decline in moisture on city population is ambiguous and tends to zero as* $L_M \to 0$ *when* $\eta_y + \eta_{p_S} = 0$ *. However total city income declines, assuming* $\eta_y + \eta_{p_S}$ *is not strongly negative*.

This strict difference between the substantial manufacturing case and the minimal or no manufacturing case will inform the empirical work on local city incomes in Section 6.

Whether a city has manufacturing is of course endogenous. In our static framework, an absence of manufacturing implies that the wage the first worker in manufacturing would receive in the city, c, is less than the equilibrium wage in the service sector ($p_S b$). Manufacturing arises if either local (potential) productivity, c, rises with, for example, enhanced education, or if the price of the manufactured good rises relative to the other goods. This latter case could be driven by changes in international prices or changes in the cost of transporting products between the local city and a port.[15] Studying the development of local industry is beyond the scope of our work and for most Sub-Saharan African countries lack of data would make this difficult. We ask whether climate affects urbanization and local incomes given existing industrial composition, but not whether it contributes to changes in industrial composition.

Finally, we note that our choice to model districts as small open economies is important. In a closed economy framework with economic growth as in Caselli and Coleman (2001), an increase agricultural productivity can lead to a decline in employment in agriculture and an increase in manufacturing, for example if demand for food is income inelastic (see also Desmet and Henderson 2015 for a more general review). National economies in our sample are small, subject to world prices for their major exports and imports. These assumptions seem even more relevant at the district level, in an empirical context where identification comes from within-country variation in moisture and hence agricultural productivity.

4. Data on urbanization, climate, and industrialization

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[14] See the expression for changes in per capita income above.

[15] Other work such as Atkin and Donaldson (2013) and Storeygard (2014) considers the transport cost story in Africa directly.

In this section we discuss our basic measures of urbanization, moisture and extent of industrialization of districts, data we need to conduct the first analysis of the effect of climate on urbanization. We leave the description of night lights and DHS occupational data to the relevant sections.

4.1 Urbanization

Scarcity of demographic and economic data hampers empirical research on climate effects in Africa. Many countries carry out censuses only irregularly, and sample surveys such as the DHS are infrequent and provide little information before 1990.[16] While there are now a number of geographically detailed climate data sets that are increasingly used by economists (see Auffhammer, Hsiang, Schlenker, and Sobel 2013), most studies have employed national level population and economic data sets which are readily available from the UN and other agencies and which, for African countries, rely heavily on imputations and interpolations.

We collected urban and rural population measures for sub-national regions (provinces and districts) from census reports. We include countries with at least two available censuses with the relevant information for a complete or nearly complete set of sub-national units, where either district boundaries changed little or common units over time can be defined. The data were extracted mostly from hardcopy census publications obtained from the U.S. Census Bureau library, the U.S. Library of Congress, the LSE library, and the British Library. The collected sample covers 32 countries but Namibia and Congo-Brazzaville are dropped because of problems with urban or district definitions.[17] We further limit the sample to intercensal periods (*L*) of less than 20 years, so Liberia is omitted because its two available censuses were 34 years apart. We have information from 2 to 5 censuses between 1960 and 2010 for each of the 29 remaining countries (Figure 3 and Appendix Table A1). For estimation purposes, Kenya is treated as two countries, before and after rapid redistricting and urban redefinition of the 1990s. Each country is divided into a number of sub-national units we call districts. The 369 districts used in estimation are shown in Figure 3.

The most notable omission is Nigeria, Africa's most populous country, because of concerns over the quality of census figures (see, e.g., Okafor, Adeleke and Oparac 2007). Other Sub-Saharan African countries are missing because either they had no censuses with needed information or in a few cases because we were unable to obtain the printed volumes. Finally, we do not include South Africa because

[16] The World Fertility Surveys of the late 1970s and early 1980s (DHS precursors), are less consistently available to researchers.

[17] For Namibia, the problem is changing district boundaries and urban definitions. For Congo most districts were originally drawn to be either wholly urban or wholly rural, making within-district analysis impossible.

it is more developed, province maps were redrawn post-Apartheid, and pre-Apartheid migration restrictions make it a special case.

4.2 Climate

With few exceptions, most studies of climate impacts on agriculture focus exclusively on precipitation. However, moisture available for plant growth is also a function of evapotranspiration. Thus, dividing precipitation by potential evapotranspiration (PET), which is a non-linear function of temperature, increasing in the relevant range, is a better measure of climatic agricultural potential. Although this measure is often called an aridity index and used to define aridity zones (UNEP 1992), we call it a moisture availability index, because larger values indicate relatively greater water availability, with values above one indicating more moisture than would be evaporated given prevailing temperature. Precipitation and temperature data are from the University of Delaware gridded climate data set (Willmott and Matsuura 2012). We estimate monthly PET from 1950 to 2010 using the Thornthwaite (1948) method based on temperature, number of days per month and average monthly day length, and subsequently summed monthly values to obtain annual totals (see, e.g., Willmott, Rowe and Mintz 1985 for details).[18]

Figure 4 shows average annual country-level moisture trends for the countries in our sample, indicating the long term downward trend over the last 60 years, consistent with Figure 2. It also shows the high inter-annual variability of moisture in these countries, even with three-year smoothing. The climate data sets have a spatial resolution of 0.5 degrees, which corresponds to about 3000 km^2 at the equator. To generate district level climate indicators, we average grid cell values that overlap with the corresponding sub-national unit, weighting by area in the case of cells that cross district boundaries.[19]

4.3 Extent of industrialization

Our model suggests that places with export industries will respond differently than other districts. Sub-national data on industrialization from African censuses is scarce; even data on the share of GDP in manufacturing at the national level is scarce before 1985. So for the first analysis of urbanization based

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[18] More specifically, potential evapotranspiration (PET) for month *i* is calculated as:

$$PET_i = \left(\frac{N_i}{30}\right)\left(\frac{L}{12}\right)\begin{cases} 0, \; T_i < 0°\text{C} \\ 16(10T_i/I)^{\alpha}, \; 0 \le T_i < 26.5 \\ -415.85 + 32.24T_i - 0.43T_i^{\,2}, \; T_i \ge 26.5 \end{cases},$$

where T_i is the average monthly temperature in degrees Celsius, N_i is the number of days in the month, L_i is day length at the middle of the month, $\alpha = (6.75 \times 10^{-7})I^3 - (7.71 \times 10^{-5})I^2 + (1.792 \times 10^{-2})I + 0.49$, and the heat index $I = \sum_{i=1}^{12}\left(\frac{T_i}{5}\right)^{1.514}$ where T_i indicates the 12 monthly mean temperatures. The Penman method provides a more precise estimate of PET, but requires data on atmospheric conditions that are not available consistently for the area and time period of this study.

[19] In practice, we use the number of 0.1-degree sub-cells as a weight.

on outcomes from 1960 onwards, we need a base from that time period. Fortunately, the *Oxford Regional Economic Atlas, Africa* (Ady 1965) maps all industries by type and city location in Africa, based on an in-depth analysis from a variety of sources from the late 1950s and early 1960s. We integrated these maps with our census data to locate all places with any of 16 different "modern" manufacturing industries: iron/steel, electrical equipment, general engineering equipment, cement, other building materials, rubber, petroleum refining, printing, general chemicals, paints/varnish, glass/pottery, footwear, and four types of textiles. Following Moradi (2005), we call the first five key industries, meaning they provide inputs to other downstream industries, and we consider these separately. Figure 5a shows the count of modern industries found in each of our districts, where the maximum is 8 of the 16. Only 16% of our districts had any of these industries, suggesting that there may be limited scope for the induced industrialization channel in our model. Figure 5b maps all industries from Ady (1965), combining the 16 modern industries with 10 agricultural processing industries: brewing, wine/spirits, tanning, canning, and the processing/milling/refining of sugar, oil, cotton, grain, tobacco and timber. Twenty-three percent of the sample has an industry in this wider set, with at most 13 different industries in a single district.

In our empirical work, we try three measures of 1960s industrial activity: presence of a key industry, count of modern industries, and count of all industries. For the analysis of growth in night lights in Section 6, which starts 30 years after these industry data, while we find the maps still to be a good proxy, we also use a country-level measure of the extent of industry to proxy for whether a city is likely to export manufactures.

5. Empirical analysis of the effect of climate on urbanization

5.1 Specifications

We estimate the effect of growth in moisture on growth in urbanization for a panel of districts that is highly unbalanced because different countries conduct censuses in different years. Growth rates are annualized to account for the different lengths of these intercensal periods. The base specification is

$$u_{ijt} = \beta_0 w_{ijt} + \beta_1 X'_{ij} + \beta_2 X'_{ij} w_{ijt} + \alpha_{jt} + \varepsilon_{ijt} \qquad (13)$$

where variables for district i, in country j, in year t, are defined as follows:

u_{ijt} is annualized growth of the urban population share from $t - L_{jt}$ to t;

$w_{ijt} = \left[lnW_{ijt} - lnW_{ij,t-L_{jt}}\right]/L_{jt}$;

W_{ijt} is average moisture from $t - 2$ to t (inclusive);

L_{jt} is the number of years between year t and the prior census;

X_{ij} are time-invariant controls;

α_{jt} is a country-year fixed effect controlling for time-varying national conditions; and

ε_{ijt} is an error term clustered by district.

In (13), growth in urbanization is a function of growth in moisture. The growth specification removes the effect of time-invariant district characteristics (distance to markets, soil quality and the like) on urbanization *levels*. Some of these factors (X_{ij}) may also affect the impact of climate changes on urban share *growth rates*, yielding heterogeneous effects. We control for country-year fixed effects to account for national time-varying conditions driving urbanization overall in a country. This also controls to some extent for variation between countries in the definition of urban areas, which poses a significant problem in cross-country urban analysis. What we are doing is demanding on the data—identification of climate effects on urbanization must come from within-country differences across districts in annualized growth rates of moisture.

We smooth the moisture levels over three years, on the assumption that potentially permanent decisions are more likely to be based on average recent experience rather than one good or bad year. As an example of the smoothing, the annualized rate of change in urban share between censuses in 1965 and 1980 is estimated as a function of the annualized rate of change in moisture between the average for 1963, 1964 and 1965 and the average for 1978, 1979 and 1980. Although this smoothing period is somewhat arbitrary, our results are robust to reasonable adjustments as noted later.

Our theoretical model suggests two important forms of heterogeneity, based on industrial capacity and aridity (L_M / L_S and f_2 / f in equation 10). Our primary measures of industrial capacity come from Ady (1965). We try both country and district-level measures of aridity for 1950-69. We examine these two dimensions separately and together. In Section 5.4, we briefly consider heterogeneity based on several additional factors: soil quality, irrigation potential, rainfall concentration with the year, variability or noisiness in moisture changes over our intervals, and changes in climate variability over time.

In Table 1 we present summary statistics on the estimating variables for all countries and for the more arid ones. The average annualized growth rate of moisture is negative, consistent with Figure 2, and the average growth rate in the urban share is positive. We are concerned that outliers in these variables could reflect measurement problems. For example, an extremely high urban share growth rate could be due to a poorly measured low base. An extremely high or low moisture growth rate could reflect intercensal changes in the density of weather stations, especially in arid regions. We thus trim the number of observations from the top and bottom of the distribution of growth rates in both urban share and in moisture. In our main specifications, we drop the highest and lowest 6 growth rates of each variable, or 24 observations out of 741, which is about 3.2% of the total sample. Below and in Table A2 we explore the robustness of results to deviations from this choice.

5.2 Identification

Our chief identification concerns are insufficient within-country variation and omitted variables. In Figure 6a, the growth in moisture variable has more density to the left of zero, consistent with overall drying; and it has a large spread of positive and negative values. However, Figure 6b shows that spread does shrink somewhat after factoring out country-year fixed effects.

With respect to omitted variables, since changes in climatic conditions are exogenous and in principle randomized by nature across districts, estimates of reduced form (or net) effects may appear to be unbiased. We have differenced out time-invariant factors affecting urbanization levels. However, it is possible that unobservables affecting growth in urbanization could be correlated with climate change within our limited sample. In fact none of the covariates we consider have significant correlation with the growth in moisture variable, except for log distance to the coast.[20] In particular, indicators of initial industrialization and moisture status are not correlated with subsequent moisture changes. In that sense there is balance in the data when we examine heterogeneity based on whether or not an area is initially industrialized and/or moist. We add two main controls: initial urbanization and log distance to the coast, both of which might represent a variety of factors. For example, initial urbanization is correlated with growth in urbanization (e.g., mean reversion) and modestly but insignificantly with growth in moisture. Controlling for initial urbanization may raise concerns because, for the first growth incident in each district, it is used in calculating the growth in urban share, the dependent variable. Below and in Table A2, we show robustness to dropping each of these controls.

5.3 Base specification results

Tables 2-4 report on three specifications of the effect of moisture growth on urbanization. In Table 2, after showing the effect with no allowance for heterogeneity, we explore the effect of allowing for heterogeneity in the likelihood of having industry. Table 3 explores effects allowing for heterogeneity in

[20] In addition to variables we use in analysis, this includes indicators for French and British colonial ties.

initial moisture level, and Table 4 combines the two sources of heterogeneity. In describing Tables 2 and 3 we focus on qualitative results, deferring most quantitative comparisons until Table 4 where both sources are present. In Table 2, column 1, the effect of moisture growth alone on urbanization is insignificant, suggesting that there are no effects on average. Significant and distinct effects only arise when heterogeneity is introduced, and thus these effects apply only to particular sub-samples.

5.3.1 Likelihood of industrialization

The rest of Table 2 explores heterogeneity based on the likelihood of having manufactures for export, as opposed to only agriculture and local services. In column 2, we interact the moisture effect with a dummy for whether the district has no key industries in the Oxford Atlas, so the base coefficient applies to areas with key industries, about 11% of the sample. It is only significant at 10%, but consistent in sign with the rest of the table. In column 3 we use a proxy for the absence of industry based on the number of modern (non-agricultural processing) industries present. The measure has a value of zero if a district has the maximal count (8) of these industries and then rises, as the number of industries declines, to a maximum of 8 in districts with no industries (84% of the sample), so the uninteracted moisture coefficient applies directly to the most industrial districts. This continuous measure is broadly analogous to L_S / L_M in equation (10) of our model, representing not only the likelihood of industry, but its possible extent. Column 4 applies an analogous measure that includes the agricultural processing industries. 77% of districts had no industry of any type in the early 1960s.

Based on either modern or all industries, point estimates in columns 3 and 4 suggest a very large effect for the most likely industrialized districts of -1.02 and –1.14. Here a one standard deviation decrease in the growth rate of moisture increases the growth rate of share urban by about 0.014, where that growth rate has a mean of 0.03. In both of these columns, as the extent of industry decreases, the effect diminishes at rates of 0.13 and 0.09, respectively, per industry lost. Thus for districts with no industry the net marginal effect of moisture growth is close to 0 in both columns. These results are consistent with the theory we presented: strong negative effects of moisture growth on urbanization in industrialized districts but little or no effect in agricultural ones.

Robustness

The results we have presented all trim the sample, include controls, and smooth climate growth rates in the same way. Appendix Table A2a explores robustness of results to the choices we made, based on the Table 2, column 4 specification. Our main specifications smooth moisture over 3 years (0 to 2 before each census) before calculating growth rates. Compared to the base in Table A2a column 1, in the last 3 columns, smoothing over 3 or 4 periods provides similar results. Smoothing over 2 periods leaves more noise and over 5 limits variation. With respect to trimming, our choice of samples is conservative. With no trimming, both the base effect and the rate of diminution are considerably enhanced in column 2 of Table A2a; we might have chosen to focus on those results. Very modest trimming initially gives smaller magnitudes than in Table 2, but then coefficients stabilize at the point we report where we trim 6 from each of the top and bottom values of growth in moisture and growth in urban share, which is about 3.2% of the sample overall. Coefficients are little affected by trimming further up to for example 8.6% of the sample in column 6. We pick the largest sample where coefficients have stabilized. Finally, in Table A2a we report the effects of dropping controls for initial urbanization and log distance to the coast in columns 7-9. The magnitudes of significant coefficients are only modestly affected.

5.3.2 Heterogeneity based on initial aridity

Table 3 examines the effect of moisture growth allowing for heterogeneity in just initial aridity. Column 1 shows the effect of allowing for heterogeneity at the country level based on whether the country overall is moist (moisture index in excess of 1.0). With this country level distinction, we have a significant negative effect of moisture growth in arid countries as expected. The net effect for moist countries is positive but small and imprecisely measured. It may seem odd to use a country-level index, when we know moisture by district. The problem is that our identification comes from within-country variation in moisture growth. Defining aridity by district leaves little such variation: in 11 of 17 arid countries all districts are arid, and in 2 more, 2 or fewer districts are non-arid. In essence, for many countries the country-level designation applies perfectly or nearly perfectly to all districts. We try two alternatives to focus on district-level heterogeneity. First, in column 2 we place the moist district cutoff at 0.75, rather than our preferred 1.0. This achieves variation within all but three our countries. This does not give significant results here, but signs are consistent with expectations, and results are stronger when both sources of heterogeneity are included in Table 4. Second, in column 3, we impose a linear structure on heterogeneous effects by interacting moisture change with the initial (1950-69 average) level of moisture in a district, a continuous variable. Results are again of the same sign as those in column 1 and now significantly different from zero. An arid district with initial moisture of 0.5 has a moisture growth elasticity of -0.35 compared to an overall -0.41 for arid countries in column 1.

5.3.3 Heterogeneity of aridity and industrialization

In Table 4 we combine the two sources of heterogeneity, to distinguish industrialization effects in arid versus moist areas. All columns have all appropriate interactions with the relevant moisture variable to distinguish arid from moist places, but only the key coefficients are shown. In the top row we show the effect of moisture growth in arid places that most likely have industry, varying the definition of industry and arid places across columns. These are all large effects. Heterogeneity is more distinct across levels of industry likelihood than levels of moisture, with differential effects for moist places not being significant. However distinguishing moist places increases and in some specifications sharpens the climate change effects in industrialized districts.

Columns 1-3 define industry likelihood analogously to columns 2-4 of Table 2, and aridity at the country level as in Table 3, column 1. In column 1, using the key industry dummy, there is a strong negative effect of -0.88 in industrial districts of arid countries, and a smaller, insignificant negative net effect of -0.20 for their moist country counterparts. In column 2, the moisture growth effect starts at -1.19 in the most industrial districts and decreases to an insignificant net effect of -0.33 in completely agricultural districts. In column 3, using the all industries measure, the effect starts at -1.21 in the most likely to be industrialized areas (with 13 industries in the 1960s) and declines at a rate of 0.068 per industry, reaching a net effect of -0.33 in completely agricultural districts. This is our main result. For the most industrialized areas in an arid country, a one standard deviation increase in moisture reduces urbanization by 0.017, or 63% of the mean growth rate in share urban. Moving from the minimum to maximum (trimmed) growth in moisture gives a decrease in the urban share growth rate of 0.097, about 250% in excess of the mean for arid areas.

The effects in column 1-3 are not significantly different for moist countries. For districts that have industry (23%), about half are in arid countries and half in moist. It is clear there is limited cell size to make nuanced distinctions between moist and arid. In columns 4 and 5, we use all industries as in column 3, but with moisture distinctions made at the district level, rather than country. In the two cases, a binary cut-off at a 0.75 and a continuous measure, moist results are still somewhat imprecise; but they suggest both smaller base (most industrialized) and slope (as industry diminishes) effects of decline in moist areas compared to arid.

The effects of trimming and smoothing choices are similar to those already discussed for Table 2. In Table A2b, columns 2-6 show that we have again picked the largest sample where coefficients stabilize, a reasonably conservative choice. Columns 7-9 show that if we drop initial urbanization or log distance to the coast or both (along with the analogous interactions with the initial moisture variable), coefficients are little changed.

In summary, we can distinguish effects of moisture growth in districts that are more (likely) industrialized compared to districts that have no industry. In our limited sample we see some evidence of a diminution of effects in more moist areas once we control for the industry distinction. However the main effect of the moisture distinction is to modestly enhance the industry distinction in arid areas.

5.4 Other dimensions of heterogeneity

The effect of moisture on urbanization may differ along many other dimensions. We focus on six here, fully interacting each with the Table 4 column 3 specification.[21] As we thus create quadruple interactions, it is not surprising that we find no compelling results for any new dimension overall, and specifically, we find no evidence that they affect the marginal effect of moisture growth in industrialized arid areas. The first three are measures of agricultural productivity that might influence the effect of moisture changes: soil water capacity and total soil suitability from Ramankutty et al. (2002), and evidence of modern irrigation infrastructure from Siebert et al. (2007).[22] The other three are measures of weather variability within and across years, which might make farmers more or less vulnerable to changes. One is a Gini of rainfall across months within the year to measure rainfall concentration within the year, using baseline 1950-69 data. The other two are the standard error of the linear prediction of rainfall between censuses to measure noise in the growth in climate variable,[23] and the intercensal change in the standard deviation of rainfall in the 10 (or 17) years before a census.

6. Climate change and city income

Having shown evidence of the population effects predicted by our model, we turn to effects on city total income. Our theory indicates that if the local town or city performs an exportable activity, then reduced (increased) moisture unambiguously raises (lowers) city income. However if the local town exists solely to provide farmers with services (or potentially goods) that are not traded outside the district, then the fortunes of the urban and rural sector are tied. Decreased moisture is then likely to decrease local city income.

Data on income or city product are not consistently available for African cities, so we use an indirect measure. Following the approach in Henderson, Storeygard and Weil (2011, 2012), we test whether the intensity of nighttime light emitted by a city is affected by the amount of rainfall within a 30 km radius around each city in the current or prior year (see Figure 7). The nighttime lights data come

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[21] Each new variable is interacted with Δmoisture, Δmoisture*(13-#industries), Δmoisture*1(country moisture>1), Δmoisture*(13-#industries)*1(country moisture>1), 1(country moisture>1), (13-#industries), (13-#industries)*1(country moisture>1).

[22] Although soil degradation can change soil conditions over the time scale of decades (see UNEP 1992), data on these dynamics are not consistently available, so soil quality is time invariant in our analysis.

[23] Based on the annualized growth rate, $w_{ijt,smooth}$, from equation (13), we can formulate the predicted value for moisture in any year between census intervals as $\hat{W}_{ijt,smooth3} = W_{ijt-L_j,smooth3} e^{w_{ijt,smooth}}$. From that we form the standard error of prediction: $SEP_{ijt} = \sqrt{\sum_{s=t-L_j}^{t} (\hat{W}_{ijs,\mathrm{smooth}3} - W_{ijs,\mathrm{smooth}3})^2 / (L_j - 2)}$.

from the U.S. Defense Meteorological Satellite Program (DMSP), a weather satellite system that captures visible light between about 8:30 p.m. and 10 p.m. We use annual data from 1992 to 2008 for 30 arc-second grid cells (0.86 km^2 at the equator). The data product typically used for socioeconomic analysis contains only stable lights after temporary light sources such as forest or savannah fires have been removed (e.g., Elvidge et al 1997). We further remove gas flares based on Elvidge et al. (2009). Light intensity for each pixel is expressed as a "digital number" (DN) linearly scaled between 0 and 63.

6.1 Specification

Our analysis includes 1,158 cities and towns in 42 countries (all of mainland sub-Saharan Africa except Somalia, plus Madagascar). We define cities as contiguous lit areas in the DMSP data set for which a population estimate is available from a comprehensive census database.[24] More specifically, we overlay lit areas for all years and find the outer envelope of lights as pictured in Figure 7. The city's total amount of light for each year is the sum of the digital number (light intensity) over all grid cells that fall within this outer envelope (maximum extent) of the city light footprint. Rainfall measures are from the Africa Rainfall Climatology Version 2 (Novella and Thiaw 2012), which combines weather station data with satellite information, resulting in a shorter time series but finer spatial resolution (0.1 degree) than Wilmott and Matsuura (2012). We use rainfall rather than moisture in this section because we are unaware of any temperature measures at such fine resolution that do not heavily rely on interpolation of sparse data. Each city's hinterland annual average rainfall is calculated as an average of grid-cell values within 30 km of the ever-lit area. Summary statistics are in Appendix Table A3.

Our specification is

$$\ln\left(light_{it}\right) = \sum_{j=0}^{k}\beta_j \ln rain_{i,t-j} + \sum_{j=0}^{k}\gamma_j X'_i \ln(rain_{i,t-j}) + \phi_i + \lambda_t + \alpha_i t + \varepsilon_{it} \qquad (14)$$

where

$light_{it}$ is light DN summed over all pixels in city i in year t;[25]

$rain_{it}$ is average rainfall in millimeters per day within 30 km of city i;

X_i are time-invariant city- (or country-) level indicators for moisture level and industrial propensity;

$\emptyset_i$ and λ_t are city and year fixed effects;

[24] http://www.citypopulation.de

[25] To deal with zeroes and low numbers in the lights data, we adjust the data as follows. There are only 11 of 19,685 observations with positive values below 6, because of the way the lights data are cleaned by NOAA, and 3,439 with zeroes. To avoid jumps when first differencing, we set all the positive values below 6 to 6 and change the zero value observations to 5, before taking logs. This adjustment tends to dampen the magnitude of effects we find.

$\alpha_i t$ is a city-specific linear time trend;

ε_{it} is an error term.

Equation (14) is an annual panel specification for cities. To identify rainfall effects on lights, we control for time-invariant city conditions, year effects (to account for annual differences in sensor settings across and within satellites), and city-specific linear growth trends. To estimate the model we first difference equation (14) eliminating the fixed effect in the levels equation and converting the time trend to a city fixed effect in the differenced version. This yields

$$\Delta \ln\left(light_{it}\right) = \sum_{j=0}^{k} \beta_j \Delta \ln rain_{i,t-j} + \sum_{j=0}^{k} \gamma_j X'_i \, \Delta \ln(rain_{i,t-j}) + \Delta\lambda_t + \alpha_i + \Delta\varepsilon_{it} \,.$$

We cluster errors by city to account for real and constructed serial correlation. The idea in empirical implementation is that each city is on a growth path and rainfall fluctuations in the local area cause it to deviate from that growth path. If climate changes are more permanent then the growth path is shifted up or down.

The empirical context is different from the urbanization analysis of Section 5 in two important respects. First, we are looking at year-to-year fluctuations rather than 10-15 year changes. This suggests local migration and income responses may be small, but empirically we do find effects. Second, because night lights data are only available after 1991, the period of analysis is shorter and starts later. This affects how we might define 'likely to be industrialized'. Using a map from 30 years before our sample period may not be ideal and by 1990 we have full data at the national level on the extent of industrialization. We thus use a dummy for national agriculture share in GDP (net of mineral resource rents) for 1989-1991 less than 30% as an alternative indicator of a district's propensity to have industry. This leaves 25% of the sample of cities defined as likely to have industry.[26] We use the same moist/arid cutoff of 1.0 at the country level as in most of Table 4. As in Tables 2-4 and the theory, these distinctions are critical.

6.2 Results

6.2.1 Results with heterogeneity by likelihood of the city being industrialized

Table 5 shows effects with heterogeneity based on having industry. As in Section 5, in column 1 the average impact of rainfall on city income (lights) overall is zero. However once we isolate the smaller subsample of cities likely to have industry for export outside the local area, we see effects. In column 2

[26] We assume that Nigeria's agricultural share (net of resource rents) is higher than 30% based on the earliest available data, from the 2000s, when it is above 50%.

where we define this likelihood based on national share of agriculture, the elasticity of lights with respect to rainfall for industrialized areas is -0.074. A one standard deviation increase in rainfall reduces city lights by 5%. Rainfall draws people out of the city and results in a loss in total city income. For agricultural areas the net coefficient is positive (0.028) but not significant. It hints at the idea that increased rainfall in agricultural areas might benefit local towns because migration effects are small but all incomes are larger.

In column 3 we use the extent of agriculture measure from the 1965 map based on modern industries. In the most industrialized areas the elasticity is now -0.17, and in zero industry areas the elasticity is close to 0. In column 4, we also show the all-industry specification. Patterns are similar to those in column 3, but the elasticity for the most industrialized areas is somewhat less than for modern industries. If we take the elasticity of -0.17 for modern industries, and apply the lights-GDP elasticity of about 0.3 from Henderson, Storeygard and Weil (2012), this implies a rainfall-city product elasticity of about -0.051 for the most industrialized places.

6.2.2 Rainfall change effects: Industrialization and initial moisture heterogeneity

In Table 6, we check whether initial moisture levels affect the marginal effects of rainfall variation found in Table 5. Here, based on both results from Section 5 and the fact that we don't have aridity defined for these data at the city level, we focus on the country-level aridity distinction. In column 1, differentiation of rainfall effects by the moisture dummy produces no significant results in the absence of differentiation by industrial propensity. In the remaining columns, the moist or not distinction gives a pattern of results that is informative. In column 2 where we define industrialized or not based on national data, the effect for industrialized arid areas are modestly enhanced relative to the case where we pool arid and moist industrialized areas in Table 5. For moist areas, point estimates suggest effects are zero for both industrialized and non-industrialized areas. In contrast, in column 3 where industrialization is based on the 1965 map for modern industries, the rainfall effects for industrialized areas are the same as in Table 5: moist areas show no difference from arid ones. That pattern is repeated for the all-industry specification in column 4. For the most industrialized areas in arid regions, if we use the elasticity of lights with respect to rainfall for the modern industry specification of -0.17, a one standard deviation increase in rainfall reduces lights by 11%.

Overall, the results are consistent with our model. Rainfall declines raise local city incomes in total for industrialized cities, as labor moves to the urban sector. But for agricultural cities, rainfall declines have a zero or even negative effect on total city incomes. This suggests that local urban areas will be hurt by any further drying out in the future unless they have an export base. Unfortunately, a small fraction of African urban areas do.

6.2.3 Leads and Lags

In Table 7 we test for lagged and lead effects of rainfall using the modern industry specification. Leads are a placebo test; we expect no effects. Column 1 repeats the base case from column 3 in Table 6. In Table 7, column 2 allows for lagged effects and column 3 for lead, with no real evidence of either. Reassuringly, lead effects never appear in a wider set of specifications. In the country-level industrialization specification, there appears to be significant lagged effect of -0.057 for industrialized arid areas (not shown), compared to a contemporaneous effect of -0.093. Experimentation led us to decide that trying to tease out longer lag structures would not produce robust results, and in general the evidence for lagged effects is weak.

6.2.4 Other considerations

We examined whether effects differ for cities that are likely to be served by hydro power. Our concern is that lights could be affected directly by electricity availability and pricing, which could be affected by climate directly, independently of climate effects on income. However, because most towns are served by national grids with uniform pricing, we don't actually expect differential effects. When we fully interacted our Table 6, column 2 specification with a measure of hydropower reliance, we found no differential effect (not shown).

7. Occupational choice within rural areas

Migration, whether temporary or permanent, is not the only possible response to adverse climate fluctuations or long term changes in the rural sector. Drier growing conditions will lower the returns to farming and farmers may leave the labor force or switch to non-farm activities. In this section, we find evidence of both, with differential patterns by gender. These possible responses must be seen in the overall context of climate change in rural economies. As noted above, if farm incomes drop, there will be less money in the rural economy in general, so alternative work opportunities may be scarce, muting the expected benefit of switching to a non-farm occupation. Our data do not provide industry information to analyze shifts between services and manufacturing in the urban sector (which may be second order effects anyway) nor do they provide relevant migration information, so we only consider responses within the rural sector.

7.1 Data and specifications

We test whether changes in climate have an impact on employment by sector within rural areas using individual-level data from the Demographic and Health Surveys (DHS, Macro International) for 18 African countries, all but two of which are in our urbanization dataset (Appendix Table A4). DHS use a two-stage sampling design, first randomly selecting enumeration areas in a country and then surveying a cluster of about 30 randomly selected households in each. The surveys oversample female household members since one of the primary purposes is to collect data on fertility and reproductive health. We compile DHS data from 2-3 repeated cross-sections for each country. In total we use 43 surveys from between 1996 and 2011, and only include people in rural locations. Our sample is restricted to those DHS that record cluster location, whether a respondent worked in the last year or not, and if so in what occupation. Work need not be paid. Summary statistics are in Appendix Table A5. Sample size is 100,788 men and 312,769 women aged 15-49.[27]

While the majority of males and females do report working (paid or unpaid), the percentages are only 82% of men and 67% of women in our sample. We don't think of this as the usual selection problem of whether to work or not and, if so, what occupation to choose based on wage differentials. Working is closely tied to the farm and the decision for many may be more whether to work on the farm or to carry out other household responsibilities not considered work. We thus model a multinomial choice between not working, working in agriculture, and working in a non-agricultural occupation. Thus, an increase in agricultural work may both draw people into the workforce and draw people out of non-agricultural work activities. We note that a comprehensive study of intra-household dynamics and choices is beyond the scope of this paper. Instead, we are estimating the reduced form effects of rainfall on occupation as stated in the surveys.[28]

For both men and women, the dominant activity is working in agriculture but this is especially true of men, both in terms of the choice among the 3 activities (58% of men vs. 44% of women) and conditional on working (71 vs. 66%). The average age of respondents is between 28 and 29 for both men and women. Men generally have more education with about 66% reporting at least primary school versus 53% of women.

Since all surveys used in our study are georeferenced at the cluster level, matching to the Willmott and Matsuura (2012) climate data is straightforward. However, different rounds of the DHS do

[27] Reducing the sample to the 25-49 age group to include only respondents who have completed all possible education does not change results.
[28] Furthermore, we are aware that people in different places may conceptualize work in different ways. Thus while we cannot be sure that we are capturing precisely the same margin in all contexts, we are identifying local changes over time in the way people answer the same question of whether they are working, and if so in what occupation.

not survey the exact same clusters, and the number of clusters typically increases over time. To look at changes in the same approximate locations over time, we created "superclusters" by matching each cluster to the geographically closest cluster in the first survey in its country.

We estimate the multinomial choice of not working, working in agriculture, and working in a non-agricultural occupation. Agricultural work is the reference occupation, so covariates' effects on it are a residual (since marginal effects must sum to zero across the three choices). The general specification is

$$y_{icjt} = \alpha x_{icjt} + \beta W_{cj,t-1} + d_{jt} + f_c + e_{icjt} \tag{15}$$

where

y_{icjt} is a choice for individual i in supercluster c, in country j and year t (i.e., not work, work in agriculture, work outside agriculture);

x_{icjt} are individual characteristics: age (and age squared) and education dummies;

$W_{cj,t-1}$ is average moisture over the three previous years (t-3 to t-1 inclusive);

f_c is a supercluster (or province) fixed effect;

d_{jt} is a country-year fixed effect; and

e_{icjt} is an error term clustered at the supercluster level.

We control for predetermined individual characteristics age and education in x_{icjt}, and estimate separate regressions by gender. We do not include controls for marital status, number of children or other indicators that could plausibly be affected by climate and instead estimate a reduced form model of climate impacts on choice. We again smooth moisture over 3 years to remove noise, but since survey timing varies within the calendar year and this year's climate may not yet have an effect at survey time, we use years *t-3* to *t-1*. We cluster standard errors by supercluster, as measured moisture does not vary within them.

Since these are not individual panel data, we cannot first- or long-difference them, but supercluster fixed effects perform an analogous role in controlling for time-invariant local effects. Inclusion of supercluster fixed effects ensures identification is based on within-cluster variation in rainfall. This is important. For example, in dry and drying areas, non-farm opportunities may be limited and there may be a low probability of non-farm work per se, so simple correlations might suggest a negative association between drying out and non-farm work.

Our main specification is a linear probability model (LPM) with supercluster fixed effects. We also estimate the model by logit and probit, but with 3,939 superclusters for females and 3,751 for males, supercluster fixed effects are not computationally feasible. In these nonlinear models we instead include province fixed effects, assuming that clusters within (larger) provinces have similar conditions. We also control for country-year effects. Multinomial logit and probit marginal effects are almost identical, so we report just the probit.[29]

7.2 Results

The results are in Table 8. We focus on the LPM results in columns 1-3 for women in panel A and for men in panel B. The effects for men and women differ. More moisture draws women out of "not work" and into farming, with no response in off-farm work. More moisture draws men out of non-farm work into farm work. This presumably reflects an average gendered division of labor for this sample. A one standard deviation increase in moisture (about 0.5) increases the probability of women working in farming by 0.03 from a mean of 0.44. Increasing moisture across its full range (3.5) raises the probability of working on the farm by 0.18, a 40% increase. A one standard deviation increase in moisture reduces the probability of men working off farm by about 3%. The control variables have expected effects: the more educated and younger women are, the less likely they are to work in agriculture. Results restricting to the first and last survey in each country are similar (not shown).

As noted above, the province fixed effects used in the probit specification are a much weaker control for underlying local conditions than supercluster fixed effects. Results for the probit in columns 4-6 of Table 8 are different from the LPM. For women probit effects are larger, perhaps reflecting identification problems in the probit, or attenuation bias from the supercluster fixed effects in the LPM. One might thus be tempted to think of the LPM estimates as a lower bound and the probit as an upper bound. However, for men the probit results are much smaller than the LPM, only marginally different from zero for not working. Re-estimating the LPM with just district fixed effects suggests that most of these differences are explained by the differences in fixed effect specification, not in estimation procedure (not shown).

In summary, based on OLS estimation with supercluster fixed effects, when climate for farming improves, women are more likely to leave household work behind to engage in farming, while men are more likely to leave non-farm work. For men at least, drying drives movement into non-farm occupations within the rural sector.

8. Conclusions

[29] Note that the covariance structure with cross-choice correlation in errors is not identified when there is no variation in covariates across choices (only across individuals).

With a high dependence on agriculture and an already highly variable and often marginally suitable agro-climate, Africa may be at higher risk from climate change than most other world regions. Agricultural adaptation through improved seeds and increased irrigation may mitigate this risk. But technological change in Africa has been slow and, despite frequent droughts in the past, irrigation infrastructure remains scarce. So for many farmers facing adverse climatic conditions the only option may be to migrate to urban areas.

Our analysis suggests that agro-climatic conditions do indeed influence urbanization rates, with better conditions retarding urbanization and unfavorable conditions leading to greater urban population growth. However, strong effects are confined to about 20% of Sub-Saharan African districts that have some degree of industrialization.

As our model predicts, decreased moisture increases total city populations and incomes in places whose cities are likely to have manufacturing, and are therefore more likely to be able to absorb workers leaving the farm into the urban labor force. Again as theory predicts, in the more usual context where local cities are unlikely to have manufacturing and rely on demand from local farmers, we find that reduced moisture leads to reduced or unchanged city incomes. Finally, we find some evidence of alternative adaptation strategies. When growing conditions are unfavorable, rural females are more likely to report not working and rural males are more likely to move from farm to non-farm work.

These results confirm the strong link between climatic conditions and urbanization in particular circumstances, adding to the growing economic literature on climate and development. Our results suggest that more severe and persistent climate changes, which will likely increase the challenges faced by Africa's farmers, could further accelerate migration to cities, but only in more industrialized areas. Support for agricultural adaptation, and creating conditions for urban economic growth, are therefore even more urgent priorities.

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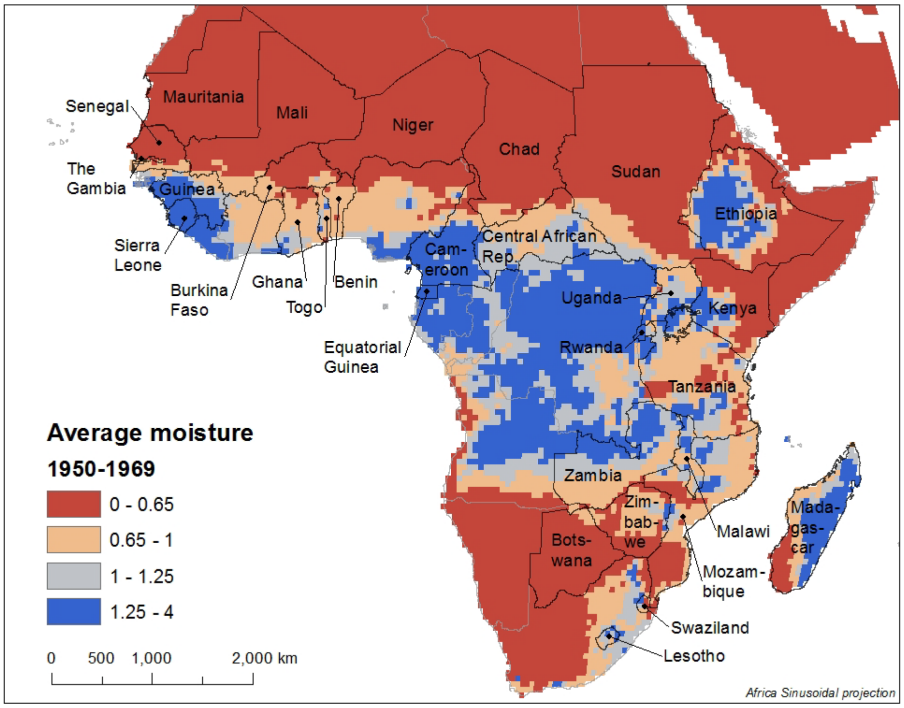
Figure 1: Historical levels of moisture (precipitation / potential evapotranspiration)



Note: Map boundaries reflect the situation during the time period covered by this study. See Appendix Table A1 for details on the time periods used for each country.

Figure 2: Decreasing moisture in Africa in the second half of the twentieth century

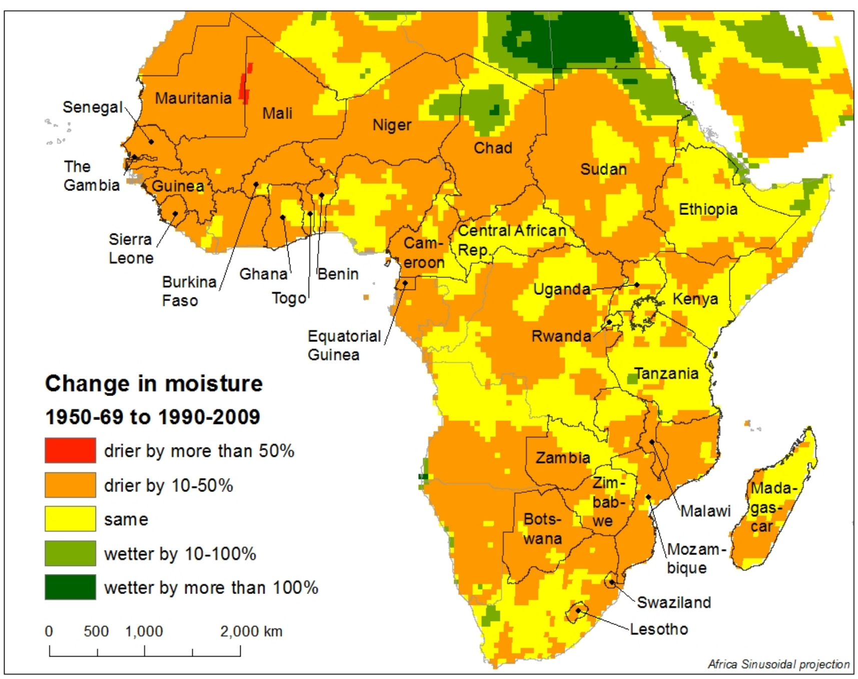
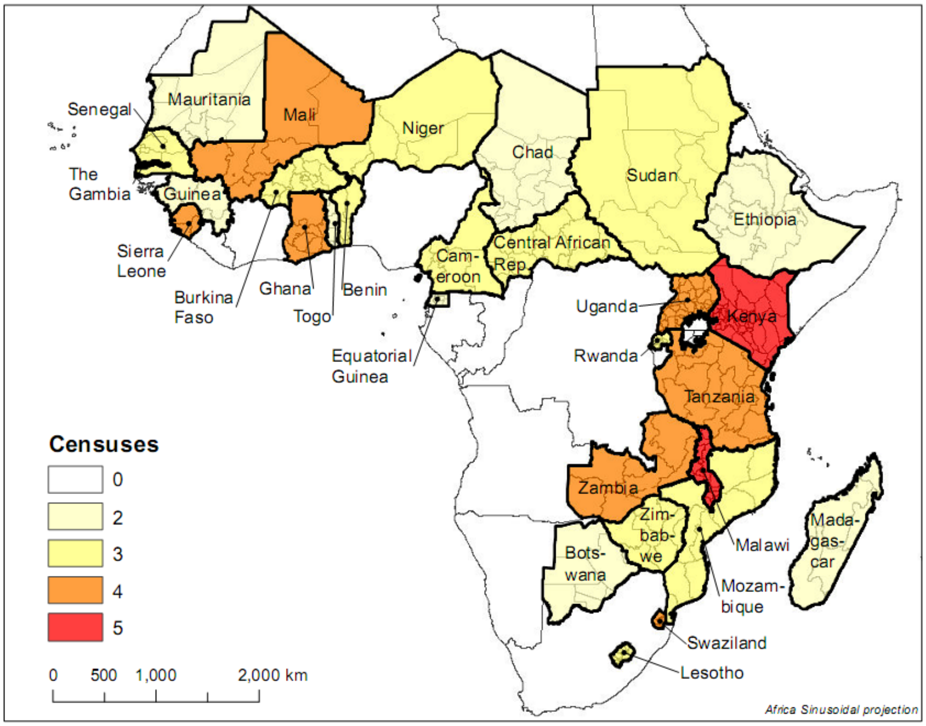


Figure 3. Census data sample



Note: Map boundaries reflect the situation during the time period covered by this study. See Appendix Table A1 for details on the time periods used for each country.

Figure 4. Variability in climate change in Africa

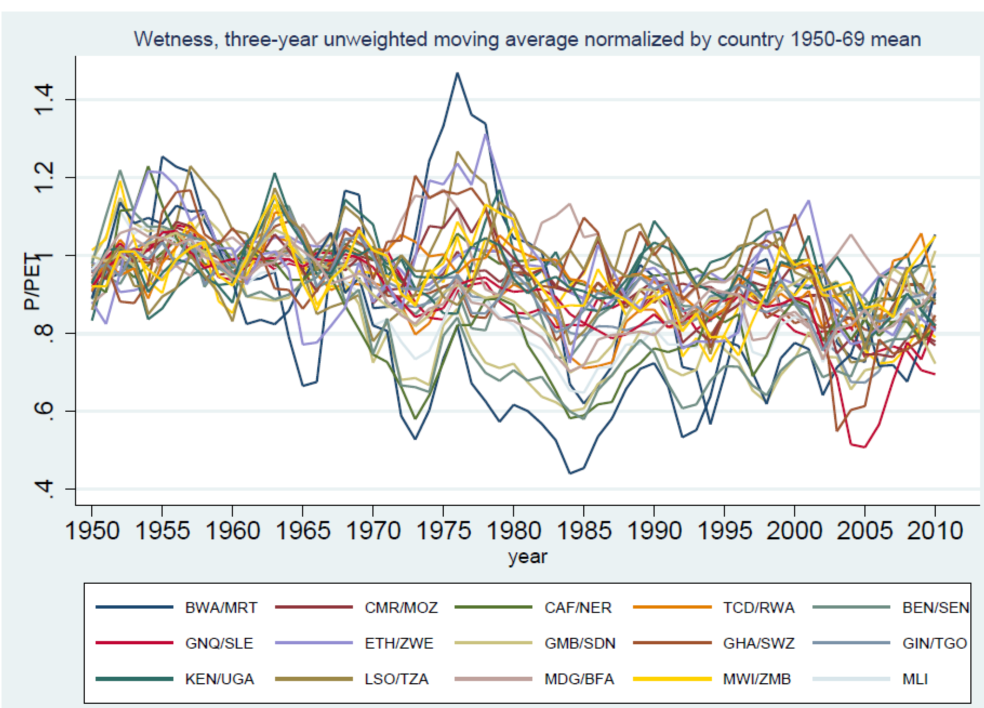


Figure 5a. Extent of industry 1965, modern (non-food processing) industries

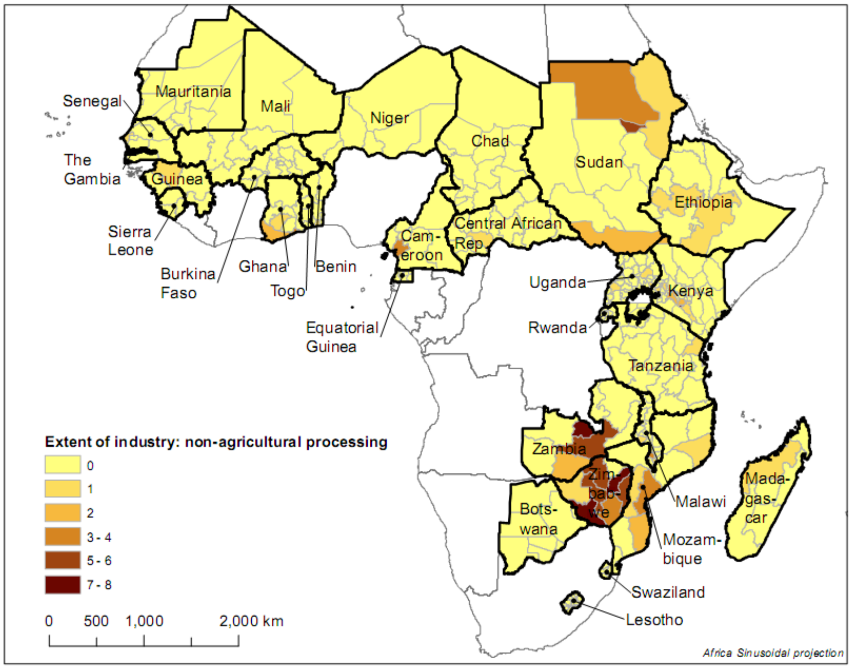


Figure 5b. Extent of industry 1965, all industries

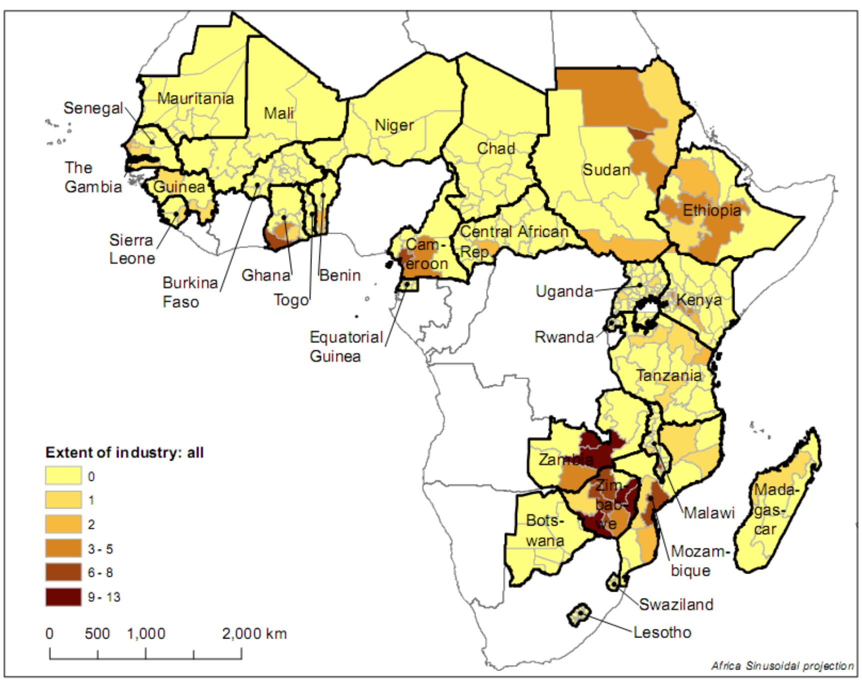


Figure 6. Spread of Dependent Variable

a. Raw data b. Factoring out country fixed effects

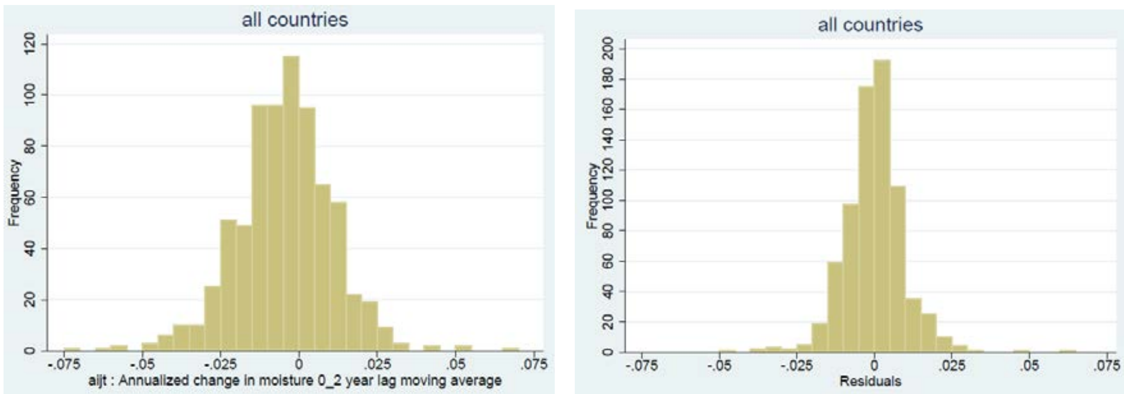


Figure 7. Spatial data integration to obtain city level lights and rain catchment data

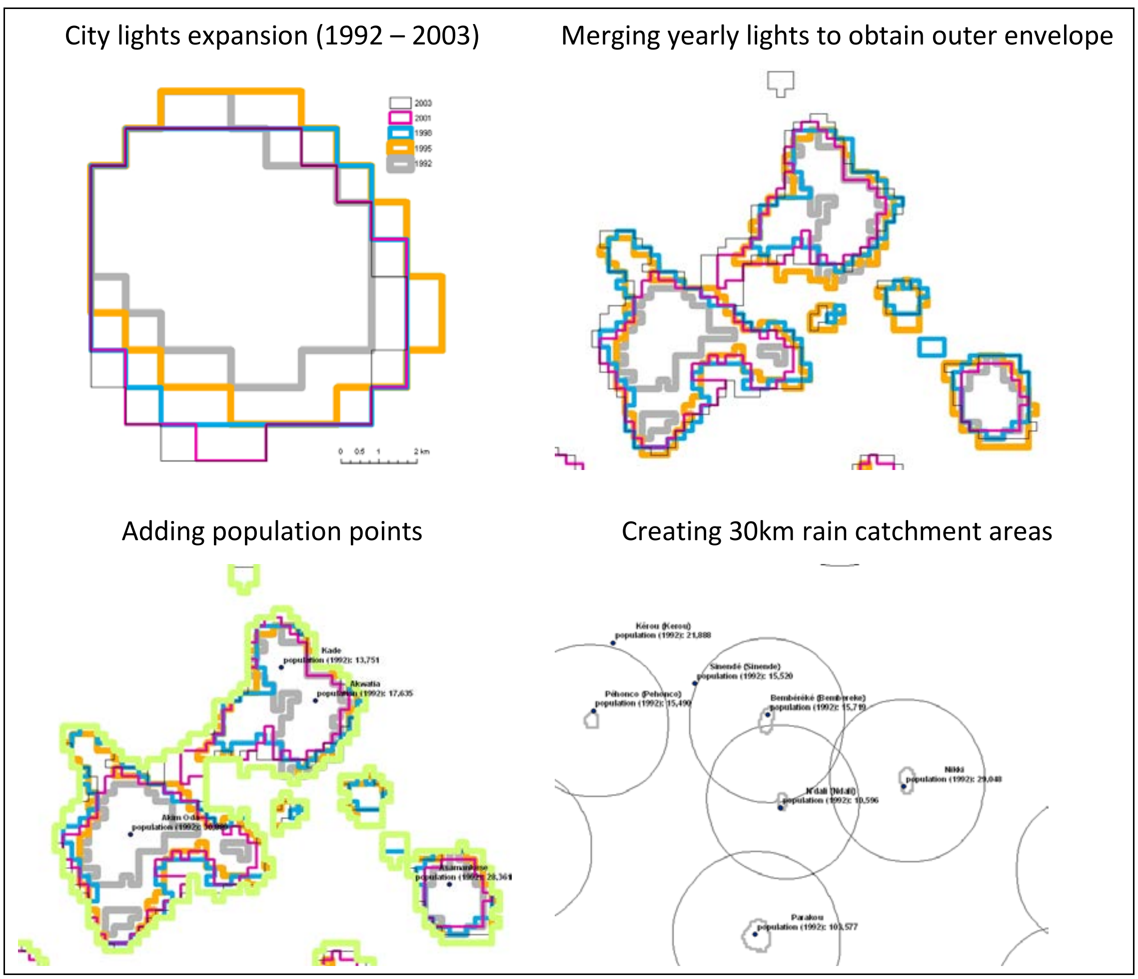


Table 1. Summary Statistics: Urban share growth

	full (N=717)				arid (N=288)			
	Mean	SD	Min	Max	Mean	SD	Min	Max
Annual moisture growth	-0.0044	0.014	-0.047	0.033	-0.0019	0.014	-0.047	0.033
District avg. moist. 1950-69	0.983	0.448	0.031	2.291	0.656	0.301	0.031	1.293
Annual growth: urban share	0.031	0.042	-0.082	0.191	0.027	0.033	-0.038	0.165
Initial urban share	0.137	0.208	0	1	0.181	0.225	0	1
ln(distance to coast)	5.969	1.215	0	7.476	5.678	1.338	0	7.419
area (square kilometers)	33441	63816	53.182	503510	60351	89414	53.182	503510
1(No key industries)	0.893	0.310	0	1	0.878	0.327	0	1
8 - #modern industries	7.530	1.385	0	8	7.396	1.633	0	8
13 - #all industries	12.113	2.333	0	13	11.844	2.711	0	13
1(district moisture > 0.75)	0.696	0.460	0	1	0.368	0.483	0	1

Note: the arid sample is countries with an average 1950-69 moisture index of less than 1

Table 2. Effect of moisture change on urbanization: Heterogeneity by likelihood of industry

	(1)	(2)	(3)	(4)
Δmoisture	-0.0768	-0.622*	-1.017***	-1.136***
	(0.181)	(0.357)	(0.331)	(0.334)
Δmoisture*1(No key industries)		0.620*		
		(0.353)		
Δmoisture*(8 - #modern industries)			0.125***	
			(0.0426)	
Δmoisture*(13 - #all industries)				0.0867***
				(0.0266)
1(No key industries)		0.00249		
		(0.00519)		
8 - #modern industries			-0.000352	
			(0.00131)	
13 - #all industries				0.000217
				(0.000740)
Initial share urban	-0.0499***	-0.0509***	-0.0554***	-0.0524***
	(0.00514)	(0.00715)	(0.00887)	(0.00817)
ln(distance to coast)	0.00121	0.00130	0.00135	0.00129
	(0.00173)	(0.00174)	(0.00171)	(0.00173)

Notes: Each column is a separate regression with 717 observations for 365 districts. The dependent variable is growth in the urbanization rate. 8 and 13 are the maximum number of modern and total industries, respectively, in any given district. Robust standard errors, clustered by district, are in parentheses. All specifications include country*year fixed effects. *** p<0.01, ** p<0.05, * p<0.1

Table 3. Effect of moisture change on urbanization: heterogeneity by degree of aridity

	(1)	(2)	(3)
Δmoisture	-0.409***	-0.295	-0.622**
	(0.136)	(0.193)	(0.241)
Δmoisture*1(country moisture>1)	0.473		
	(0.304)		
Δmoisture*1(district moisture>0.75)		0.334	
		(0.258)	
Δmoisture*District moisture 1950-69			0.545**
			(0.265)
1(district moisture>0.75)		0.0188	
		(0.0202)	
District moisture 1950-69			0.0230
			(0.0187)

Notes: Each column is a separate regression with 717 observations for 365 districts. The dependent variable is growth in the urbanization rate. Controls not reported are initial urbanization and ln(distance to the coast) and each of these interacted with the moisture variable relevant to each column. Robust standard errors, clustered by district, are in parentheses. All specifications include country*year fixed effects. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 4. Effect of moisture change on urbanization: heterogeneity by industrialization and aridity

	(1)	(2)	(3)	(4)	(5)
industry measure	**Key**	**Modern**	**All**	**All**	**All**
aridity measure	**1(country moisture>1)**			**1(dist. moisture>0.75)**	**dist. moisture**
Δmoisture	-0.876***	-1.187***	-1.213***	-1.929***	-2.509***
	(0.194)	(0.361)	(0.367)	(0.460)	(0.880)
Δmoisture*1(No key industries)	0.574***				
	(0.188)				
Δmoisture*(8 - #modern industries)		0.107**			
		(0.0473)			
Δmoisture*(13 - #all industries)			0.0683**	0.132***	0.153**
			(0.0294)	(0.0391)	(0.0716)
Δmoisture*1(country moisture>1)	0.341	0.0789	-0.0803		
	(0.673)	(0.643)	(0.661)		
Δmoisture*1(district moisture>0.75)				1.021**	
				(0.478)	
Δmoisture*District moisture 1950-69					1.395
					(0.955)
Δmoisture*1(No key industries)*1(country moisture>1)	0.0739				
	(0.642)				
Δmoisture*(8 - #modern industries)*1(country moisture>1)		0.0444			
		(0.0800)			
Δmoist_grow*(13 - #all industries)*1(country moisture>1)			0.0400		
			(0.0509)		
Δmoist_grow*(13 - #all industries)*1(district moisture>0.75)				-0.0527	
				(0.0464)	
Δmoist_grow* Extent_ag_all*District moisture 1950-69					-0.0670
					(0.0778)

Notes: Each column is a separate regression with 717 observations for 359 districts. The dependent variable is growth in the urbanization rate. 8 and 13 are the maximum number of modern and total industries, respectively, in any given district. Robust standard errors, clustered by district, are in parentheses. All specifications include country*year fixed effects and controls for initial urbanization, ln (distance to the coast) and the relevant district industry variable. They also include any district moisture variable and each of initial urbanization, ln(distance to coast) and district industry variable interacted with the relevant moisture (district or country) variable. *** p<0.01, ** p<0.05, * p<0.1

Table 5. Change in city output and rainfall: heterogeneity by industrialization

	(1)	(2)	(3)	(4)
Δln(rain)	-0.0095	-0.074***	-0.170***	-0.138***
	(0.012)	(0.015)	(0.066)	(0.052)
Δln(rain)*1(agriculture/GDP>30%)		0.102***		
		(0.022)		
Δln(rain)*(9 - #modern industries)			0.018**	
			(0.008)	
Δln(rain)*(13 - #all industries)				0.0102**
				(0.004)

Notes: Each column is a separate regression with 19685 observations (18527 first differences) for 1,158 cities. The dependent variable is Δln(adjusted lights digital number). 9 and 13 are the maximum number of modern and total industries, respectively, in any given city. Rainfall is measured within a 30 km radius of the city-light. Robust standard errors, clustered by district, are in parentheses. All differenced specifications include city and year fixed effects . *** p<0.01, ** p<0.05, * p<0.1

Table 6. Change in city output and rainfall: industrialization and aridity

	(1)	(2)	(3)	(4)
Δln(rain)	-0.0069	-0.091***	-0.169**	-0.139**
	(0.012)	(0.015)	(0.080)	(0.060)
Δln(rain)*1(agriculture/GDP>30%)		0.133***		
		(0.022)		
Δln(rain)*(9 - #modern industries)			0.018**	
			(0.009)	
Δln(rain)*(13 - #all industries)				0.0105**
				(0.005)
Δln(rain)*1(country moisture>1)	-0.015	0.098*	-0.0051	0.0054
	(0.040)	(0.058)	(0.126)	(0.115)
Δln(rain)*1(country moisture>1)*1(agriculture/GDP>30%)		-0.180**		
		(0.078)		
Δln(rain)*1(country moisture>1)*(9 - #modern industries)			-0.00104	
			(0.016)	
Δln(rain)*1(country moisture>1)*(13 - #all industries)				-0.0016
				(0.010)

Notes: Each column is a separate regression with 19685 observations (18527 first differences) for 1,158 cities. The dependent variable is Δln(adjusted lights digital number). 9 and 13 are the maximum number of modern and total industries, respectively, in any given city. Rainfall is measured within a 30 km radius of the city-light. Robust standard errors, clustered by district, are in parentheses. All differenced specifications include city and year fixed effects . *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 7. Change in city output and rainfall: leads and lags

	(1)	(2)	(3)
Δln(rain(t))	-0.169**	-0.124**	-0.139**
	(0.080)	(0.061)	(0.070)
Δln(rain(t))*(9 - #modern industries)	0.018**	0.012*	0.016**
	(0.009)	(0.007)	(0.008)
Δln(rain(t))*1(country moisture>1)	-0.0051	0.101	0.036
	(0.126)	(0.097)	(0.126)
Δln(rain(t))*(9 - #modern industries)*1(country moisture>1)	-0.00104	-0.0069	-0.0038
	(0.016)	(0.013)	(0.016)
Δln(rain(t-1))		0.0074	
		(0.038)	
Δln(rain(t-1))*(9 - #modern industries)		-0.0059	
		(0.005)	
Δln(rain(t-1))*1(country moisture>1)		-0.037	
		(0.085)	
Δln(rain(t-1))*(9 - #modern industries)*1(country moisture>1)		0.024**	
		(0.012)	
Δln(rain(t+1))			0.039
			(0.051)
Δln(rain(t+1))*(9 - #modern industries)			-0.0016
			(0.006)
Δln(rain(t+1))*1(country moisture>1)			0.068
			(0.138)
Δln(rain(t+1))*(9 - #modern industries)*1(country moisture>1)			-0.012
			(0.018)
Observations	18,527	17,369	17,369
Cities	1,158	1,158	1,158

Notes: The dependent variable is Δln(lights adjusted digital number). 9 and 13 are the maximum number of modern and total industries, respectively, in any given city. Rainfall is measured within a 30 km radius of the city-light. Robust standard errors, clustered by district, are in parentheses. All differenced specifications include city and year fixed effects . *** p<0.01, ** p<0.05, * p<0.1

Table 8. Probability of working in agriculture, other sectors

Panel A: women	**Linear Probability Model**			**Probit**		
	(1)	(2)	(3)	(4)	(5)	(6)
	not work	work non-farm	work farm	not work	work non-farm	work farm
average moisture	-0.055***	-0.004	0.059***	-0.074***	-0.022**	0.096***
	(0.018)	(0.015)	(0.022)	(0.010)	(0.009)	(0.014)
age	-0.044***	0.022***	0.021***	-0.051***	0.024***	0.027***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
$age^2/1000$	0.57***	-0.31***	-0.26***	0.65***	-0.32***	-0.33***
	(0.012)	(0.011)	(0.011)	(0.015)	(0.012)	(0.014)
primary education	-0.018***	0.064***	-0.046***	-0.028***	0.079***	-0.051***
	(0.003)	(0.003)	(0.004)	(0.005)	(0.004)	(0.006)
secondary	0.064***	0.130***	-0.194***	0.087***	0.175***	-0.262***
	(0.005)	(0.004)	(0.006)	(0.007)	(0.006)	(0.009)
Higher	-0.074***	0.435***	-0.360***	0.126***	0.488***	-0.613***
	(0.014)	(0.016)	(0.010)	(0.019)	(0.014)	(0.021)
area fixed effects	supercluster	supercluster	supercluster	province	province	province

Panel B: men	**Linear Probability Model**			**Probit**		
	(1)	(2)	(3)	(4)	(5)	(6)
	not work	work non-farm	work farm	not work	work non-farm	work farm
average moisture	-0.012	-0.055**	0.067***	-0.011*	-0.008	0.019
	(0.013)	(0.022)	(0.025)	(0.006)	(0.011)	(0.013)
age	-0.064***	0.040***	0.025***	-0.053***	0.038***	0.016***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
$age^2/1000$	0.88***	0.57***	-0.31***	0.72***	-0.55***	-0.17***
	(0.016)	(0.018)	(0.018)	(0.015)	(0.021)	(0.022)
primary education	0.028***	0.085***	-0.113***	0.052***	0.110***	-0.162***
	(0.003)	(0.004)	(0.005)	(0.004)	(0.006)	(0.006)
secondary	0.122***	0.140***	-0.262***	0.139***	0.199***	-0.338***
	(0.005)	(0.006)	(0.007)	(0.005)	(0.007)	(0.008)
higher	0.074***	0.453***	-0.527***	0.203***	0.496***	-0.700***
	(0.009)	(0.013)	(0.011)	(0.010)	(0.012)	(0.016)
area fixed effects	supercluster	supercluster	supercluster	province	province	province

Notes: Each LPM column reports coefficients from one regression. The three probit columns report marginal effects from a single multinomial regression with farm work as the reference category. Female sample size is 312,769 individuals in 3,939 superclusters in 148 provinces in 18 countries over 43 country-years. Male sample size is 100,788 individuals in 3,751 superclusters in 121 provinces in 16 countries over 37 country-years. All regressions contain country*year fixed effects, in addition to the smaller area fixed effects listed. Robust standard errors, clustered by supercluster, are in brackets. *** p<0.01, ** p<0.05, * p<0.1.

Table A1. Urbanization country sample

Country	# units	Year 0	Year 1	Year 2	Year 3	Year 4	Cen-suse	mis-sing*	panel units
Benin	6	1979	1992	2002			3		12
Burkina Faso	12	1985	1996	2006			3		24
Botswana	8	1991	2001				2		8
C. Afr. Rep.	16	1975	1988	2003			3		32
Cameroon	7	1976	1987	2005			3		14
Eq. Guinea	6	1983	1994				2		6
Ethiopia	11	1994	2007				2		11
Ghana	7	1960	1970	1984	2000		4		21
Guinea	4	1983	1996				2		4
Gambia	7	1993	2003				2		7
Kenya	39	1969	1979	1989			3	8	70
Kenya (2)	40	1999	2009				2		40
Lesotho	10	1986	1996	2006			3		20
Madagascar	6	1975	1993				2		6
Mali	8	1976	1987	1998	2009		4		24
Mozambique	11	1980	1997	2007			3	1	21
Mauritania	13	1977	1988				2		13
Malawi	23	1966	1977	1987	1998	2008	5		92
Niger	7	1977	1988	2001			3		14
Rwanda	9	1978	1991	2002			3		18
Sudan	9	1973	1983	1993			3		18
Senegal	8	1976	1988	2002			3		16
Sierra Leone	4	1963	1974	1985	2004		4		12
Swaziland	4	1966	1976	1986	1997		4		12
Chad	14	1993	2009				2		14
Togo	5	1970	1981				2		5
Tanzania	21	1967	1978	1988	2002		4	1	62
Uganda	38	1969	1980	1991	2002		4	8	106
Zambia	8	1969	1980	1990	2000		4	1	23
Zimbabwe	8	1982	1992	2002			3		16
Total	369		30 countries				89	19	741

*= sample is smaller by this number in the initial intercensal period (first two in Uganda) because of some units with zero urban

Table 2a. Varying smoothing, trimming and controls in Table 2, column 4

	Base	**Trimming**				
	(1)	(2)	(3)	(4)	(5)	(6)
Δmoisture	**-1.136*** **	-1.467**	-0.820**	-0.868***	-1.120***	-1.052***
	(0.334)	(0.576)	(0.318)	(0.323)	(0.329)	(0.272)
Δmoisture	**0.0867*** **	0.123***	0.0740***	0.0685***	0.0898***	0.0796***
*(13-#all industries)	**(0.0266)**	(0.0456)	(0.0250)	(0.0260)	(0.0257)	(0.0222)
13 - #all industries	**0.000217**	-0.00192	-0.000132	5.88e-05	0.000238	0.000561
	(0.000740)	(0.00125)	(0.000787)	(0.000746)	(0.000750)	(0.000711)
Initial share urban	**-0.0524*** **	-0.0782***	-0.0569***	-0.0535***	-0.0523***	-0.0479***
	(0.00817)	(0.0153)	(0.00917)	(0.00837)	(0.00794)	(0.00678)
ln(distance to coast)	**0.00129**	0.00190	0.00207	0.00195	0.00123	0.000824
	(0.00173)	(0.00171)	(0.00168)	(0.00169)	(0.00171)	(0.00149)
Observations	**717**	741	733	725	709	677
Trimmed	**24**	0	8	16	32	64
Smoothing	**0-2**	0-2	0-2	0-2	0-2	0-2
districts	**359**	369	366	363	356	350

	Drop controls			**Smoothing**		
	(7)	(8)	(9)	(10)	(11)	(12)
Δmoisture	-0.836**	-1.112***	-0.959**	-0.479*	-1.028***	-1.131*
	(0.370)	(0.329)	(0.374)	(0.281)	(0.356)	(0.582)
Δmoisture	0.0659**	0.0863***	0.0704**	0.0357	0.0725**	0.0825*
*(13-#all industries)	(0.0293)	(0.0263)	(0.0297)	(0.0233)	(0.0296)	(0.0470)
13 - #all industries	0.00368***	0.000236	0.00312***	0.000104	8.61e-05	0.000208
	(0.000427)	(0.000743)	(0.000517)	(0.000731)	(0.000756)	(0.000794)
Initial share urban		-0.0546***		-0.0505***	-0.0513***	-0.0515***
		(0.00822)		(0.00798)	(0.00809)	(0.00818)
ln(distance to coast)			0.00456**	0.00125	0.00139	0.00127
			(0.00184)	(0.00173)	(0.00174)	(0.00175)
Observations	717	717	717	717	717	717
Trimmed	24	24	24	24	24	24
Smoothing	0-2	0-2	0-2	0-1	0-3	0-4
districts	359	359	359	359	359	359

Notes: see notes to Table 2

Table 2b. Varying trimming and controls in Table 4, column 3

	Base	Trimming					Controls		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Δmoisture	**-1.213*** **	-2.067**	-0.876**	-0.894**	-1.218***	-1.538***	-1.059***	-1.204***	-1.131***
	(0.367)	(1.026)	(0.357)	(0.373)	(0.368)	(0.361)	(0.352)	(0.369)	(0.348)
Δmoisture*(13 - #all industries)	**0.0683** **	0.151*	0.0502*	0.0468	0.0676**	0.0923***	0.0528*	0.0679**	0.0576**
	(0.0294)	(0.0846)	(0.0286)	(0.0292)	(0.0298)	(0.0287)	(0.0277)	(0.0295)	(0.0275)
Δmoisture*1(country moisture>1)	**-0.0803**	0.734	-0.272	-0.316	-0.0490	0.778	0.245	0.0160	0.0206
	(0.661)	(1.166)	(0.638)	(0.645)	(0.653)	(0.513)	(0.656)	(0.637)	(0.695)
Δmoist_grow*(13 - #all industries)	**0.0400**	-0.0290	0.0589	0.0562	0.0440	-0.0233	0.0271	0.0361	0.0359
*1(country moisture>1)	**(0.0509)**	(0.0931)	(0.0474)	(0.0488)	(0.0499)	(0.0407)	(0.0511)	(0.0496)	(0.0532)
Controls for initial urban share and log distance to coast	**All**	All	All	All	All	All	None	Initial Urb	coast
Observations	**717**	741	733	725	709	677	717	717	717
Trimmed	**24**	0	8	16	32	64	24	24	24
Smoothing	**0-2**	0-2	0-2	0-2	0-2	0-2	0-2	0-2	0-2
districts	**359**	369	366	363	356	350	359	359	359

Notes: see notes to Table 4

Table A3. Summary statistics for lights data

Variable	Count	Mean	SD	Min	Max
ln(rain) 30km	19685	0.701	0.69	-8.589	2.469
%GDP (net of res. rents) in agriculture (89-91)	18359	37.23	15.37	3.19	68.63
Dummy: %GDP in agriculture > 30%	19685	0.738	0.44	0	1
Δln(rain) 30 km	18527	0.011	0.33	-4.996	6.022
Δln(adjusted lights)	18527	0.065	0.68	-6.792	6.970
8 - #modern industries	19705	8.833	0.85	0	9
13 - #all industries	19705	12.687	1.40	0	13

Table A4. DHS data sets used in the occupational choice analysis

Country	Years	Note
Benin	1996, 2001	
Burkina Faso	1998-1999, 2003, 2010-2011	
Cameroon	2004, 2011	
Ethiopia	2000, 2005, 2010-2011	
Ghana	1998-1999 (female only),	
Guinea	1999, 2005	
Kenya	2003, 2008-2009	
Lesotho	2004-2005, 2009-2010	
Madagascar	1997, 2008	female only
Malawi	2000, 2004-2005, 2010	
Mali	1995-1996, 2001, 2006	
Namibia	2000, 2006-2007	
Nigeria	2003, 2008	
Rwanda	2005, 2010-2011	
Senegal	2005, 2010-2011	
Tanzania	1999, 2009-2010	female only
Uganda	2000-2001, 2006, 2011	
Zimbabwe	1999 (female only), 2005-	

Table A5. Summary statistics for the DHS data

	Men (N=100,788)				Women (N=312,769)			
	Mean	Std. dev.	Min	Max	Mean	Std. dev.	Min	Max
Agriculture	0.585	0.493	0	1	0.439	0.496	0	1
Not Working	0.178	0.382	0	1	0.334	0.472	0	1
Other Occupation	0.238	0.426	0	1	0.227	0.419	0	1
Primary	0.425	0.494	0	1	0.377	0.485	0	1
Secondary	0.248	0.432	0	1	0.152	0.359	0	1
Post-secondary	0.027	0.161	0	1	0.010	0.098	0	1
Age	28.36	9.847	15	49	28.624	9.61	15	49
Avg. moisture	0.874	0.48	0.02	3.49	0.881	0.489	0.02	3.491